

Lecture # 1 :

Subject: Selection of Engineering Materials

References:

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 2. Selection and use of Engineering Materials, by FAA Crane & JA Charles, 1987.
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 5. Nanomaterials Handbook, Edited by Yury Gogotsi, 2006.
 6. Nanostructured Materials: Processing, Properties and Potential Applications, Edited by Carl C. Koch, 2002.
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1. Introduction to Roles & Responsibilities of Materials Engineer:

Some of Materials Engineer responsibilities are :

1) Design Process:

- a) Drawing the basic design.
- b) Proper selection of materials :

Selection according to different parameters such as :

- Mechanical loads,
- Wear,
- Electrical insulation,
- Thermal properties
- Availability & cost.

This includes: Selection of the proper manufacturing processes,

- 2) Proper choice (selecting) of substitute (alternative) materials when needed.
- 3) Contributing and evaluating materials tests results,
- 4) Studying and composing materials data sheets before placing an order,
- 5) Enhancing the performance of the materials by carrying out research activities.

2. Introduction to Materials Selection:

One of the most challenging task of materials engineer is the proper selection of the material for a particular job, *e.g.*, a particular component of a machine or structure. An engineer must be in a position to choose the optimum combination of properties in a material at the lowest possible cost without compromising the quality.

Factors affecting the selection of materials:

(i) Component shape:

The shape and size of a component has great effect on the choice of the processing unit which ultimately effects the choice of the material. To make it more clear, we consider an example, let the best possible production method is selected, under given conditions, it is *die casting*, obviously, now the choice of the material becomes limited, i.e. one can only choose materials with lower melting points, *e.g. aluminium, zinc, magnesium* and *thermoplastics*.

(ii) Dimensional tolerance:

There are some materials which can be finished to close tolerance while others cannot. Obviously, the required dimensional tolerance for finished components will, influence the choice of materials.

(iii) Mechanical properties:

To select a suitable material for specific conditions, all mechanical properties, *e.g.*, toughness, hardness, strength, etc. guide us.

(iv) Fabrication (Manufacturing) requirements:

Method of processing of the material also affects the properties of a component, *e.g.*, *forged components* can be stronger than the *casted components*. Different types of working processes may also give different types of fibre structure. However, investment casting can provide precise dimensions at low cost in comparison to machine operations.

Note: fabrication requirements are: castability, i.e., ease in casting a material, weldability-ease in welding the material, machinability-ease to machine a material, formability-ease to form a material, hardenability etc.

(v) Service requirements:

Service requirements are :

- ✓ dimensional stability,
- ✓ strength,
- ✓ toughness,
- ✓ heat resistance,
- ✓ corrosion resistance,
- ✓ fatigue and creep resistance,
- ✓ electrical and thermal conductivity etc.

(vi) Cost :

(A) Cost of the material:

In most of the cases, the cost of raw material accounts about 50 % of the finished cost. Obviously, the cost of the material is a major factor which influences the choice of the material or process. We must note that the use of cheaper material will not always reduce the final cost of the component or product. Use of cheaper material may be associated with higher processing cost due to large number of operations to be performed and also more scrap. We can easily see that this sometimes makes the overall cost more than that of expensive raw material in combination with low processing cost due to lesser number of operations and lesser scrap. The type of material affects the detailed aspect of design and hence the choice of material as well as the process is selected at the early design state *e.g.* whether the material is to be joined by spot welding, screws or rivetes, must be decided at the design state.

(B) Cost of processing:

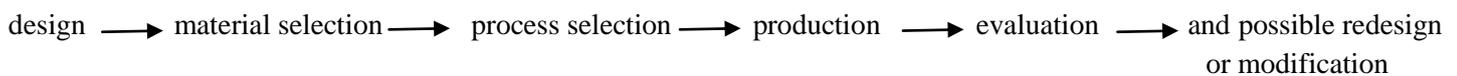
In most of the industries, the processing cost (labour cost) and other costs such as overhead costs account for about 50% of the production cost. Overhead cost in automatic industries is much more than the other costs. If one can somehow reduce all such costs, the total production cost will automatically reduce.

(vii) Availability of the material:

We may find that sometimes the availability of the material becomes a governing factor. When the desired material supply is limited, then a costly material which is available in ample quantity may be chosen.

Procedure for materials selection:

The selection of an appropriate material and its subsequent conversion into a useful product with desired shape and properties can be a rather complex process. Nearly every engineered item goes through a sequence of activities that includes:



Summary:

The selection of a specific material for a particular use is a very complex process. However, one can simplify the choice if the details about:

- (i) operating parameters,
- (ii) manufacturing processes,
- (iii) functional requirements
- (iv) cost considerations are known.

Table 1.1 Factors affecting selection of materials

(i) <i>Manufacturing processes</i>	(ii) <i>Functional requirements</i>	(iii) <i>Cost considerations</i>	(iv) <i>Operating parameters</i>
<ul style="list-style-type: none"> • Plasticity • Malleability • Ductility • Machinability • Casting properties • Weldability • Heat • Tooling • Surface finish 	<ul style="list-style-type: none"> • Strength • Hardness • Rigidity • Toughness • Thermal conductivity • Fatigue • Electrical treatment • Creep • Aesthetic look 	<ul style="list-style-type: none"> • Raw material • Processing • Storage • Manpower • Special treatment • Inspection • Packaging properties • Inventory • Taxes and custom duty 	<ul style="list-style-type: none"> • Pressure • Temperature • Flow • Type of material • Corrosion requirements • Environment • Protection from fire • Weathering • Biological effects

- Therefore, when we talk about choosing materials for a component, we take into account many different factors. These factors can be broken down into the following areas:

Material Properties

The expected level of performance from the material

Material Cost and Availability

- Material must be priced appropriately (not cheap but right)
- Material must be available (better to have multiple sources)

Processing

- Must consider how to make the part, for example:
- Casting
- Machining
- Welding

Environment

- The effect that the service environment has on the part
- The effect the part has on the environment
- The effect that processing has on the environment

Lecture # 2 & 3 :

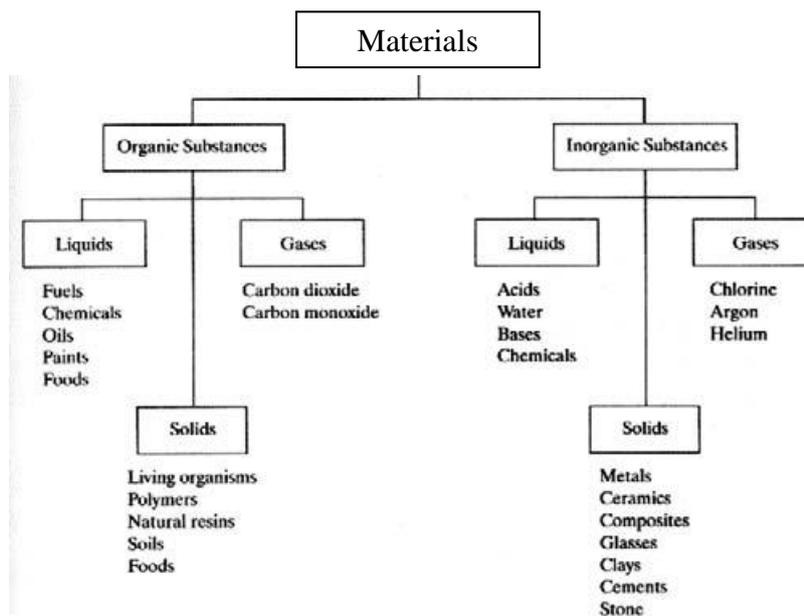
3. Introduction to Engineering Materials:

Basic Classifications of Materials:

The basic factors for classifications of materials in material science and engineering are:

- (i) The chemical composition of the material,
- (ii) The mode of the occurrence of the material in the nature,
- (iii) The refining and the manufacturing process to which the material is subjected prior it acquires the required properties,
- (iv) The atomic and crystalline structure of material.
- (v) The industrial and technical use of the material.

According to **Budinski** : materials may be classified as shown below:



Generally, materials engineering may be classified into the following categories:

- 1) Metals and alloys.
- 2) Ceramics.
- 3) Polymers.
- 4) Composites.
- 5) Advanced materials: such as semiconductors, biomaterials, smart materials, and nanoengineered materials.

1.) Metals and alloys:

Metals are elements which have free valence electrons which are responsible for their good thermal and electrical conductivity. Metals readily lose their electrons to form positive ions. The metallic bond is held by electrostatic force between delocalized electrons and positive ions.

Note : Engineering metals are generally *Alloys*. There are metallic materials formed by mixing two or more elements, such as:

- Mild steel Fe + C
- Stainless steel Fe + C + Cr + Mn ...etc.
 - C → improves strength
 - Cr → improves the corrosion resistance ...etc.

✓ **Classification of metals and alloys:**

- Ferrous:
Such as : *Plain carbon steel, Alloy steel, Cast iron,*
- Nonferrous:
Such as : *Light Alloys (Al, Mg, Ti, Zn), Heavy Alloys (Cu, Pb, Ni), Refractory Metals (Mo, Ta, W), Precious metals (Au, Ag, Pt)*

✓ **General properties:**

- High electrical conductivity.
- High thermal conductivity.
- Ductile and relatively high stiffness.
- Toughness and strength.
- They are ready to machining, casting, forming, stamping and welding.
Nevertheless, they are susceptible to corrosion.

✓ **Applications:**

- Structures: buildings, bridges, etc.
- Automobiles: body, springs, engine block, etc.
- Airplanes: engine components, fuselage, landing gear assembly, etc.
- Trains: rails, engine components, body, wheels
- Machine tools: drill bits, hammers, screwdrivers, saw blades, etc.
- Electrical wiring.
- Magnets

✓ **Examples:**

- Pure metal elements (Cu, Fe, Zn, Ag, etc.)
- Alloys (bronze =Cu-Sn, brass=Cu-Zn, steel=Fe-C)

2.) Ceramics:

Inorganic, non-metallic crystalline compounds, usually oxides (SiO_2 , Al_2O_3 , MgO , TiO_2 , BaO), Carbides (SiC), Nitrides (Si_3N_4), Borides (TiB_2), Silicides (WSi_2 , MoSi_2). Some literature includes glasses in the same category, however; glasses are amorphous (non-crystalline) compounds i.e. they possess “short range” order of atoms.

✓ Classification:

There are various classification systems of ceramic materials, which may be attributed to one of two principal categories: *application base system* or *composition base system*.

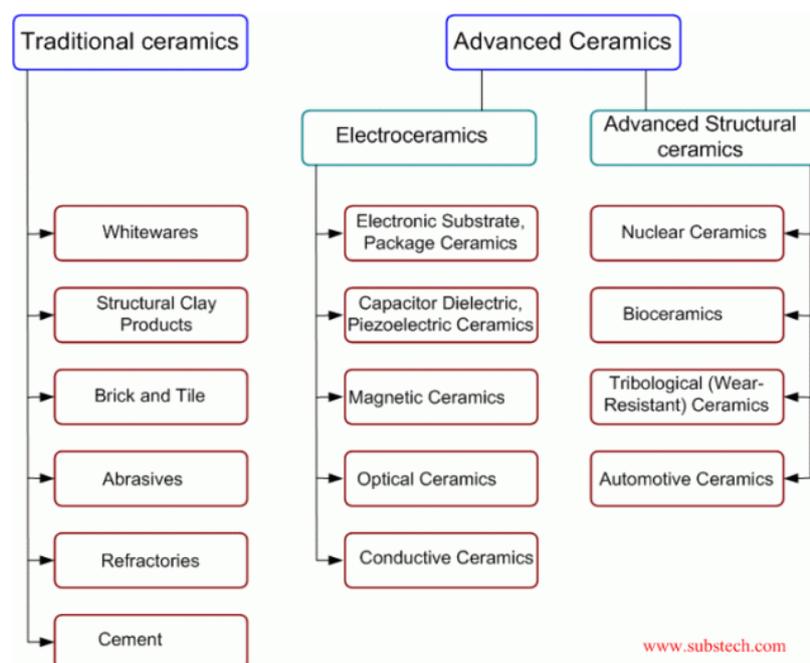
✚ Application base classification of ceramic materials:

i. Traditional Ceramics:

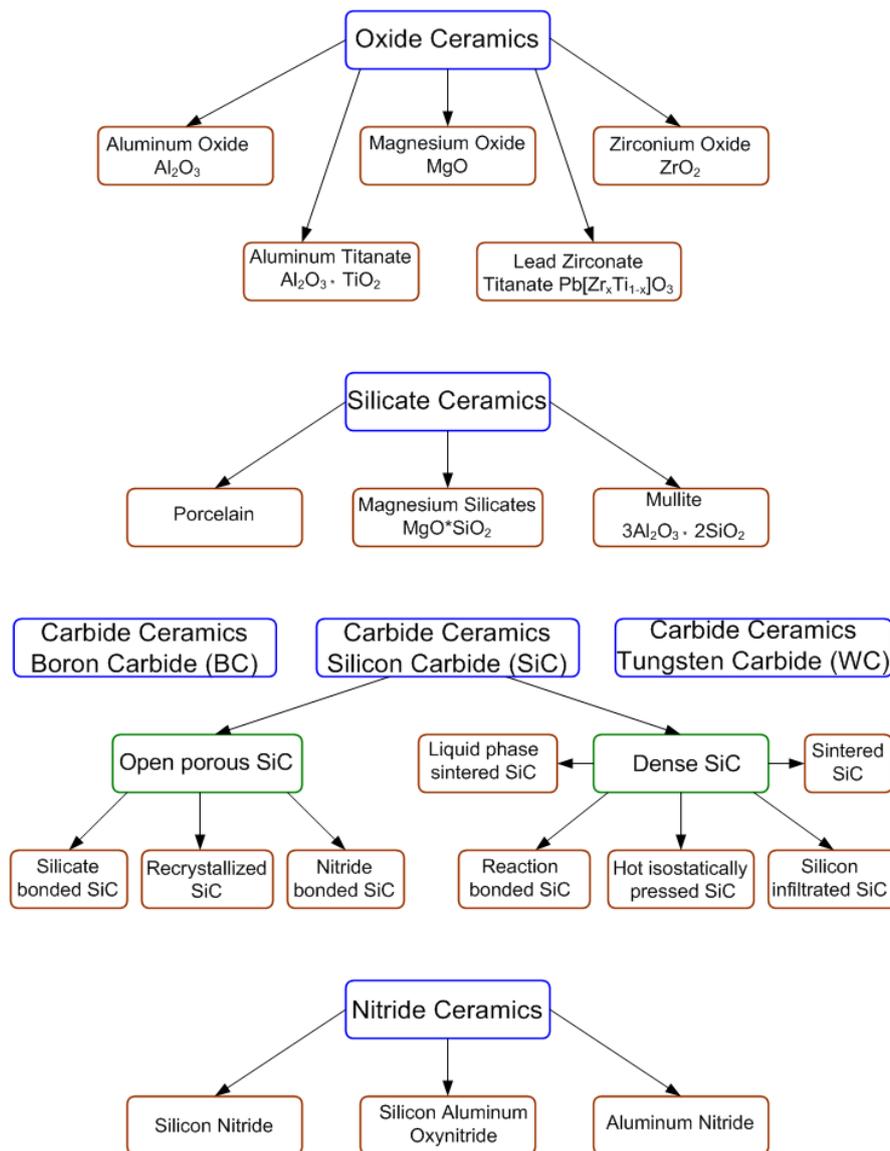
Includes pottery, china, porcelain products...etc, these products utilizes natural ceramic ores.

ii. Advanced Ceramics:

Alumina, magnesia, Carbides, Nitrides, Borides, Silicides ...etc, they are synthetic materials, usually of better mechanical properties. Electronic ceramics falls in the same category.



Composition base classification of ceramic materials:



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✓ **General properties:**

- Light weight.
- Hard.
- High strength.
- Stronger in compression than tension.
- Tend to be brittle.
- Low electrical conductivity,
- High temperature resistance.
- Corrosion resistance.

✓ **Applications:**

- Electrical insulators
- Thermal insulation and coatings
- Windows, television screens, optical fibers (glass)
- Corrosion resistant applications
- Electrical devices: capacitors, varistors, transducers, etc.
- Highways and roads (concrete).
- Building blocks (bricks).
- Building binders (cement, gypsum).
- Biocompatible coatings (fusion to bone)
- Magnetic materials (audio/video tapes, hard disks, etc.)

3.) **Polymers:**

A **polymer** (the name means "many parts") is long chain molecule made up many repeating units, called **monomers**. Polymers can be natural (organic) or synthetic. The properties of polymers are linked directly to their structure, which is dictated mostly by intermolecular bonds.

✓ **Examples:**

Polymers are everywhere: in plastics (bottles, toys, packaging), cosmetics, shampoos and other hair care products, contact lenses, nature (crab shells, amber), food (proteins, starches, gelatin, gum, gluten), fabric, balls, sneakers, and even in your DNA!.

✓ **General properties:**

Compared with metals:

- Polymers have lower density, lower stiffness and tend to creep.
- High thermal expansion and corrosion resistance.
- Low electrical and thermal conductivities.
- The prime weakness is that polymers do not withstand high temperatures.

✓ **Description of polymers:**

Polymers generally formed via a "Polymerization Process", in which the polymer chain builds up from monomers with the aid of heat and/or chemical agents. The C-C bonds form the backbone of the polymer chain; when the chains grow very long, they get tangled (twisted) and lose their lattice order, thus, changing increasingly to the amorphous state. Consequently, polymers are semi-crystalline to some "degree of crystallinity" that can be measured by X-ray Diffraction.

✓ **Classification:** according to their properties:

i.) Plastics: (Hard), they can be semi-crystalline or amorphous (glassy).

1. Thermoplastics: such as Polyethylene (PE) and Polymethylmethacrylate (Acrylic and PMMA) are composed of “linear” polymer chains. They flow under shear when heated. They can be compression- or injection- molded.

2. Thermosets: such as Polystyrene (PS) and Polyvinylchloride (PVC) are composed of “branched” polymer chains. They not flow when heated. The monomers are ‘cured’ in a mold.

ii.) Elastomers: (Soft) Rubbery cross-linked solids that will deform elastically under stress, e.g. natural rubber

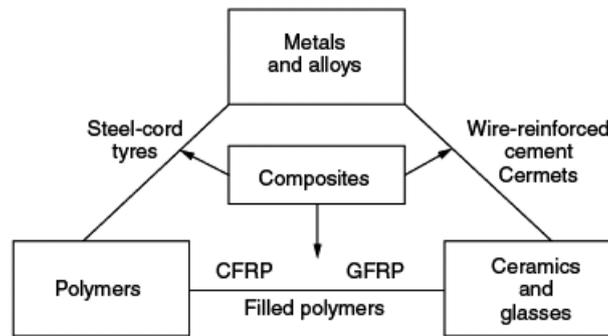
iii.) Solutions: Viscosity modifiers, lubricants.

✓ **Applications & Examples**

- Adhesives and glues
- Containers
- Moldable products (computer casings, telephone handsets, disposable razors)
- Clothing and upholstery material (vinyls, polyesters, nylon)
- Water-resistant coatings (latex)
- Biomaterials (organic/inorganic interfaces)
- Liquid crystals
- Low-friction materials (Teflon)
- Synthetic oils and greases
- Soaps and surfactants

4.) Composite:

- A combination of two or more materials to achieve better properties than that of the original materials. These materials are usually composed of a “Matrix” and one or more of “Filler” material.
- The primary objective of engineering composites is to increase **strength to weight ratio**.
- Composite material properties are not necessarily *isotropic*, i.e., directional properties can be synthesized according to the type of filler materials and the method of fabrication.



✓ **General properties:**

- Low weight,
- High stiffness.
- Brittle.
- Low thermal conductivity.
- High fatigue resistance.
- Their properties can be **tailored** according to the component materials.

✓ **Classification:**

i.) Particulate composites (small particles embedded in a different material): e.g. Cermets (Ceramic particle embedded in metal matrix) and Filled polymers.

ii.) Laminate composites: e.g. (golf club shafts, tennis rackets).

iii.) Fiber reinforced composites: e.g. Fiber glass (GFRP) and Carbon-fiber reinforced polymers (CFRP)

✓ **Applications:**

- Sports equipment (golf club shafts, tennis rackets, bicycle frames)
- Aerospace materials
- Thermal insulation
- Concrete
- "Smart" materials (sensing and responding)
- Brake materials

✓ **Examples:**

- Reinforced cement concrete, a structural composite obtained by combining cement (the matrix, i.e., the binder, obtained by a reaction known as hydration, between cement and water), sand (fine aggregate), gravel (coarse aggregate), and, thick steel fibers.
- Wood is a natural composite of cellulose fibers in a matrix of polymer called lignin.

➤ Summary of some types of materials:

Table 1.3 Important grouping of materials

<i>Material group (1)</i>	<i>Important characteristics (2)</i>	<i>Typical examples of engineering use (3)</i>
1. Metals and Alloys	Lusture, hardness, thermal and electrical conductivity, resistance to corrosion, malleability, stiffness and the property of magnetism	Iron and steels, aluminium, copper, silver, gold, zinc, magnesium, brasses, bronzes, manganin, invar, super alloy, boron, rare-earth alloys, conductors, etc.

(Contd.)

(Contd.)

<i>Material group (1)</i>	<i>Important characteristics (2)</i>	<i>Typical examples of engineering use (3)</i>
2. Ceramics and Glasses	Thermal resistance, hardness, brittleness, opaqueness to light, electrical insulation abrasiveness, high temperature strength and resistance to corrosion	Silica, soda-lime-glass, concrete, cement, refractories, Ferrites and garnets, ceramic superconductors, MgO, CdS, Al ₂ O ₃ , SiC, BaTiO ₃ , etc.
3. Organic Polymers	Soft, light in weight, poor conductors of electricity and heat, dimensionally unstable, ductile, combustible, low thermal resistance	<i>Plastics:</i> PVC, PTFE, polyethylene, polycarbonate <i>Fibres:</i> terylene, nylon, cotton, natural and synthetic rubbers, leather <i>Other uses:</i> refrigerants, explosives, insulators, lubricants, detergents, fuels, vitamins, medicines for surface treatment, adhesives, fibre-reinforced plastics, etc.
4. Composites (i) Metals and alloys and ceramics (ii) Metals and alloys and organic polymers (iii) Ceramics and organic polymers	They are better than any of the individual components as regards to their properties like strength, stiffness, heat resistance, etc.	<ul style="list-style-type: none"> • Steel-reinforced concrete, dispersion hardened alloys. • Vinyl coated steel, whisker-reinforced plastics. • Fibre-reinforced plastics, carbon-reinforced rubber.

Table 1.4 Important properties for different groupings of materials

<i>Property</i>	<i>Metals</i>	<i>Ceramics</i>	<i>Polymers</i>	<i>Composites (wood)</i>
1. Tensile strength (N/mm ²)	200–2000	10–400	30–100	20–110
2. Density (10N/mm ²)	2–8 × 10 ³	2–17 × 10 ³	1–2 × 10 ³	0.5 × 10 ³
3. Hardness	medium	high	low	low
4. Tensile modulus (10 ³ N/mm ²)	100–200	150–450	0.7–3.5	4–20
5. Melting point (°C)	200–3500	2000–4000	70–200	—
6. Thermal expansion	medium	low	high	low
7. Thermal conductivity	high	medium	low	low
8. Electrical conductivity	good conductors	insulator	insulator	insulator

5.) Advanced Materials:

Materials that are utilized in high-technology (or high-tech) applications are sometimes termed *advanced materials*. *High technology* mean a device or product that operates or functions using relatively intricate and sophisticated principles; examples include electronic equipment (camcorders, CD/DVD players, etc.), computers, fiber-optic systems, spacecraft, aircraft, and military rocketry. These advanced materials are typically traditional materials whose properties have been enhanced, and also newly developed, high-performance materials. They may be of all material types (e.g., metals, ceramics, polymers), and are normally expensive.

Advanced materials include:

- *Semiconductors* (having electrical conductivities intermediate between conductors and insulators).
- *Biomaterials* (which must be compatible with body tissues).
- *Smart materials* (those that sense and respond to changes in their environments in predetermined manners).
- *Nanomaterials* (those that have structural features on the order of a nanometer, some of which may be designed on the atomic/molecular level).

➤ **Semiconductors**

- Semiconductors have electrical properties that are intermediate between the electrical conductors (i.e., metals and metal alloys) and insulators (i.e., ceramics and polymers).
- The electrical characteristics of these materials are extremely sensitive to the presence of minute concentrations of impurity atoms, for which the concentrations may be controlled over very small spatial regions.
- Semiconductors have made possible the advent of integrated circuitry that has totally revolutionized the electronics and computer industries (not to mention our lives) over the past three decades.

➤ **Biomaterials**

- Biomaterials are employed in components implanted into the human body to replace diseased or damaged body parts.
- These materials must not produce toxic substances and must be compatible with body tissues (i.e., must not cause adverse biological reactions).
- All of the preceding materials (metals, ceramics, polymers, composites, and semiconductors) may be used as biomaterials.

➤ **Smart Materials**

- *Smart* (or *intelligent*) *materials* are a group of new and state-of-the-art materials now being developed that will have a significant influence on many of our technologies.
- The adjective *smart* implies that these materials are able to sense changes in their environment and then respond to these changes in predetermined manners—traits that are also found in living organisms.
- The “smart” concept is being extended to rather sophisticated systems that consist of both smart and traditional materials
- Components of a smart material (or system) include some type of sensor (that detects an input signal), and an actuator (that performs a responsive and adaptive function). Actuators may be called upon to change shape, position, natural frequency, or mechanical characteristics in response to changes in temperature, electric fields, and/or magnetic fields.

○ **Example:**

One type of smart system is used in helicopters to reduce aerodynamic cockpit noise that is created by the rotating rotor blades. Piezoelectric sensors inserted into the blades monitor blade stresses and deformations; feedback signals from these sensors are fed into a computer-controlled adaptive device, which generates noise-cancelling antinoise.

➤ **Nanomaterials**

Nanomaterials are defined as engineered materials with a least one dimension in the range of 1-100 nm. The *nano*-prefix denotes that the dimensions of these structural entities are on the order of a nanometer (10^{-9} m) as a rule, less than 100 nanometers (equivalent to approximately 500 atom diameters).

Particles of “*nano*” size have been shown to exhibit enhanced or novel properties including reactivity, greater sensing capability and increased mechanical strength. The nanotechnology offers simple, clean, fast, efficient, and economic for the synthesis of a variety of organic molecules, have provided the momentum for many chemists to switch from traditional method.

- Nanomaterials may be any one of the four basic types: metals, ceramics, polymers, and composites. However, unlike these other materials, they are not distinguished on the basis of their chemistry, but rather, size;
- Prior to the advent of nanomaterials, the general procedure scientists used to understand the chemistry and physics of materials was to begin by studying large and complex structures, and then to investigate the fundamental building blocks of these structures that are smaller and simpler. This approach is sometimes termed “top-down” science.
- The development of scanning probe microscopes permits observation of individual atoms and molecules, therefore, it has become possible to design and build new structures from their atomic level constituents, one atom or molecule at a time (i.e., “materials by design”).
- This ability to carefully arrange atoms provides opportunities to develop mechanical, electrical, magnetic, and other properties that are not otherwise possible. We call this the “bottom-up” approach, and the study of the properties of these materials is termed *nanotechnology*.

✓ **Classification**

All conventional materials like metals, semiconductors, glass, ceramic or polymers can in principle be obtained with a nano-scale dimension. The classification of nanomaterials can follow different criteria like *the size, the phase composition and the way of manufacturing.*

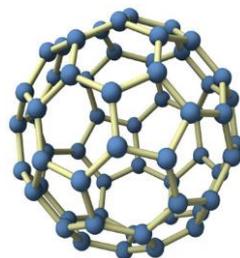
Criterion	Examples
Dimension	
3D < 100 nm	Nanoparticles,
2D < 100 nm	Carbon nanotubes, nanofibers
1D < 100 nm	Coatings, multi-layers
Phase composition	
Single phase solids	Crystalline, amorphous, layers
Multi-phase solids	Composites
Multi-phase systems	Colloids, aerogels
Manufacturing process	
Gas phase reaction	CVD, flame synthesis, etc
Liquid phase reaction	Solvothermal, sol-gel, etc.
Mechanical procedures	Ball milling, plastic deformation

✓ **Examples:**

➤ **Nanomaterials classification according to the size criteria:**

✚ **Nanoscale in three dimensions: such as**

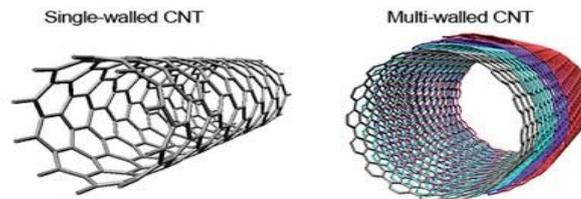
- Nanoparticles: are often defined as particles of less than 100 nm in diameter. Nanoparticles are formed by tens or hundreds of atoms and can have different size and shape.
- Fullerenes : (carbon 60):Spherical molecule formed of exagonal carbon structure (carbon atoms forming a “ball” of nanometer diameter).



✦ Nanomaterials in two dimensions

Two dimensional nanomaterials such as tubes (carbon nanotubes) and wires.

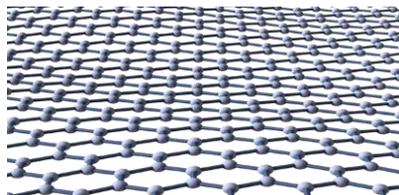
Carbon nanotubes: are linear structures that can reach microns of length with nanometric diameter. They can be single or multiwall.



✦ Nanomaterial in one dimension

In this category belong nanomaterials such as thin films and engineered surfaces such as grapheme and inorganic layer.

- Graphene: is formed by a layer of a carbon atoms, while other inorganic layers can be grown to modify the surfaces of bulk materials.

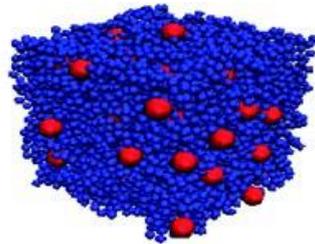


- Nanolayers: are a very important class of nanomaterials. Often they are used to modify the surface of bulk materials.

➤ Nanomaterials classification according to phase composition criterion:

In the **nanocomposites** (phase composition criterion) materials a nanomaterial (nanoparticles, nanotubes, layers) acts as a filler of a matrix material that in most cases is a polymer.

- *Inorganic nanoparticles* (red spots) are mixed with the polymeric matrix (Blue). The nanomaterial contribute to the nanocomposites new or improved properties (mechanical, electrical, optical etc.).



Snapshot of polymer nanocomposites

- In the nanocomposites the material matrix can be different from a polymer. Another common matrix is the ceramic or the glass (inorganic nano-composites): the glass is mixed with nanoparticles to obtain different colors.



✓ **Properties:**

a) Mechanical properties

- Very strong and withstand extreme strain.
- Most of the materials fracture on bending because of the presence of more defects, but nanomaterials possess only few defects in the structure.

(b) Electrical properties

- The electrical properties of nanomaterials vary between metallic to semiconducting materials.
- It depends on the diameter of the nanomaterials.
- The very high electrical conductivity of nanomaterial is due to minimum defects in the structure.

(c) Thermal conductivity

- The thermal conductivity of nanomaterials are very high, is due to the vibration of covalent bonds.
- Its thermal conductivity is 10 times greater than the metal.
- The very high thermal conductivity of nanomaterial is also due to minimum defects in the structure.

✓ **Applications:**

Because of these unique and unusual properties, nanomaterials are finding in:

- **Medicine:** diagnostics, drug delivery, synthetic bones.
- **Energy:** energy production, energy saving, fuel cells.
- **Information and Communication Technology:** optoelectronic devices, TV, displays, memory storages.
- **Heavy industry:** construction (nanoparticle in glass, coatings etc.), automotive, aerospace, catalysis.
- **Consumer goods:** food packaging, food detection of contaminants, sporting goods, textiles, cosmetics.

Lecture #4:

4. Selection for Properties

4.1 Introduction

A number of questions need to be answered before a decision can be made as to the specification required of a material and hence a decision as to the optimum material for a particular task. The questions can be grouped under four general headings:

- 1. *What properties are required?***
- 2. *What are the processing requirements and their implications for the choice of material?***
- 3. *What is the availability of materials?***
- 4. *What is the cost?***

The following indicate the type of questions that are likely to-be considered in trying to arrive at answers to the above general questions:

❖ Properties:

1. What mechanical properties are required?

This means consideration of such properties as strength, stiffness, hardness, ductility, toughness, fatigue resistance, wear properties, etc. Coupled with this question is another one: Will the properties be required at low temperatures, about room temperature or high temperatures?

2. What chemical properties are required?

This means considering the environment to which the material will be exposed and the possibility of corrosion.

3. What thermal properties are required?

This means consideration of such properties as specific heat capacity, linear coefficient of expansion and thermal conductivity.

4. What electrical properties are required?

For example, does the material need to be a good conductor of electricity or perhaps an insulator?

5. What magnetic properties are required?

Does the material need to have soft or hard magnetic properties or perhaps be essentially non-magnetic?

6. What dimensional conditions are required?

For example, does the material need to be capable of a good surface finish, have dimensional stability, be flat, have a particular size, etc.

❖ Processing Parameters:

1. Are there any special processing requirements which will limit the choice of material?

For example, does the material have to be cast or perhaps extruded?

2. Are there any material treatment requirements?

For example, does the material have to be annealed or perhaps solution hardened?

3. Are there any special tooling requirements?

For example, does the hardness required of a material mean special cutting tools are required?

❖ Availability:

1. Is the material readily available?

Is it, for example, already in store, or perhaps quickly obtainable from normal suppliers?

2. Are there any ordering problems for that material?

Is the material only available from special suppliers? Is there a minimum order quantity?

3. What form is the material usually supplied in?

For example, is the material usually supplied in bars or perhaps sheet? This can affect the processes that can be used.

❖ Cost:

1. What is the cost of the raw material?

Could a cheaper material be used?

2. What quantity is required?

What quantity of product is to be produced per week, per month, per year?

What stocking policy should be adopted for the material?

3. What are the cost implications of the process requirements?

Does the process require high initial expenditure? Are the running costs high or low?

Will expensive skilled labor be required?

4. What are the cost penalties for over specification?

If the material is, for example stronger than is required, will this significantly increase the cost? If the product is manufactured to higher quality than is required, what will be the cost implications?

4.2 Selection of Materials according to their Mechanical Properties:

Mechanical properties describe the behavior of material in terms of deformation and resistance to deformation under specific mechanical loading condition. These properties are significant as they describe the load bearing capacity of structure. Elastic modulus, strength, hardness, toughness, ductility, malleability are some of the common mechanical properties of engineering materials:

4.2.1 Selection for Static Strength :

+ Concepts of Stress & Strain

➤ Stress

When a material is subject to external forces which stretch it and make it extend, then it is said to be in *tension* (Figure 1.1(a)). When a material is subject to forces which squeeze it and make it contract, then it is said to be in *compression* (Figure 1.1(b)). An object, in some situations, can be subject to both tension and compression, e.g. a beam (Figure 1.2) which is *being bent*, the bending causing the upper surface to contract and so be in compression and the lower surface to extend and be in tension.

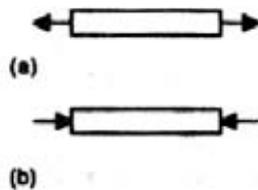


Figure 1.1 (a) *Tension*,
(b) *compression*

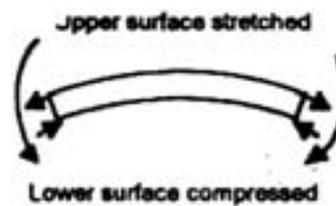


Figure 1.2 *Bending*

If we stretch a strip of material by a force **F** applied over its cross-sectional area **A**, then the force applied per unit area is **F/A** (Figure 1.3), this being termed the stress:

$$\text{Stress} = \text{force/area} \dots\dots\dots(2)$$

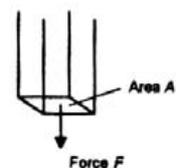
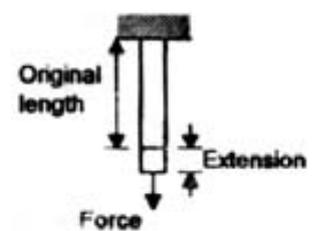


Figure 1.3 *Stress*

The area used in calculations of stress is generally the original area that existed before the application of the forces, not the area after the force has been applied. This stress is thus sometimes referred to as the **engineering stress**, the term *true stress* being used for the force divided by the actual area existing in the stressed state.

➤ Strain

When a material is subject to tensile or compressive forces, it changes in length, the term strain, (Figure 1.4), being used for the fractional change in length:



$$\text{Strain} = \frac{\text{change in length}}{\text{original length}} \dots\dots\dots(3)$$

Since strain is a ratio of two lengths it has no units.

Strain is frequently expressed as a percentage.

$$\text{Strain as a \%} = \frac{\text{change in length}}{\text{original length}} \times 100 \dots\dots\dots(4)$$

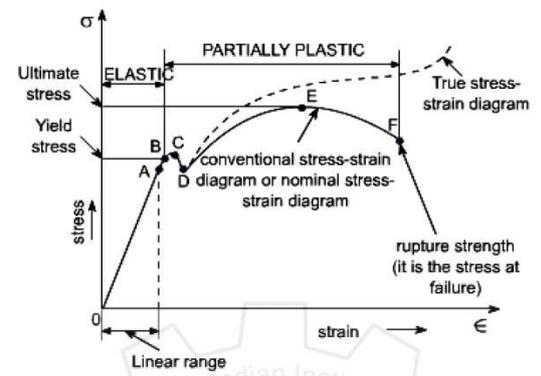
Thus the strain of 0.01 as a percentage is 1%, (i.e. the change in length is 1% of the original length).

➤ Stress-strain behaviour

- The behaviour of materials subject to tensile and compressive forces can be described in terms of their stress-strain behavior. If gradually increasing tensile forces are applied to, say, a strip of **Mild steel**, then initially when the forces are released the material springs back to its original shape. The material is said to be elastic.
- Stresses computed on the basis of the original area of the specimen are often referred to as the conventional or nominal stresses. Alternately, the stresses computed on the basis of the actual area of the specimen provide the so called true stress.
- Within the elastic limit, the material returns to its original dimension on removal of the load. The elastic modulus is referred to the slope of the stress-strain behavior in the elastic region and its SI unit is conceived as N.m^{-2} . The elastic modulus is also referred to as the constant of proportionality between stress and strain according to **Hooke's Law**. Beyond the elastic limit, the materials retains a permanent, irreversible strain (or deformation) even after the load is removed. The modulus of rigidity of a material is defined as the ratio of shear stress to shear strain within the elastic limit. The bulk modulus is referred to the ratio of pressure and volumetric strain within the elastic limit.

Typical stress-strain curve of Carbon-steel under uniaxial tensile loading is shown in the following figure:

- ✓ **Point 'A'** indicates the proportional limit. Stress-strain behavior is linear only up to this point.
- ✓ **Point 'B'** represents the point at which the material starts yielding.
- ✓ **Between point A and B**, the stress strain behavior is not linear, though it is in *elastic* region.
- ✓ **Point 'C'** is referred to the upper *yield point*.
- ✓ The material behavior **after point 'D'** is highly nonlinear in nature.
- ✓ **Point 'E'** is the maximum stress that the material can withstand.
- ✓ **Point 'F'** schematically indicates the point of *rupture*.



Based on the typical stress-strain behavior of an engineering material, a few reference points are considered as important characteristics of the material:

- ✓ The *proportional limit* is referred to the stress just beyond the point where the stress / strain behavior of a material first becomes non-linear.
- ✓ The *yield strength* refers to the stress required to cause permanent plastic deformation.

- ✓ The ultimate tensile strength refers to the maximum stress value on the engineering stress-strain curve and is often considered as the maximum load-bearing strength of a material.
- ✓ The rupture strength refers to the stress at which a material ruptures typically under bending.

Proof stress:

With some materials, e.g. **mild steel**, there is a noticeable dip in the stress-strain graph at some stress beyond the elastic limit. The strain increases without any increase in load. The material is said to have yielded and the point at which this occurs is the yield point. Some materials, such as **aluminium alloys** (Figure 1.7), do not show a noticeable yield point and it is usual here to specify **proof stress**. The **0.2% proof stress** is obtained by drawing a line parallel to the straight line part of the graph but starting at a strain of 0.2%. The point where this line cuts the stress-strain graph is termed the 0.2% yield stress. A similar line can be drawn for the 0.1% proof stress.

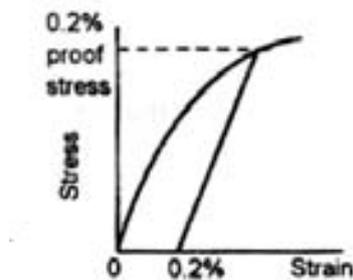


Figure 1.7 0.2% proof stress

Stress-strain graphs for a number of materials:

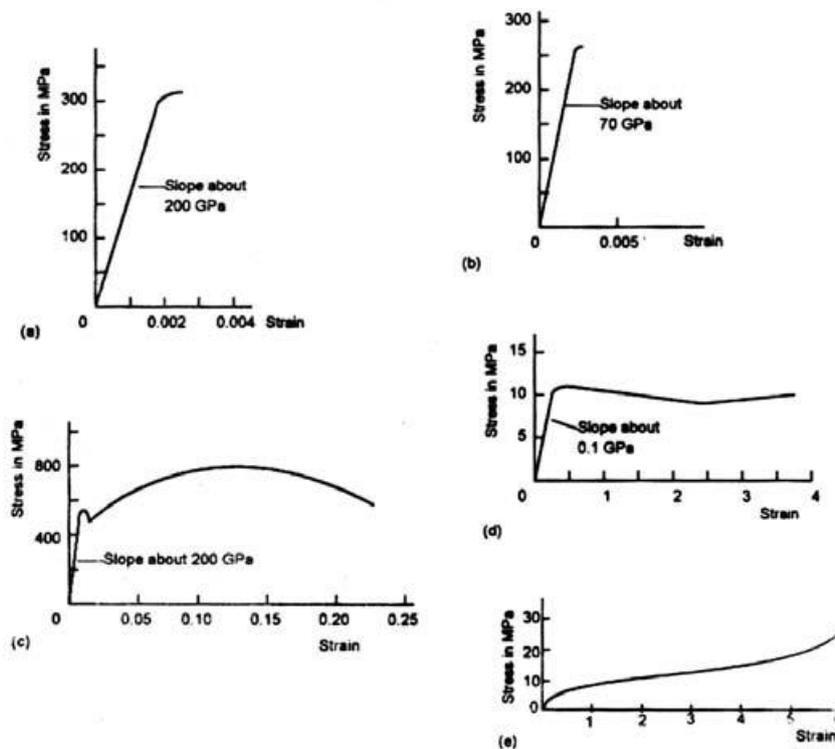


Figure 1.9: The stress-strain graphs for a number of materials :a) cast iron, (b) glass, (c) mild steel, (d)polyethylene, (e) rubber

a: Cast Iron

The stress-strain graph for cast iron (Figure 1.9(a)) is virtually just a straight line with virtually all elastic behavior and little plastic deformation. The slight curved part at the top of the graph indicates a small departure from straight-line behavior and a small amount of plastic behavior. The graph gives the limit of proportionality as about 280 MPa, the tensile strength about 300 MPa and the modulus of elasticity about 200 GPa.

b: Glass

The stress-strain graph for glass (Figure 1.9(b)) has a similar shape to that for cast iron, with virtually all elastic behavior and little plastic deformation. The graph indicates the limit of proportionality is about 250 MPa, the tensile strength about 260 MPa and the modulus of elasticity about 70 GPa.

c: Mild steel

The stress-strain graph for mild steel (Figure 1.9(c)) shows a straight-line portion followed by a considerable amount of plastic deformation. Much higher strains are possible than with cast iron or glass, i.e. mild steel stretches much more. The limit of proportionality is about 240 MPa, the tensile strength about 400 MPa and the modulus of elasticity about 200 GPa.

d: Polyethylene

The stress-strain graph for polyethylene (Figure 1.9(d)) shows only a small region where elastic behavior occurs and a very large amount of plastic deformation possible. Very large strains are possible a length of such material being capable of being stretched to almost four times its initial length. The limit of proportionality is about 8 MPa, the tensile strength about 11 MPa and the modulus of elasticity about 0.1 GPa.

e: Rubber

The tensile strength is about 25 MPa. Very large strains are possible and the material shows an elastic behavior to very high strains. The modulus of elasticity is not so useful a quantity for elastomers as it refers to only a very small portion of the stress-strain graph. A typical modulus would be about 30 MPa.

Brittle & Ductile Materials:

- For some materials, the difference between the elastic limit stress and the stress at which failure occurs is very small, as with the **cast iron** in Figure 1.9(a) with very little plastic deformation occurring. Thus, the length of a piece of cast iron after breaking is not much different from the initial length. Such materials are said to be brittle.

- In contrast to a material which suffers a considerable amount of plastic strain before breaking, and as said to be ductile, e.g. the **mild steel** in Figure 1.9(c).

If you drop a glass, a brittle material, and it breaks, then it is possible to stick all the pieces together again and restore the glass to its original shape. If a car is involved in a collision, the bodywork of mild steel is less likely to shatter like the glass but more likely to dent and show permanent deformation, i.e. the material has shown plastic deformation. Ductile materials permit manufacturing methods which involve bending them to the required shapes or using a press to squash the material into the required shape. Brittle materials cannot be formed to shape in this way.

The percentage of elongation of a test piece after breaking is used as a measure of ductility:

$$\text{Percentage elongation} = \frac{\text{final length} - \text{initial length}}{\text{initial length}} \times 100\%$$

- A reasonably ductile material, such as **mild steel**, will have a percentage elongation of about 20%,
- A brittle material such as a **cast iron** less than 1%.
- **Thermoplastics** tend to have percentage elongations of the order of 50 to 500%, **thermosets** of the order of 0.1 to 1%.
- **Thermosets** are brittle materials, **thermoplastics** generally not.

- The stress-strain properties of **plastics** depend on the rate at which the strain is applied, unlike **metals** where the strain rate is not usually a significant factor, and the properties change significantly when there is a change in temperature (Figure 1.10) with both the modulus of elasticity and the tensile strength decreasing with an increase in temperature.
- Because of that for many **polymeric materials**, as with the **rubber** in Figure 1.9(e), there is no initial straight line part of the stress-strain graph and a value for the modulus of elasticity cannot be arrived at, the secant modulus is sometimes quoted, this being the stress/strain value at on, strain (Figure 1.11).

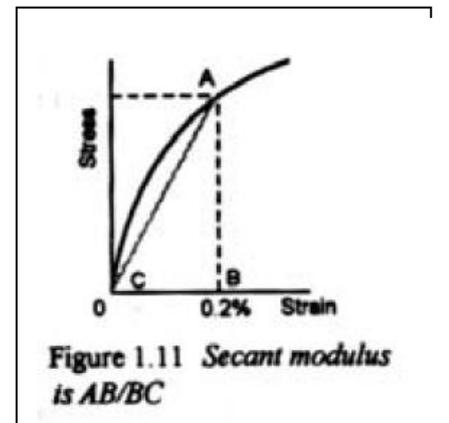
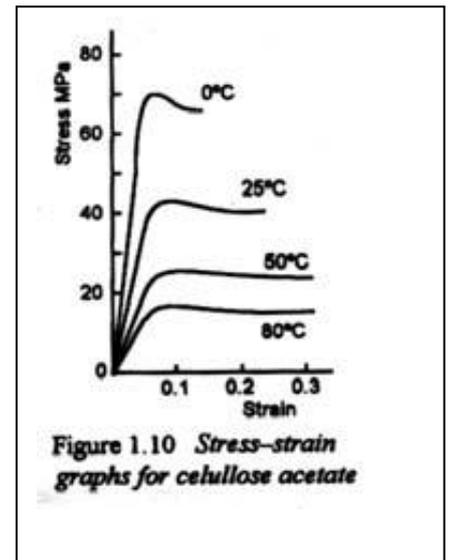


Table 1.1 gives typical values of yield stress or 0.2 % proof stress, tensile strength and modulus of elasticity for a range of materials.

Table 1.1 Typical tensile properties of materials at 20°C

Material	Yield/0.2% proof stress MPa	Tensile strength MPa	Modulus of elasticity GPa
<i>Metals</i>			
Mild steel	230	400	200
Chromium alloy steel	500–600	700–1000	200
Cast iron	150–600	150–600	120–170
Copper alloys	60–300	160–600	120–170
Aluminium alloys	50–300	100–400	70
<i>Thermoplastics</i>			
Polyvinyl chloride		35–60	2–4
Polyethylene		30	1
Cellulose acetate		13–62	0.5–2.8
<i>Thermosets</i>			
Phenol formaldehyde		50–55	5–6
Epoxy, cast		200–420	3.2
<i>Elastomers</i>			
Natural rubber		30	
Neoprene		28	

Examples

Example (1):

Which of the following plastics is the stiffest?

ABS tensile modulus 2.5 GPa

Polycarbonate tensile modulus 2.8 GPa

Polypropylene tensile modulus 1.3 GPa

PVC tensile modulus 3.1 GPa

A./ The stiffest plastic is the one with the highest tensile modulus and so is the PVC.

Example (2):

A sample of carbon steel has a tensile strength of 400 MPa and a percentage elongation of 35%. A sample of an aluminium-manganese alloy has a tensile strength of 140 MPa and a percentage elongation of 10%. What does this data tell you about the mechanical behavior of the materials?

A./ The higher value of the tensile strength of the carbon steel indicates that the material is stronger and, for the same cross-sectional area, a bar of carbon steel could withstand higher tensile forces than a corresponding bar of the aluminium alloy. The higher percentage elongation of the carbon steel indicates that the material has a greater ductility than the aluminium alloy. Indeed the value is such as to indicate that the carbon steel is very ductile. The steel is thus stronger and more ductile.

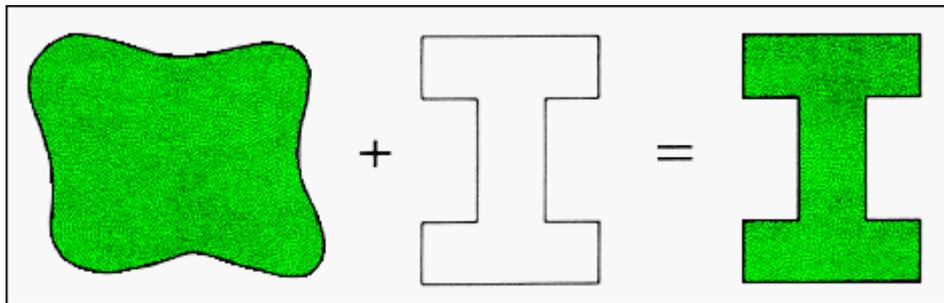
Selection for static strength

Static strength can be defined as: the ability to resist a short-term steady load at moderate temperatures without breaking or crushing or suffering excessive deformations.

- If a component is subject to a **uni-axial stress** the yield stress is commonly taken as a measure of the strength if the material is *ductile* and the tensile strength if it is *brittle*.
- Measures of static strength are thus yield strength, proof stress, tensile strength, compressive strength and hardness, the hardness of a material being related to the tensile strength of a material.
- If the component is subject to **biaxial or triaxial stresses**, *e.g.* a shell subject to internal pressure, then there are a number of theories which can be used to predict material failure.
- The maximum principal stress theory, which tends to be used with *brittle materials*, predicts failure as occurring when the maximum principal stress reaches the tensile strength value, or the elastic limit stress value, that occurs for the material when subject to simple tension.
- The maximum shear stress theory, used with *ductile materials*, considers failure to occur when the maximum shear stress in the biaxial or triaxial stress situation reaches the value of the maximum shear stress that occurs for the material at the elastic limit in simple tension. With biaxial stress, this occurs when the difference between the two principal stresses is equal to the elastic limit stress.
- Another theory that is used with *ductile materials* is that failure occurs when the strain energy per unit volume is equal to the strain energy at the elastic limit in simple tension.
- It should be recognized that a *requirement for strength* in a component requires not only a consideration of the static strength of the material but also the design.

For bending: an I-beam is more efficient than a rectangular cross-section beam because the material in the beam is concentrated at the top and bottom surfaces where the stresses are high and is not 'wasted' in regions where the stresses are low. A thin shell or skin can be strengthened by adding ribs or corrugations.

The diagram below illustrates this concept. The material (green free-form) is converted into a structural component (in this case a girder) by selecting an I shape that distributes the material mainly at the top and bottom of the structural component. Experiment shows that this shape is good in sustaining vertical bending loads, and I-beams of this type are employed in building construction. Selection of different shapes, or the same shape but with different height-to-width ratios will change the material performance as a structural element.



❖ Mechanical properties of different types of materials:

- *For most ductile-wrought materials:*

The mechanical properties in compression are sufficiently close to those in tension that was for the more readily available tensile properties to be used as an indicator of strength in both tension and compression. **Metals in the cast** condition, however, may be stronger in compression than in tension.

- *Brittle materials*, such as **ceramics**, are generally stronger in compression than in tension.
- There are some materials where there is significant *anisotropy*, (i.e. the properties depend on the direction in which it is measured). This can occur with, for example **wrought materials** where there are elongated inclusions and the processing results in them becoming orientated in the same direction, or in **composite materials** containing unidirectional fibers.

- The mechanical properties of **metals** are very much affected by the treatment they undergo, whether it be heat treatment or working. Thus it is not possible to give anything other than a crude comparison of alloys in terms of tensile strengths.
 - The properties of **polymeric materials** are very much affected by the additives mixed in with them in their formulation and thus only a crude comparison of mechanical properties of different polymers is possible. There is also the problem with thermoplastics in that, even at 20°C they can show quite significant creep and this is more marked as the temperature increases. Thus their strengths are very much time dependent. Unreinforced thermoplastics have low strengths when compared with most metals; however, their low density means they have a favorable strength to weight ratio.
- ✓ Table 24.1 gives a general comparison of tensile strengths of a range of materials, all the data referring to temperatures around about 20°C.

Table 24.1 *Materials according to strengths*

Strength (MPa)	Material
<10	Polymer foams
2 to 12	Woods perpendicular to the grain
2 to 12	Elastomers
6 to 100	Woods parallel to the grain
60 to 100	Engineering polymers
20 to 60	Concrete
20 to 60	Lead alloys
80 to 300	Magnesium alloys
160 to 400	Zinc alloys
100 to 600	Aluminium alloys
80 to 1000	Copper alloys
250 to 1300	Carbon and low-alloy steels
250 to 1500	Nickel alloys
500 to 1800	High-alloy steels
100 to 1800	Engineering composites
1000 to >10 000	Engineering ceramics

- ✓ Table 24.2 gives a general comparison of typical specific strengths, i.e. tensile strength divided by the density, to give a measure of strength per unit mass.

Table 24.2 Specific strength at 20°C

Material	Density (Mg/m ³)	Strength to weight ratio (MPa/Mg m ³)
Aluminium alloys	2.6 to 2.9	40 to 220
Copper alloys	7.5 to 9.0	8 to 110
Lead alloys	8.9 to 11.3	1 to 3
Magnesium alloys	1.9	40 to 160
Nickel alloys	7.8 to 9.2	30 to 170
Titanium alloys	4.3 to 5.1	40 to 260
Zinc alloys	5.2 to 7.2	30 to 60
Carbon and low-alloy steels	7.8	30 to 170
High-alloy steels	7.8 to 8.1	60 to 220
Engineering ceramics	2.2 to 3.9	>300
Glasses	2 to 3	200 to 800
Thermoplastics	0.9 to 1.6	15 to 70
Polymer foams	0.04 to 0.7	0.4 to 12
Engineering composites	1.4 to 2	70 to 900
Concrete	2.4 to 2.5	8 to 30
Wood	0.4 to 1.8	5 to 60

- ✓ Table 24.3 gives commonly used steels for different levels of tensile strength, the relevant limiting ruling sections being quoted.

Table 24.3 Steel selection

Tensile strength (MPa)	BS steel code	Description of steel	Limiting ruling section (mm)	
620 to 770	080M40	Medium carbon steel, hardened and tempered	63	
	150M36	Carbon-Mn steel, hardened and tempered	150	
	503M40	1% Ni steel, hardened and tempered	250	
700 to 850	150M36	1.5% manganese steel, hardened and tempered	63	
	708M40	1% Cr-Mo steel, hardened and tempered	150	
	605M36	1.5% Mn-Mo steel, hardened and tempered	250	
770 to 930	708M40	1% Cr-Mo steel, hardened and tempered	100	
	817M40	1.5% Ni-Cr-Mo steel, hardened and tempered	250	
	850 to 1000	630M40	1% Cr steel, hardened and tempered	63
850 to 1000	709M40	1% Cr-Mo steel, hardened and tempered	100	
	817M40	1.5% Ni-Cr-Mo steel, hardened and tempered	250	
	930 to 1080	709M40	1.5% Cr-Mo steel, hardened and tempered	63
930 to 1080	817M40	1.5% Ni-Cr-Mo steel, hardened and tempered	100	
	826M31	2.5% Ni-Cr-Mo steel, hardened and tempered	250	
	1000 to 1150	817M40	1% Ni-Cr-Mo steel, hardened and tempered	63
1000 to 1150	826M31	2.5% Ni-Cr-Mo steel, hardened and tempered	150	
	1080 to 1240	826M31	2.5% Ni-Cr-Mo steel, hardened and tempered	100
	826M40	2.5% Ni-Cr-Mo steel, hardened and tempered	250	
1150 to 1300	826M40	2.5% Ni-Cr-Mo steel, hardened and tempered	150	
1240 to 1400	826M40	2.5% Ni-Cr-Mo steel, hardened and tempered	150	
>1540	835M30	4% Ni-Cr-Mo steel, hardened and tempered	150	

Note about Table 24.3:

The limiting ruling section is the maximum diameter of round bar at the centre of which the specified properties may be obtained. The reason for this is that during heat treatment, different rates of cooling occur at the centers of bars, or indeed any cross-section, due purely to differences in sizes and this affects the microstructure produced by the treatment.

Lecture #5:

4.2.2 Selection for stiffness

Stiffness : the ability of a material to resist deflection when loaded.

- If we consider a cantilever of length L subject to a point load F at its free end (Figure 24.1), then the deflection y at the free end is given by:

$$y = \frac{FL^3}{3EI}$$

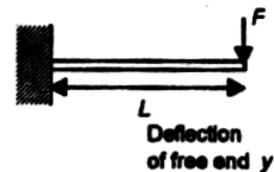


Figure 24.1 *Cantilever*

Where:

E : tensile modulus

I : second moment of area of the beam cross-section with respect to the neutral axis.

- For a given shape and length cantilever: the greater the tensile modulus results in the smaller the deflection. Also, the greater the tensile modulus the greater the stiffness. The deflection of a beam is a function of both E and I .
- For a given material: a beam can be made stiffer by increasing its second moment of area. The second moment of area of a section is increased by placing as much as possible of the material as far as possible from the axis of bending. Thus an I-section is a particularly efficient way of achieving stiffness. Similarly a tube is more efficient than a solid rod.
- Another situation which is related to the value of EI is the **buckling of columns** when subject to compressive loads. The standard equation used for buckling has it occurring for a column of length L when the load F reaches the value. This is Euler's equation. The bigger the value of EI the higher the load required to cause buckling. Hence we

can say that the column is stiffer the higher the value of EI. Note that a short and stubby column is more likely to fail by crushing when the yield stress is exceeded rather than buckling. Buckling is, however, more likely to be the failure mode if the column is slender.

- The tensile modulus of a **metal** is little affected by changes in its composition or heat treatment. However, the tensile modulus of **composite materials** is very much affected by changes in the orientation of the fillers and the relative amounts.

Table 24.4 shows typical tensile modulus values for materials at 20°C.

Table 24.4 *Materials according to tensile modulus*

Tensile modulus (GPa)	Material
<0.2	Polymer foams
<0.2	Elastomers
0.2 to 10	Woods parallel to grain
0.2 to 10	Engineering polymers
2 to 20	Woods perpendicular to grain
10 to 11	Lead alloys
20 to 50	Concrete
40 to 45	Magnesium alloys
50 to 80	Glasses
70 to 80	Aluminium alloys
43 to 96	Zinc alloys
110 to 125	Titanium alloys
100 to 160	Copper alloys
200 to 210	Steels
80 to 1000	Engineering ceramics

4.2.3 Selection for fatigue resistance

- The failure of a component when subject to fluctuating loads is as a result of cracks which tend to start at some discontinuity in the material and grow until failure occurs.

The main factors affecting fatigue properties are:

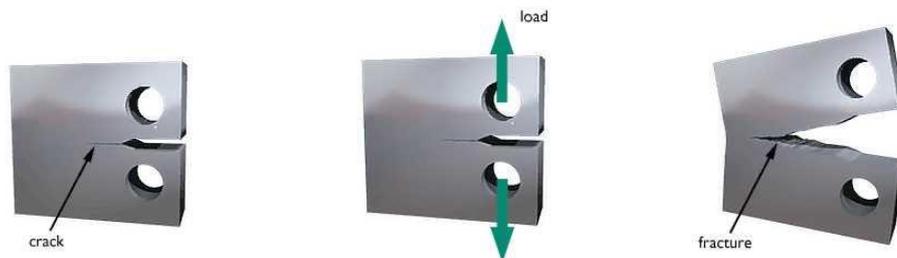
- ✓ Stress concentrations caused by component design,
 - ✓ Corrosion,
 - ✓ Residual stresses,
 - ✓ Surface finish/treatment,
 - ✓ Temperature,
 - ✓ The microstructure of the alloy and its heat treatment.
 - ✓ Only to a limited extent does the choice of material determine the fatigue resistance of a component.
- In general, for **metals** the endurance limit or fatigue limit at about 10^7 to 10^8 cycles lies between about a third and a half of the static tensile strength.
 - ✓ For **steels** the fatigue limit is typically between 0.4 and 0.5 that of the static strength. Inclusions in the **steel**, such as sulphur or lead to improve machinability, can, however, reduce the fatigue limit.
 - ✓ For **grey cast iron** the fatigue limit is about 0.4 that of the static strength.
 - ✓ For **nodular and malleable irons**, in the range 0.5 for ferritic grades, to 0.3 for the higher strength pearlitic malleable irons, for blackheart, whiteheart and the lower strength pearlitic malleable irons about 0.4.
 - ✓ With **aluminium alloys** the end limit is about 0.3 to 0.4 that of the static strength.
 - ✓ For **copper alloys** about 0.4 to 0.5.
 - Fatigue effects with **polymers** are complicated by the fact that the alternating loading results in the polymer becoming heated. This causes the elastic modulus to decrease and at high enough frequencies this may be to such an extent that failure occurs. Thus, fatigue in polymers is very much frequency dependent.

4.2.4 Selection for toughness

Toughness: can be defined as the resistance offered by a material to fracture. A tough material is resistant to crack propagation.

Another definition:

Toughness: can be defined in terms of the work that has to be done to propagate a crack through a material, a tough material requiring more energy than a less tough one.



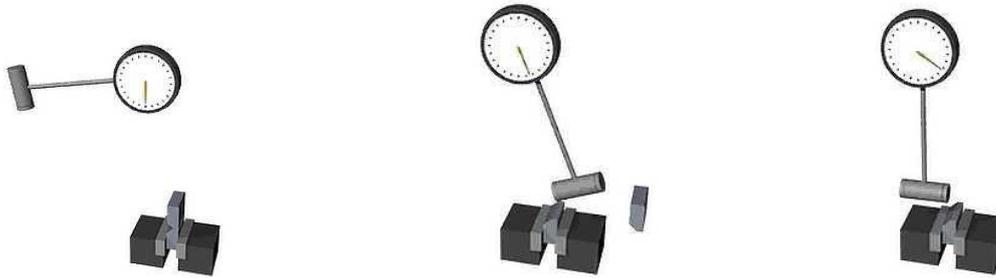
- ✓ Think of trying to tear a sheet of paper or a sheet of some cloth. If there is an initial 'crack' then the material is much more easily torn. In the case of the paper, the initial 'cracks' may be perforations put there to enable the paper to be torn easily. In the case of a sheet of cloth, it may be the initial 'nick' cut in the edge by a dressmaker to enable it to be torn easily. In the case of, say, the skin of an aircraft where there may be holes, such as windows or their fastenings, which are equivalent to cracks, there is a need for cracks not to propagate. A tough material is required.
- ✓ A measure of toughness is given by two main measurements:
 1. The resistance of a material to **impact loading** which is measured in the Charpy or Izod tests by the amount of energy needed to fracture a test piece, the higher the energy the more ductile a material is.

Izod test:

A specimen of standard size with a notch on one side is clamped in a vice. A heavy pendulum is lifted to a height h_0 above the vice and is released. It swings under gravity, strikes the specimen and continues to height h_1 shown by the final reading on the dial gauge.

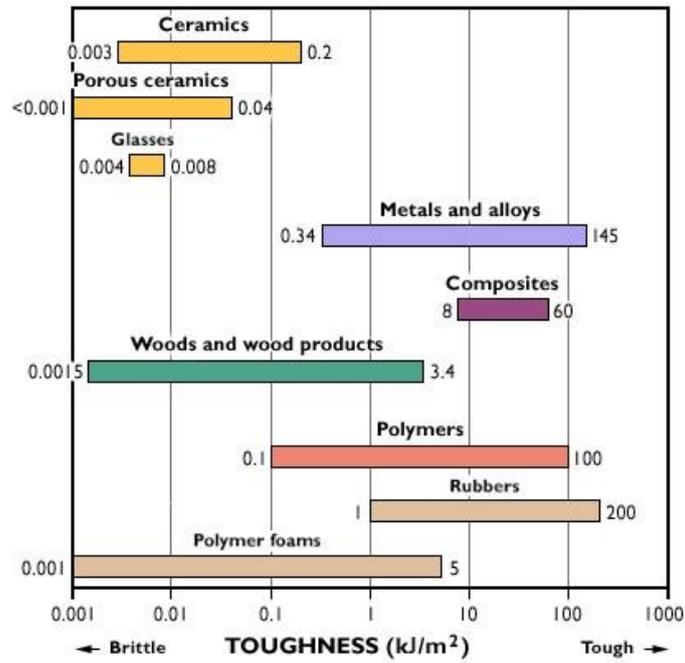
Impact energy = energy absorbed = mass of pendulum * g * (h₁ - h₀)

where: g is the acceleration due to gravity.



2. The resistance of a material to the propagation of an existing crack in a fracture toughness test, this being specified by the plain strain fracture toughness K_{1c}. The lower its value is the less tough the material.
- ✓ Within a given type of **metal alloy** there is an inverse relationship between yield stress and toughness, the higher the yield stress the lower the toughness.
 - Thus if, for instance, the yield strength of **low alloy, quenched and tempered steels** is pushed up by metallurgical means, then, the toughness declines. **Steels** become less tough with increasing carbon content and larger grain size.
 - ✓ The toughness of **plastics** is improved by incorporating rubber or another tougher polymer, copolymerization, or incorporating tough fibers.

For example, styrene-acrylonitrile (SAN) is brittle and far from tough. It can, however, be toughened with the rubber polybutadiene to give the tougher acrylonitrile-butadiene-styrene (ABS).



➤ Table 24.5 gives typical values of the plane strain fracture toughness at 20°C.

Table 24.5 Plane strain fracture toughness at 20°C

Plain strain fracture toughness (MN m ^{-3/2})	Material
<1.0	Polymer foams
0.07 to 0.9	Woods perpendicular to grain
0.1 to 0.3	Concrete
0.3 to 0.6	Glasses
0.5 to 10	Engineering polymers
1 to 10	Woods parallel to the grain
2 to 10	Engineering ceramics
7 to 11	Cast irons
10 to 11	Magnesium alloys
10 to 60	Aluminium alloys
10 to 100	Engineering composites
20 to 150	Steels
50 to 110	Copper alloys
60 to 110	Titanium alloys
60 to 110	Nickel alloys

4.2.5 Selection for creep and temperature resistance

The creep resistance of a **metal** can be improved by incorporating a fine dispersion of particles to impede the movement of dislocations.

- The **Nimonic series of alloys**, based on an 80/20 nickel-chromium alloy, have good creep resistance as a consequence of fine precipitates formed by the inclusion of small amounts of titanium, aluminium, carbon or other elements.
- Creep increases as the temperature increases and is thus a major factor in determining the temperature at which materials can be used.
- Another factor is due to the effect on the material of the surrounding atmosphere. This can result in surface attack and scaling which gradually reduces the cross-sectional area of the component and so its ability to carry loads. Such effects increase as the temperature increases. The **Nimonic series of alloys** have good resistance to such attack. Typically they can be used up to temperatures of the order of 900°C.
- For most **metals** creep is essentially a high-temperature effect. This is not the case with **plastics**. Here creep can be significant at room temperatures.
- Generally **thermosets** have higher temperature resistance than **thermoplastics**; however, the addition of suitable fillers and fibers can improve the temperature properties of thermoplastics.

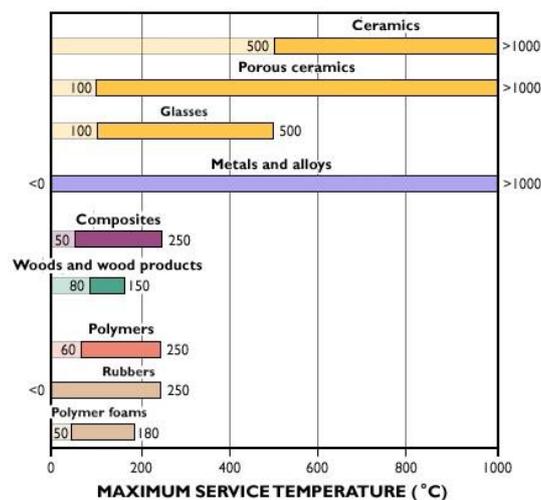


Table 24.6 indicates typical temperature limitations for a range of materials.

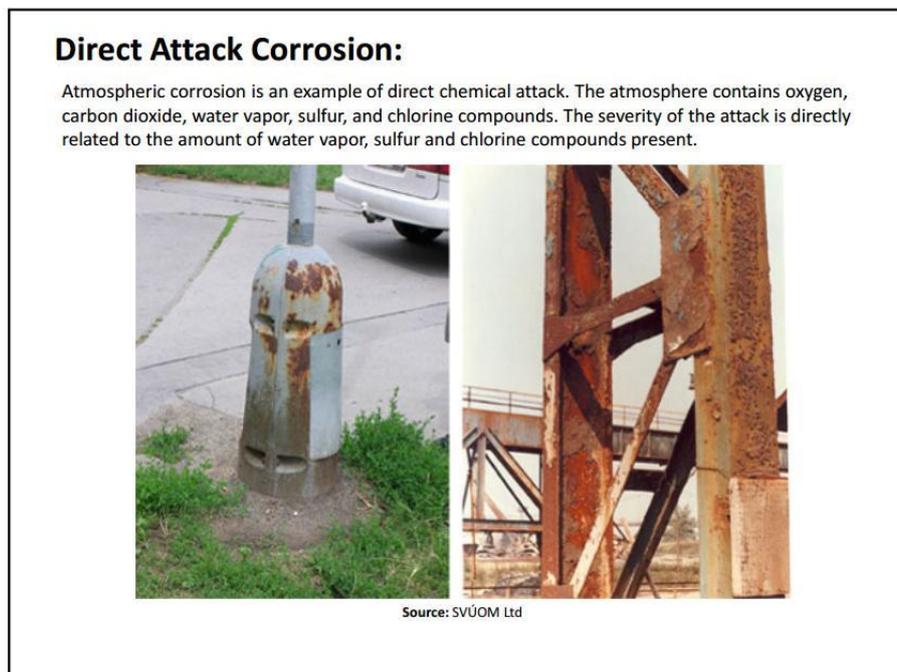
Table 24.6 *Temperature limitations of materials*

Temperature limit (°C)	Materials
Room temp. to 150	Few thermoplastics are recommended for prolonged use above about 100°C. Glass-filled nylon can, however, be used up to 150°C. The only engineering metal which has limits within this range is lead.
150 to 400	Magnesium and aluminium alloys can in general only be used up to about 200°C, though some specific alloys can be used to higher temperatures. For example, the aluminium alloy LM13 (AA336.0) is used for pistons in engines and experiences temperatures of the order of 200 to 250°C while some cast aluminium bronzes can be used up to about 400°C with wrought aluminium bronzes up to about 300°C. Plain carbon and manganese-carbon steels are widely used for temperatures in this range.
400 to 600	Plain carbon and manganese-carbon steels cannot be used above about 400–450°C. For such temperatures low-alloy steels are used. For temperatures up to about 500°C a carbon-0.5% Mo steel might be used, up to about 525°C a 1% Cr-0.5% Mo steel, up to about 550°C a 0.5% Cr-Mo-V steel, and up to about 600°C a steel with 5 to 12% Cr. Titanium alloys are also widely used in this temperature range. The alpha-beta alloy 6% Al-4% V (IMI318) is used up to about 450°C. Near alpha alloys can be used to higher temperatures, e.g. the alloy IMI 829 is used up to about 600°C.
600 to 1000	Metals most widely used in this temperature range are the austenitic stainless steels, Ni-Cr and Ni-Cr-Fe alloys, and cobalt base alloys. Austenitic stainless steels with 18% Cr-8% Ni can be used up to about 750°C. A range of high-temperature alloys based on the nickel-chromium base are able to maintain their strength, resistance to creep and oxidation resistance at high temperatures, e.g. Nimonic series alloys such as Nimonic 90 which can be used up to about 900°C, Nimonic 901 to about 1000°C. Another series of high-temperature alloys are the Ni-Cr-Fe alloys, such as the Inconel and Incoloy series. For example, Inconel 600 can be used up to virtually 1000°C and Incoloy 800H to 700°C.
Above 1000	The materials which can be used at temperatures in excess of 1000°C are the refractory metals, i.e. molybdenum, niobium, tantalum and tungsten, and ceramics. The refractory metals, and their alloys, can be used at temperatures in excess of 1500°C. Surface protection is one of the main problems facing the use of these alloys at high temperatures. Ceramics can also be used at such high temperatures but tend to suffer from the problems of being hard, brittle and vulnerable to thermal shock. Alumina is used in furnaces up to about 1600°C, silicon nitride to about 1200°C and silicon carbide to about 1500°C.

Lecture #6:

4.2.6 Selection for corrosion resistance

- For **metals** subject to atmospheric corrosion the most significant factor in determining the chance of corrosive attack is whether there is an aqueous electrolyte present. This could be provided by condensation of moisture occurring as a result of the climatic conditions. The amount of pollution in the atmosphere can also affect the corrosion rate. Corrosion can often be much reduced by the **selection** of appropriate materials. For **metals immersed in water**, the corrosion depends on the substances that are dissolved or suspended in the water.



- **Carbon steels** and **low-alloy steels** are not particularly corrosion resistant, rust being the evidence of such corrosion. In an industrial atmosphere, in fresh and sea water, **plain carbon steels and low-alloy steel** have poor resistance. Painting, by providing a protective coating of the surface, can reduce such corrosion.

- The addition of chromium to steel can markedly improve its corrosion resistance. **Steels with 4-6% chromium** have good resistance in an industrial atmosphere, in fresh and sea water.
- **Stainless steels** have an excellent resistance in an industrial atmosphere and fresh water but can suffer some corrosion in sea water.
- The corrosion resistance of **grey cast iron** is good in an industrial atmosphere but not so good in fresh or sea water, though still better than that of **plain carbon steels**.
- **Aluminium** when exposed to air develops an oxide layer on its surface which then protects the substrate from further attack. In air, **aluminium and its alloys** have good corrosion resistance. When immersed in fresh or sea water, most aluminium alloys offer good corrosion resistance, though there are some exceptions which must be clad in order to have good corrosion resistance.
- **Copper in air** forms a protective green layer which protects it from further attack and thus gives good corrosion resistance. **Copper** has also good corrosion resistance in fresh and sea water, hence the widespread use of copper piping for water distribution systems and central heating systems. **Copper alloys** likewise have good corrosion resistance in industrial atmospheres, fresh and sea water through demetallification can occur with some alloys, *e.g. dezincification of brass with more than 15% zinc*.
- **Nickel and its alloys** have excellent resistance to corrosion in industrial air, fresh and sea water,
- **Titanium and its alloys** have excellent resistance, probably the best resistance of all metals, in industrial air, fresh and sea water and is thus widely used where corrosion could be a problem.
- **Plastics** do not corrode in the same way as metals and thus, in general, have excellent corrosion resistance. For example, the increasing use of plastic pipes for the transmission of water and other chemicals.

- **Polymers** can deteriorate as a result of exposure to ultraviolet radiation, *e.g.* that in the rays from the sun, heat and mechanical stress. To reduce such effects, specific additives are used as fillers in the formulation of a plastic.
- **Most ceramic materials** show excellent corrosion resistance.
- **Glasses** are exceedingly stable and resistant to attack, hence the widespread use of glass containers. *Enamels*, made of silicate and borosilicate glasses, are widely used as coatings to protect steels and cast irons from corrosive attack.
- Table 24.7 gives a rough indication of the corrosion resistance of materials to different environments

Corrosion resistance	Material
Aerated water	
High resistance	All ceramics, glasses, lead alloys, alloy steels, titanium alloys, nickel alloys, copper alloys, PTFE, polypropylene, nylon, epoxies, polystyrene, PVC
Medium resistance	Aluminium alloys, polythene, polyesters
Low resistance	Carbon steels
Salt water	
High resistance	All ceramics, glasses, lead alloys, stainless steels, titanium alloys, nickel alloys, copper alloys, PTFE, polypropylene, nylon, epoxies, polystyrene, PVC, polythene
Medium resistance	Aluminium alloys, polyesters
Low resistance	Low-alloy steels, carbon steels
UV radiation	
High resistance	All ceramics, glasses, all alloys
Medium resistance	Epoxies, polyesters, polypropylene, polystyrene, HD polyethylene, polymers with UV inhibitor
Low resistance	Nylon, PVC, many elastomers
Strong acids	
High resistance	Glasses, alumina, silicon carbide, silica, PTFE, PVC, polythene, epoxies, elastomers, lead alloys, titanium alloys, nickel alloys, stainless steels
Medium resistance	Magnesium oxide, aluminium alloys
Low resistance	Carbon steels, polystyrene, polyurethane, nylon, polyesters
Strong alkalis	
High resistance	Alumina, nickel alloys, steels, titanium alloys, nylon, polythene, polystyrene, PTFE, PVC, polypropylene, epoxies
Medium resistance	Silicon carbide, copper alloys, zinc alloys, elastomers, polyesters
Low resistance	Glasses, aluminium alloys
Organic solvents	
High resistance	All ceramics, glasses, all alloys, PTFE, polypropylene
Medium resistance	Polythene, nylon, epoxies
Low resistance	Polystyrene, PVC, polyesters, ABS, most elastomers

4.2.6.1 Dissimilar metal corrosion

Table 24.8 shows the *galvanic series of metals in sea water*. The series will differ if the environment is freshwater or industrial atmosphere, though the same rough sequence tends to occur but the potentials are likely to vary.

The list is in order of corrosion tendency, giving the free corrosion potentials, and enables the prediction of the corrosion resistance of a combination of dissimilar metals. The bigger the separation of any two metals in the series, the more severe the corrosion of the more active of them when a junction between the pair of them is exposed to sea water. The more negative potential metal acts as the anode and the less negative or positive as the cathode in an electrochemical cell.

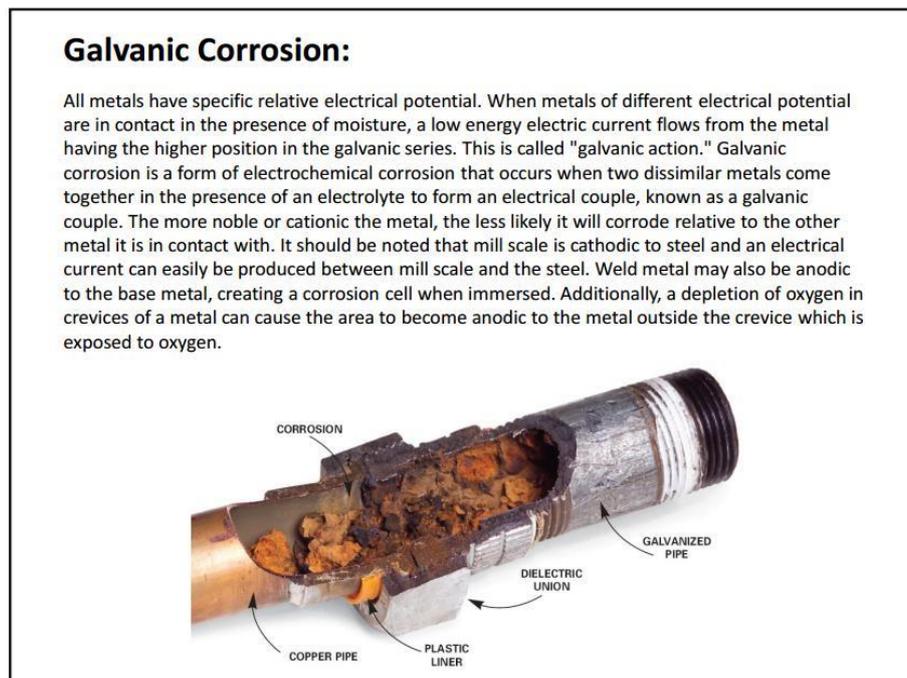


Table 24.8 Galvanic series for sea water.

Metal	Free corrosion potential (V)
Magnesium	-1.60 to -1.63
Zinc	-0.9 to -1.2
Aluminium alloys	-0.75 to -1.0
Mild steel	-0.6 to -0.7
Low alloy steel	-0.58 to -0.62
Aluminium bronze	-0.3 to -0.4
Yellow/red brass	-0.3 to -0.4
Tin	-0.3 to -0.34
Copper	-0.3 to -0.37
Lead/tin solder (50/50)	-0.3 to -0.35
Aluminium brass	-0.27 to -0.34
Manganese bronze	-0.27 to -0.32
Silicon bronze	-0.25 to -0.29
Tin bronze	-0.24 to -0.31
Stainless steel (410, 416)	-0.25 to -0.35
Nickel silver	-0.22 to -0.27
Cupronickel (80/20)	-0.2 to -0.3
Stainless steel (430)	-0.2 to -0.25
Lead	-0.2 to -0.22
Cupronickel (70/30)	-0.18 to -0.22
Nickel-chromium alloys	-0.13 to -0.17
Silver braze alloys	-0.1 to -0.2
Nickel	-0.1 to -0.2
Silver	-0.1 to -0.15
Stainless steel (302, 304, 321, 347)	-0.05 to -0.1
Nickel-copper alloys	-0.02 to -0.12
Stainless steel (317, 317)	0 to -0.1
Titanium	+0.05 to -0.05
Platinum	+0.25 to +0.20
Graphite	+0.2 to +0.3

4.2.7 Selection for wear resistance

- **Wear** : is the progressive loss of material from surfaces as a result of contact with other surfaces. It can occur as a result of sliding or rolling contact between surfaces or from the movement of fluids containing particles over surfaces.

Because wear is a surface effect, surface treatments and coatings play an important role in improving wear resistance. Lubrication can be considered to be a way of keeping surfaces apart and so reducing wear.

➤ **Properties of wear materials**

- A wear material may be used to reduce dimensional changes due to unwanted material removal, reduce frictional losses, to tailor the physical performance of a component, and/or to provide a physically stable working surface.
- The proper selection of a material for a wear application will strongly depend on both the type of wear to be countered and on the wear environment. The wear environment can be dry, wet, warm, cold, and so on. Wear taking place in a corrosive marine environment will be more damaging than the marine environment or the wear alone.
- Wear phenomenon is a factor in applications where it might not be readily apparent. Optical windows that are exposed to the natural elements have a need for wear protection where dust, sand, and ice can impact and roughen soft optical surfaces. Fan and propeller blades in water can experience wear by cavitation erosion in water and bug and dust impact erosion in air.

➤ **Mechanisms for wear :**

A number of different mechanisms for wear have been identified:

1- Adhesive wear

On an atomic scale, even smooth surfaces appear rough and thus when two surfaces are brought together; contact is made at only a few points (Figure 1.13). The forces holding the surfaces together can result in very high stresses at the few very small area of contact. Surface projections become plastically deformed by the pressure and can weld together. Sliding involves breaking these welded bonds, the breaks resulting in cavities being produced on one surface, projections on the other and frequently tiny abrasive particles.

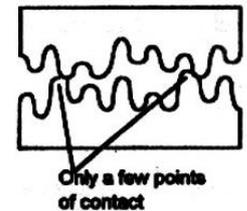
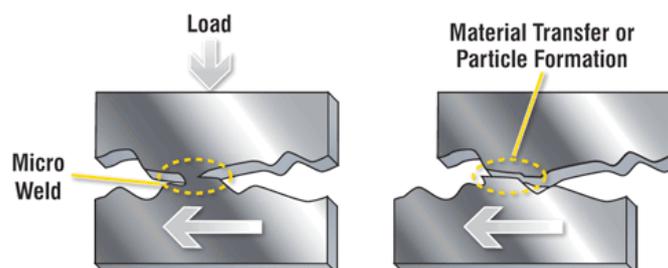


Figure 1.13 Principle of two surfaces in contact

- **Adhesive wear or scoring, galling or seizing, is used for this type of wear when two solid surfaces slide over one another under pressure.**
- **How to reduce wear rate for this type:**
 - ✓ If the harnesses of the two surfaces are high, the wear rate can be reduced.
 - ✓ Also, high strength, high toughness and ductility all contribute to reducing such wear, preventing the tearing of material from the surfaces.



2- Abrasive wear

The term *abrasive wear* is used when material is removed from a surface by contact with hard particles; sliding resulting in the pushing out of the softer material by the harder material (figure 1.14). Such wear is common in machinery used to handle abrasive materials. **Materials with a high hardness, high toughness and high strength are most resistant to such wear.**

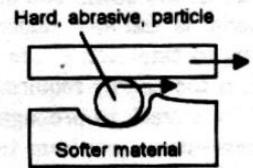


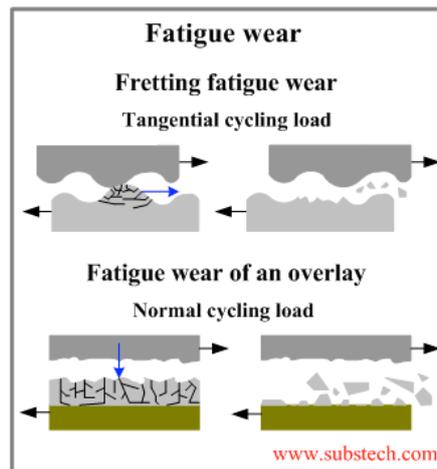
Figure 1.14 Principle of abrasive wear

3- Corrosive wear

When rubbing between surfaces takes place in a corrosive environment, surface reactions can take place and reaction products formed on the surfaces. These generally poorly adhere to the surfaces and the rubbing removes them. The process thus involves the repeated forming of reaction products and their removal by the rubbing. **Lubricants can be used to separate surfaces and protect the surfaces from the corrosive environment.**

4- Surface fatigue

- Surface fatigue is a process by which the surface of a material is weakened by cyclic loading, which is one type of general material fatigue.
- One of the types of fatigue wear is **fretting wear** caused by cycling sliding of two surfaces across each other with a small amplitude (oscillating). The friction force produces alternating compression-tension stresses, which result in surface fatigue.
- Fatigue of overlay of an engine bearing may result in the propagation of the cracks up to the intermediate layer and total removal of the overlay.



➤ **Wear resistance for different materials:**

- **Mild steels** have poor wear resistance. However, increasing the carbon content increases the wear resistance.
- **Surface harden-able carbon or low alloy steels** enable wear resistance to be improved as a result of surface treatments such as carburizing, cyaniding or carbonitriding.
- Even better wear resistance is provided by nitriding **medium-carbon chromium or chromiumaluminium steels**, or by **surface hardening high-carbon high-chromium steels**.
- **Grey cast iron** has good wear resistance for many applications.
- Better wear resistance is provided by **white irons**.
- Among **non-ferrous alloys, beryllium coppers and cobalt-base alloys, such as Stellite**, offer particularly good wear resistance.

4.2.7.1 Bearing materials

Bearing is a device supporting a mechanical element and providing its movement relatively to another element with minimum power loss.

- **Metallc materials** for use as bearing surfaces need to be hard and wear resistant, with a low coefficient of friction, but at the same time sufficiently tough.

Generally these requirements are met by the use of a soft, but tough, alloy in which hard particles are embedded.

- Because the real areas of contact are so small, the pressure at the contact points will be very high, even under light loading. With *metals*, the pressure will generally be high enough to cause appreciable plastic deformation and adhesion between the two surfaces at these points. This is termed cold welding for metals. These junctions are sheared when surfaces slide over each other. The frictional force thus arises from the force to shear junctions and the force required to plough the asperities of one surface through those of the other surface.

Bearing materials can be classified into five categories:

1- White metals

- These are *tin-base or lead-base alloys* with the addition of mainly antimony or copper. They have a microstructure of hard intermetallic compounds of tin and antimony embedded in a soft matrix. The hard particles support the load, since the asperities penetrate the softer material, but the greater area of contact between the surfaces is with the soft material. Thus sliding takes place within a thin smeared film of the softer material.
- *White metals* have relatively low fatigue strength and this can limit their use to low-load conditions. Reducing the thickness of the bearing material can improve the fatigue properties but does require care because of the size of the hard intermetallic particles.
- *Tin-base alloys* resist corrosion better, have higher thermal conductivity, have higher modulus of elasticity and higher yield stress but are significantly more expensive than *lead-base alloys*. Both forms of alloy are relatively soft.

Table 24.9 shows typical properties.

Table 24.9 Composition and properties of bearing metals

Alloy and composition %	Manufacturing process	0.1% proof stress MPa	Strength MPa	Hardness HV
<i>Whitemetal: tin base</i>				
89.2 Sn, 7.5 Sb, 3.3 Cu	Cast on steel strip	65	76	27
	Centrifugal casting on steel	39	70	31
<i>Whitemetals: lead base</i>				
84 Pb, 10 Sb, 6 Sn	Cast on steel strip	30	42	16
79.5 Pb, 10 Sb, 10 Sn, 0.5 Cu	Centrifugal casting on steel	60	73	25
<i>Copper-base alloys</i>				
90 Cu, 10 Sn, 0.5 P	Cast on steel	233	420	120
75 Cu, 20 Pb, 5 Sn	Cast on steel	124	233	70
80 Cu, 10 Pb, 10 Sn	Sintered on steel	249	303	120
73.5 Cu, 22 Pb, 4.5 Sn	Sintered on steel	81	121	46
<i>Aluminium-base alloys</i>				
92 Al, 6 Sn, 1 Cu, 1 Ni	Cast on steel	50	140	45
89.7 Al, 6 Sn, 1.5 Cu, 1.4 Ni, 0.9 Mg, 0.5 Si	Cast on steel	83	207	78

2- Copper-base alloys

These offer a wider range of strength and hardness than white metals. They include:

- ✓ *Tin-bronzes* with between 10 and 18% tin.
- ✓ *Leaded tin-bronzes* containing 1 or 2% lead,
- ✓ *Phosphor bronzes*.
- ✓ *Copper-lead alloys* containing about 25 to 30% lead.

Comparison:

The properties of the *copper-lead alloys* depend on the lead content, the higher the amount of lead the lower the fatigue strength but the better the sliding properties. They have poorer corrosion resistance than white metals but better wear resistance, a higher modulus of elasticity and better fatigue resistance. The bronzes have higher strengths, hardness, modulus of elasticity and better fatigue resistance than the copper-lead alloys and the whitemetals. They tend to be used for high load-bearing loads.

3- Aluminium-base alloys

- **Aluminium-tin alloys** with about 5 to 7% tin, 1% copper, 1% nickel and small amounts of other elements.
- Properties of bearing materials are: high fatigue strength, hardness and strength which makes them suitable for high-load bearings.
- **Disadvantage** : high thermal expansivity
- **Table 24.9** shows typical properties.

4- Non-metallic bearing materials

- **Polymers** suitable for bearing materials include phenolics, nylon, acetal and PTFE.
- For some applications the polymers have **fillers**, e.g. graphite-filled nylon, PTFE with a silicon lubricant, acetal with PTFE filler. In addition to the fillers used to decrease the coefficient of friction, other fillers such as glass fibers are added to increase strength and dimensional stability.
- **Polymers** have the advantage of a very low coefficient of friction but the disadvantage of a low thermal conductivity.
- **Polymer** rubbing against **polymer** can lead to high rates of wear, but **polymer** against **steel** gives a very low wear rate.
- **Polymers** have thermal expansivities much greater than **metals** and so can present problems, e.g. a higher running clearance between surfaces is needed. They tend to be used under low load conditions where they have the advantage of being cheap.

Table 24.10 shows the properties of commonly used polymeric bearing materials.

Table 24.10 Properties of polymeric bearing materials sliding against steel

Material	Max. load pressure MPa	Max. temp. °C	Max. speed m/s
Phenolics	30	150	0.5
Nylon	10	100	0.1
Acetal	10	100	0.1
PTFE	6	260	0.5
Nylon with graphite filler	7	100	0.1
Acetal with PTFE filler	10	100	0.1
PTFE with silicon filler	10	260	0.5
Phenolic with PTFE filler	30	150	0.5

5- Metal-non-metallic bearing materials

- **Graphite-impregnated metals and PTFE-impregnated metals** are widely used bearing materials. Such materials are able to utilize the load-bearing and temperature advantages of metals with the low coefficient of friction and soft properties of the non-metals.
- **Graphite-impregnated metals** rubbing against a **steel** mating surface can be used with load pressures up to about 40 MPa and operating temperatures up to 500°C,
- **PTFE impregnated metals** can be used with loads up to 100 MPa and temperatures of 250°C.
- **Table 24.11** gives data and simple comparisons for the various types of bearing materials.

Table 24.11 Comparison of bearing materials

Material	Hardness BH	Yield stress MPa	Strength MPa	Fatigue strength MPa	Elastic modulus GPa	Density Mg/m ³
Tin-base whitemetal	17-25	30-65	70-120	25-35	51-53	7.3-7.7
Lead-base whitemetal	15-20	20-60	40-110	22-30	29	9.6-10
Copper-lead	20-40	40-60	50-90	40-50	75	9.3-9.5
Phosphor bronze	70-150	130-230	280-420	90-120	80-95	8.8
Leaded tin bronze	50-80	80-150	160-300	80	95	8.8
Aluminium-base	70-75	50-90	140-210	130-170	73	2.9
Polymers	5-20		20-80	5-40	1-10	1.0-1.3

Table 24.11 Continued

Material	Thermal conductivity W m ⁻¹ K ⁻¹	Relative corrosion resistance	Relative wear resistance	Relative cost
Tin-base whitemetal	50	5	2	7
Lead-base whitemetal	24	4	3	1
Copper-lead	42	3	5	1.5
Phosphor bronze	42	2	5	2
Leaded tin bronze	42	2	3	2
Aluminium-base	160	3	2	1.5
Polymers	0.1	5	5	0.3

Note: the larger the number for relative corrosion resistance and for relative wear resistance the better the resistance.

A bearing material is inevitably a compromise between the opposing requirements of softness and high strength. One way of achieving strength with a relatively soft bearing material is to use the soft material as a lining on a steel backing, e.g. **whitemetals, aluminium or copper-base alloys** as thin layer on a steel backing. **Plastics** when bonded to a steel backing can be used at higher speeds than otherwise would be possible, because the **steel** is able to dissipate heat better than the plastic alone and also the thinner the layer of plastic the smaller the amount by which it will expand.

Lecture #7:

4.2.8 Selection for thermal properties

Thermal properties that are generally of interest in the **selection of materials** include how much a material will expand for a particular change in temperature; how much the temperature of a piece of material will change when there is a heat input into it, and how good a conductor of heat it is.

Some important definitions:

- **Linear expansivity α or coefficient of linear expansion:** is a measure of the amount by which a length of material expands when the temperature increases. It is defined as:

$$\alpha = \frac{\text{change in length}}{\text{original length} \times \text{change in temperature}}$$

and has the unit of K^{-1}

- **Heat capacity** the amount of heat needed to raise the temperature of an object by 1 K. Thus if 300 J is needed to raise the temperature of a block of material by 1 K, then its heat capacity is 300 J/K.
- The **specific heat capacity c** is the amount of heat needed per kilogram of material to raise the temperature by 1 K, hence:

$$c = \frac{\text{amount of heat}}{\text{mass} \times \text{change in temperature}}$$

It has the unit of $\text{J kg}^{-1} \text{K}^{-1}$.

- Because **metals** have smaller specific heat capacities than **plastics**, weight-for-weight metals require less heat to reach a particular temperature than plastics,

e.g. **copper** has a specific heat capacity of about $340 \text{ J kg}^{-1} \text{ K}^{-1}$ while **polythene** is about $1800 \text{ J kg}^{-1} \text{ K}^{-1}$.

➤ The **thermal conductivity** λ of a material is a measure of the ability of a material to conduct heat (or a measure of the rate at which heat is transferred through the material). There will only be a net flow of heat energy through a length of material when there is a difference in temperature between the ends of the material.

The thermal conductivity is defined in terms of the quantity of heat that will flow per second divided by the temperature gradient (Figure 1.18), i.e.:

$$\lambda = \frac{\text{quantity of heat/second}}{\text{temperature gradient}} \quad \text{and has the unit of } \text{Wm}^{-1}\text{K}^{-1}.$$

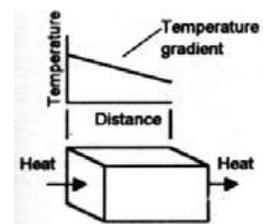


Figure 1.18 Thermal conductivity

- A high thermal conductivity means a good conductor of heat. It means a small temperature gradient for a particular rate of heat flux.
- **Metals** tend to be good conductors, e.g. *copper* has a thermal conductivity of about $400 \text{ Wm}^{-1}\text{K}^{-1}$.
- Materials that are bad conductors of heat have low thermal conductivities, e.g. **plastics** have thermal conductivities of the order $0.3 \text{ Wm}^{-1}\text{K}^{-1}$ or less.
- Very low thermal conductivities occur with **foamed plastics**, i.e. those containing bubbles of air. For example, *foamed polymer polystyrene*, known as expanded polystyrene and widely used for thermal insulation, has a thermal conductivity of about 0.02 to $0.03 \text{ W m}^{-1}\text{K}^{-1}$.

➤ **Table 1.4 gives typical values of the linear expansivity, the specific heat capacity and the thermal conductivity for metals, polymers and ceramics.**

Table 1.4 Thermal properties

Material	Linear expansivity 10^{-6} K^{-1}	Specific heat capacity $\text{J kg}^{-1} \text{ K}^{-1}$	Thermal conductivity $\text{W m}^{-1} \text{ K}^{-1}$
<i>Metals</i>			
Aluminium	24	920	230
Copper	18	385	380
Mild steel	11	480	54
<i>Polymers</i>			
Polyvinyl chloride	70–80	840–1200	0.1–0.2
Polyethylene	100–200	1900–2300	0.3–0.5
Epoxy cast resin	45–65	1000	0.1–0.2
<i>Ceramics</i>			
Alumina	8	750	38
Fused silica	0.5	800	2
Glass	8	800	1

Thermal properties for different types of materials:

- In general, **metals** have high thermal conductivities while **polymers** and **ceramics** have low conductivities. The specific heat capacity of a material is the energy required to raise the temperature of 1 kg of that material by 1°C.
- In general, **metals** have low specific heats while **polymers** having higher values.
- Materials expand when heated and the problems of differential expansion between different materials in a component can often be an important concern.
- In general, **ceramics** have low coefficients of expansion, **metals** higher values and **polymers** even higher.

- Table 24.12 gives typical values for 20°C,

Table 24.12 Thermal properties

Material	α (10^6 K^{-1})	c ($\text{kJ kg}^{-1} \text{ K}^{-1}$)	λ ($\text{W m}^{-1} \text{ K}^{-1}$)
Metals			
Aluminium	24	0.90	220 to 230
alloys	20 to 24	0.84	120 to 200
Copper	17	0.39	370
alloys	16 to 20	0.39	30 to 160
Iron	12	0.44	81
carbon steels	10 to 15	0.48	47
cast irons	10 to 11	0.27 to 0.46	44 to 53
alloy steels	12	0.51	13 to 48
stainless steel	11 to 16	0.51	16 to 26
Magnesium	25	1.02	156
alloys	25 to 27		80 to 140
Nickel	13	0.44	92
alloys	10 to 19	0.48 to 0.50	11 to 30
Tin	23	0.23	67
alloys	22 to 24		53 to 67
Titanium	8	0.52	22
alloys	8 to 9		5 to 12
Zinc	40	0.54	116
alloys	25 to 35		107 to 116
Polymers			
Thermoplastics	40 to 300	0.8 to 2.0	0.1 to 0.4
ABS	80 to 100	1.5	0.13 to 0.20
nylon 6	80 to 100	1.6	0.17 to 0.21
polythene	110 to 200	1.9 to 2.3	0.25 to 0.35
polypropylene	100 to 120	1.9	0.16
polystyrene	60 to 80	1.2	0.12 to 0.13
PVC	50 to 250	1.1 to 1.7	0.12 to 0.15
Thermosets	10 to 60	1.0 to 2.0	0.1 to 0.4
epoxy	60	1.1	0.17
phenol formaldehyde	30 to 40	1.6 to 1.8	0.13 to 0.25
Elastomers	50 to 250	1.3 to 1.8	0.1 to 0.3
natural rubber	22	1.9	0.18
neoprene	24	1.7	0.21
Cellular polymers			0.02 to 0.04
Ceramics			
Alumina	8 to 9	0.7	20 to 40
Bonded carbides	4 to 6	0.2 to 1.0	40 to 120
Glasses	3 to 9	0.5 to 0.7	0.5 to 2
Composites			
Concrete	7 to 14	3.3	0.1 to 2
Wood		1.7	0.1 to 0.2
across grain	35 to 60		
along grain	3 to 6		

Example:

By how much will a 10 cm strip of (a) copper, (b) PVC expand when the temperature changes from 20 to 30°C? Use the data given in Table 1.4.

A./

(from equation of *Linear expansivity*)

(a) For copper: expansion = $18 \times 10^{-6} \times 0.10 \times 10 = 18 \times 10^{-6} \text{ m} = 0.018 \text{ mm}$

(b) For the PVC: expansion = $75 \times 10^{-6} \times 0.10 \times 10 = 75 \times 10^{-6} \text{ m} = 0.075 \text{ mm}$

The expansion of the PVC is some four times greater than that of the copper.

4.2.9 Selection for electrical properties

- The **electrical resistivity** ρ : is a measure of the electrical resistance of a material, being defined by:

$$\rho = \frac{RA}{L}$$

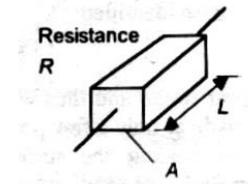


Figure 1.15 Resistivity

Where:

R : is the resistance of a length L of a material of cross sectional area A (Figure 1.15). The unit of resistivity is the ohm meter (Ωm).

- An electrical insulator such as a **ceramic** will have a very high resistivity, typically of the order of $10^{10} \Omega\text{m}$ or higher. An electrical conductor such as **copper** will have a very low resistivity, typically of the order of $10^{-4} \Omega\text{m}$.
- The term *semiconductor* is used for those materials which have resistivities roughly halfway between conductors and insulators, i.e., of the order of $10^2 \Omega\text{m}$.

Some important definitions:

- The **electrical conductance** **G** of a length of material is the reciprocal of its resistance and has the unit of Ω^{-1} . This unit is given a special name, the siemen (S).
- The **electrical conductivity** σ is the reciprocal of the resistivity:

$$\sigma = \frac{1}{\rho} = \frac{L}{RA} = \frac{LG}{A}, \text{ the unit of conductivity is: } \Omega^{-1}\text{m}^{-1} \text{ or S/m.}$$

- ✓ Since conductivity is the reciprocal of the resistivity:
 - An **electrical insulator** will have a very low conductivity; of the order of 10^{-10} S/m .
 - An **electrical conductor** will have very high conductivity, of the order of 10^8 S/m .
 - **Semiconductors** have conductivities of the order of 10^{-1} S/m .

- ✓ **Table 1.2** shows typical values of resistivity and conductivity for insulators, semiconductors and conductors .

Table 1.2 Typical resistivity and conductivity values at about 20°C

Material	Resistivity $\Omega \text{ m}$	Conductivity S/m
<i>Insulators</i>		
Acrylic (a polymer)	$> 10^{14}$	$< 10^{-14}$
Polyvinyl chloride (a polymer)	$10^{12}-10^{13}$	$10^{-13}-10^{-12}$
Mica	$10^{11}-10^{12}$	$10^{-12}-10^{-11}$
Glass	$10^{10}-10^{14}$	$10^{-14}-10^{-10}$
Porcelain (a ceramic)	$10^{10}-10^{12}$	$10^{-12}-10^{-10}$
Alumina (a ceramic)	10^9-10^{12}	$10^{-12}-10^{-9}$
<i>Semiconductors</i>		
Silicon (pure)	2.3×10^3	4.3×10^{-4}
Germanium (pure)	0.43	2.3
Gallium arsenide	0.05	20
<i>Conductors</i>		
Nichrome (alloy of nickel and chromium)	108×10^{-8}	0.9×10^6
Manganin (alloy of copper and manganese)	42×10^{-8}	2×10^6
Nickel (pure)	7×10^{-8}	14×10^6
Copper (pure)	2×10^{-8}	50×10^6

Example :

Using the value of electrical conductivity given in Table 1.2, determine the electrical conductance of a 2m length of Nichrome wire at 200°C if it has a cross-sectional area of 1 mm².

A./

Using the equation $\sigma = L/RA$, with the conductance $G = 1/R$, then we have $\sigma = LG/A$ and so:

$$G = \frac{\sigma A}{L} = \frac{0.9 \times 10^6 \times 1 \times 10^{-6}}{2} = 0.45 \text{ S}$$

Electrical properties for different types of materials :

- In general, **metals** are good electrical conductors with low resistivities. The **metals** in common use in engineering which have the highest electrical conductivities are **silver, copper and aluminium**. In each the conductivity is highest annealed condition when the material is of the highest purity and in the fully. Often, however, a compromise has to be reached in that the high purity, fully annealed, metals do not have sufficient strength to enable them to be, for example, **strung** as wire between posts.
 - **Polymers and ceramics** have, in general, very low electrical conductivities and are classified as being electrical insulators.
- ✓ Table 24.13 shows the resistivities and conductivities of a range of commonly used solid metals and alloys at about 20°C. Note that conductance is the reciprocal of resistance and has the unit Siemens (S) and that conductivity is the reciprocal of the resistivity and has the unit S/m. **In engineering, conductivity is often expressed as a percentage of the conductivity that annealed copper has at 20°C. Such values are said to be IACS values.**
- ✓ Table 24.14 shows resistivities for insulators.

Table 24.13 Resistivities of conductors at 20°C

Material	Resistivity (10 ⁸ Ω m)	IACS value (%)
Aluminium (99.996% pure)	2.65	64.9
Brass, cartridge (70%)	6.2	28
yellow	6.4	27
Constantan (55% Cu, 45% Ni)	49.9	3.5
Copper (>99.90 %, electrolytic)	1.71	101
(>99.95%, oxygen free)	1.71	101
-1% cadmium wire	2.2	80
-15% zinc alloy	4.7	37
-20% zinc alloy	5.4	32
-2% nickel alloy	5.0	35
-6% nickel alloy	9.9	17
Gold	2.35	75
Iron (99.99% pure)	9.7	17.7
-0.65% C (carbon steel)	18	9.5
Manganin (87% Cu, 13% Mn)	48.2	3.5
Nichrome (80% Ni, 20% Cu)	108	1.6
Nickel (99.8%)	8.0	23
Phosphor bronze (3%)	8.6	20
Platinum	10.6	16
-10% iridium alloy	25	7
-10% rubidium alloy	43	4
Silver	1.59	106
-10% copper alloy	2	85
-15% cadmium alloy	4.9	35
Steel, stainless	56	3.1
17% cobalt	28	6.3
Tungsten	5.65	30

Table 24.14 Resistivities of insulators at 20°C

Material	Resistivity (Ω m)
Ceramic: alumina	10 ⁹ to 10 ¹²
porcelain	10 ¹⁰ to 10 ¹²
Diamond	10 ¹⁰ to 10 ¹¹
Glass: soda lime	10 ⁹ to 10 ¹¹
Pyrex	10 ¹²
Elastomer: butyl	10 ¹³
natural rubber	10 ¹³ to 10 ¹⁵
polyurethane	10 ¹⁰
Mica	10 ¹¹ to 10 ¹⁵
Paper (dry)	10 ¹⁰
Polymer: acrylic	10 ¹² to 10 ¹⁴
cellulose acetate	10 ⁸ to 10 ¹²
melamine	10 ¹⁰
polyamide (nylon)	10 ¹⁰ to 10 ¹³
polypropylene	10 ¹³ to 10 ¹⁵
polythene: high density	10 ¹⁴ to 10 ¹⁵
low density	10 ¹⁴ to 10 ¹⁸
polyvinyl chloride: rigid	10 ¹² to 10 ¹⁴
flexible	10 ⁹ to 10 ¹³

Lecture #8:

4.2.9 Selection for magnetic properties

➤ Materials can be grouped into THREE general categories:

1. Diamagnetic materials:

- They have a weak, negative susceptibility to magnetic fields.
- They are slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed.
- In diamagnetic materials all the electron are paired so there is no permanent net magnetic moment per atom.
- Examples: copper, silver, and gold.

2. Paramagnetic materials:

- They have a small, positive susceptibility to magnetic fields.
- These materials are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed.
- Examples: magnesium, molybdenum and lithium.

3. Ferromagnetic materials :

- They have a large, positive susceptibility to an external magnetic field.
- They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed.
- Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment.
- Examples: Iron, nickel, and cobalt.

➤ **Soft & Hard Magnetic Materials:**

❖ **Soft magnetic materials:**

- ✓ Easy to magnetize and demagnetize.
- ✓ Used for making temporary magnets.
- ✓ Soft magnetic materials should not possess any void and its structure should be homogeneous so that the materials are not affected by impurities.
- ✓ Having low coercivity.
- ✓ A typical soft magnetic material used for a transformer core is an iron-3% silicon alloy

❖ **Hard magnetic materials:**

- ✓ Materials which retain their magnetism and are difficult to demagnetize.
- ✓ These materials retain their magnetism even after the removal of the applied magnetic field. So, these materials are used for making permanent magnets.
- ✓ Impurities increase the strength of hard magnetic materials.
- ✓ High coercivity so that it is difficult to demagnetize
- ✓ The main materials used for permanent magnets are the iron-cobalt-nickelaluminium alloys, ferrites and rare earth alloys.

➤ Selection of magnetic materials:

In considering the selection of a magnetic material, the questions to be posed are as to whether soft or hard, and often in the case of soft as to whether the material is a good electrical conductor.

Table 24.15 gives the properties of some commonly encountered soft magnetic materials. Table 24.16 those for hard magnetic materials.

Table 24.15 Soft magnetic materials

Material	Max. B (T)	Max. μ_r	Coercive field (A/m)	Energy loss/cycle (J/m ³)	Curie temp. (K)	Resistivity ($\mu\Omega$ m)
Pure iron	2.2	200 000	4	30	1043	0.1
Mild steel	2.1	2 000	143	500	1000	0.1
Silicon iron	2.0	30 000	12	30	1030	0.5
Fe + 3% Si						
Permalloy	1.1	100 000	4	4	800	0.2
Fe + 78.5% Ni						
Supermalloy	0.8	800 000	0.16	4	620	0.6
79% Ni, 16% Fe, 5% Mo						
Ferroxcube	0.25	1 500	0.8	13	570	10*
Mn Zn ferrite						

Table 24.16 Hard magnetic materials

Material	Remanence (T)	Coercive field (kA/m)	Max. (BH) (kJ/m ³)	Curie temp. (K)
<i>Isotropic</i>				
Alni	0.56	46	10	1030
Magloy 6				
Alnico	0.72	45	13.5	1070
Magloy 5				
*Feroba 1	0.22	135	8	720
*Ferroxdure 100				
*Neoperm D1				
<i>Anisotropic</i>				
Alcomax 3	1.26	52	43	1130
Magloy 1				
Ticonal 600				
Columax	1.35	59	60	1130
Magloy 100X				
*Feroba 2	0.39	150	29	720
*Ferroxdure 300				
*Neoperm E2				
*Feroba 3	0.37	240	26	720
*Ferroxdure 380				
*Neoperm E3				
<i>Steels</i>				
6% tungsten	1.05	5.2	2.4	1030
6% chromium	0.95	5.2	2.4	1030
3% cobalt	0.72	10	2.8	1070
15% cobalt	0.83	14	4.9	1110

A number of alternative trade names are given for entries. * These are ferrites. The other isotropic and anisotropic materials are all iron, cobalt, nickel, aluminium alloys.

Notes:

- ✚ The Curie temperature is the temperature at which thermal energy results in the loss of ferromagnetism.
- ✚ The term **magnetic flux density B** is used for the amount of flux passing through unit area. Thus if flux passes through an area A . The unit of B is the tesla (T), which is equal to 1 Wb/m^2 .
- ✚ μ_r : relative permeability.
- ✚ The **coercivity**, also called the **coercive field** or **coercive force**: The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero after achieving saturation. Coercivity is usually measured in oersted or ampere/meter units.

4.3 Available forms of materials

A major factor affecting the choice of material is the form and size it can be supplied in. If the design indicates, for example, an I-girder with specified dimensions in a particular steel and that is not a size in which the material is normally supplied, then there may well have to be a change in the material used since the cost of obtaining the non-standard size of the material may rule it out. The 'as supplied' form and size can determine whether further processing is required and, if so, to what extent.

The surface conditions of the supplied material may also be important, particularly if the material is to be used without further processing. Thus, for example, **hot rolled steel** could have a **loose flaky scale** on its surface and thus have to be machined.

- A particular manufacturer might supply **steel** as:
 - rounds,
 - squares,
 - flats,
 - T-shapes,
 - channels,
 - circular hollow sections,
 - square hollow sections,
 - rectangular hollow sections,
 - rolled steel joists,
 - universal beams and columns,
 - sheets, galvanized sheets, plates, etc. with a variety of sizes and surface finishes.

- **Polymeric** materials are generally supplied as granules ready for processing. However, the composition of the **granules**, for what is the same polymeric material, can vary depending in what other materials, e.g. **fibers**, have been added.

4.4 Cost of materials

Costs can be considered in relation to:

- *The basic costs of the raw materials:*

In comparing the basic costs of materials, the comparison is often on the basis of the cost per unit weight or cost per unit volume.

Table 1.9 shows the relative costs of some materials.

However, often a more important comparison is on the basis of the cost per unit strength or cost per unit stiffness for the same volume of material. This enables the cost of, say, a beam to be considered in terms of what it will cost to have a beam of a certain strength or stiffness. Hence if, for comparison purposes, we consider a beam of volume 1m^3 then, if the tensile strength of the material is 500 MPa and the cost per cubic meter £800, the cost per MPa of strength will be $800/500 = \text{£}1.6$.

Table 1.9 *Relative costs of materials in relation to that of mild steel ingot*

Material	Relative cost/kg	Relative cost/m ³
Cobalt	100	112
PTFE	39	11
Nickel	28	32
Chromium	26	24
Tin	19	18
Titanium	17	10
Brass sheet	16	17
Al-Cu alloy sheet	14	5.3
Nylon 66	12	1.8
Phosphor bronze ingot	10	12
Magnesium ingot	9.2	2.1
Acrylic	8.9	1.4
Copper tubing	8.7	10
ABS	8.3	1.1
Aluminium ingot	4.3	1.5
Polystyrene	3.6	0.50
Zinc ingot	3.6	3.3
Polyethylene (HDPE)	3.4	0.43
Polypropylene	3.2	0.34
Natural rubber	3.1	0.50
Polyethylene (LDPE)	2.3	0.29
PVC, rigid	2.3	0.43
Mild steel sheet	1.9	1.9
Mild steel ingot	1.0	1.0
Cast iron	0.8	0.79

The costs of materials change with time, and to eliminate the need to specify any particular unit of currency, relative costs are used for the purpose of materials selection when we only require to determine the optimum material. The relative costs tend to be per unit mass defined in relationship to that of *mild steel*, often mild steel bar. Thus:

$$\text{relative cost} = \frac{\text{cost per kg of material}}{\text{cost per kg of mild steel}}$$

Tables 24.17 gives some typical values. The relative cost per kg can be converted into relative cost per m³ by multiplying it by the density.

Table 24.15 Relative costs of materials

Material	Relative cost per kg	Material	Relative cost per kg
<i>Metals</i>		<i>Polymers</i>	
Mild steel bar (black)	1.0	Polyethylene	3
Mild steel bar (bright)	1.3	Polypropylene	3
Mild steel sheet	1.4	Polystyrene	3
Medium-carbon steel	1.6	PVC	6
High-carbon steel bar	2.3	ABS	12
Cast iron casting	2.4	Phenolics	12
Manganese steel bar	2.5	Acrylics	12
Brass sheet	5.1	Cellulose acetate	15
Copper sheet	8.3	Acetals	15
Stainless steel sheet	8.5	Polycarbonate	36
Aluminium bar	8.5	Nylons	45
Nickel chrome steel bar	4.6	Polyurethane	60
Brass bar	6.6	PTFE	90
Aluminium sheet	7.1	Fluorosilicones	240
Aluminium casting	9.6		
Stainless steel bar	9.6		
Phosphor bronze bar	16.0		
Monel bar	20.6		

- *The costs of manufacturing products:*

The costs of manufacturing will depend on the processes used. Some processes require a large capital outlay and then can be used to produce large numbers of the product at a relatively low cost per item. Other processes may have little in the way of setting-up costs but a large cost per unit product.

- *The life and maintenance costs of the finished product:*

The cost of maintaining a material during its life can often be a significant factor in the **selection of materials**. A feature common to many *metals* is the need for a surface coating to protect them from corrosion by the atmosphere.

3. Selection of Processes

3.1 Introduction

Processing of materials:

For their use, materials have to be engineered by processing and manufacture in order to fulfil their purpose as the physical basis of products designed for the needs of the economy and society.

There are the following main technologies to transform matter into engineered materials :

- **Machining**, i.e. shaping, cutting, drilling, etc. of solids,
- **Net forming of suitable matter**, e.g. liquids, moulds,
- **Nanotechnology assembly** of atoms or molecules.

In addition to these methods, there are also further technologies, like **surfacing and joining**, which are applied to process, shape and assemble materials and products.

Making a decision :

In making a decision about the manufacturing process to be used for a product there are a number of questions that have to be answered:

1. What is the material?

The type of material to be used influences the choice of processing method. For example, **for casting of high melting point material**, the process must be either sand casting or investment casting.

2. What is the shape?

The shape of the product is generally a very important factor in determining which type of process. For example, a product in the form of **a tube** could be produced by centrifugal casting, drawing or extrusion but not generally by other methods.

3. What is the kind of detail is involved?

Is the product to have holes, threads, inserts, hollow sections, fine detail, etc.? Thus, forging could not be used if there was a requirement for hollow sections.

4. What dimensional accuracy and tolerances are required?

High accuracy would rule out sand casting, though investment casting might well be suitable.

5. Are any finishing processes to be used?

Is the process used to give the product its final finished state or will there have to be an extra finishing process? For example, planing will not produce as smooth a surface as grinding.

6. What quantities are involved?

Some processes are economic for small quantities; others are economic for large quantities or continuous production. For example, open die forging could be economic for small numbers.

3.2 Surface finish

A sand cast product will have a surface finish which is much rougher than one which has been die cast.

Roughness is defined as the irregularities in the surface texture which are inherent in the production process but *excluding* waviness and errors of form.

- ✓ Roughness takes the form of a series of peaks and valleys which may vary in both height and spacing and is a characteristic of the process used.
- ✓ Waviness may arise from such factors as machine or work deflections, vibrations, heat treatment or warping strains.
- ✓ Figure 25.1 illustrates the terms roughness, waviness and error of form

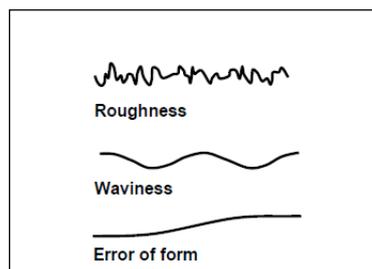
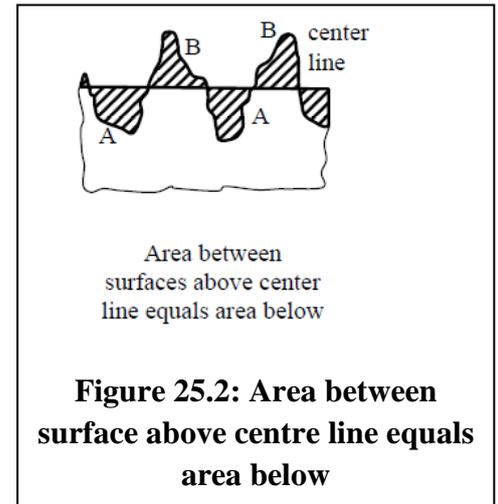


Figure 25.1: Terms

Arithmetical mean deviation (R_a):

It is one measure of roughness and defined as the arithmetical average of the variation of the profile above and below a reference line throughout the prescribed sampling length. The reference line may be the centre line, this being a line chosen so that the sums of the areas contained between it and those parts of the surface profile which lie on either side of it are equal (Figure 25.2).



For a sample length in millimeters and areas in square millimeters R_a is defined as:

$$R_a = \frac{\text{sum of areas } A + \text{sum of areas } B}{\text{sample length}} \times 1000$$

Tables:

- ✓ **Table 25.1** indicates the significance of R_a values in terms of the surface texture. The degree of roughness that can be tolerated for a component depends on its use.

For example, precision sliding surfaces will require R_a values of the order of 0.2 to 0.8 μm with more general sliding surfaces 0.8 to 3 μm . Gear teeth are likely to require R_a values of 0.4 to 1.6 μm , friction surfaces such as clutch plates 0.4 to 1.5 μm , mating surfaces 1.5 to 3 μm .

Table 25.1 Relation of R_a values to surface texture

Surface texture	Roughness R_a μm
Very rough	50
Rough	25
Semi-rough	12.5
Medium	6.3
Semi-fine	3.2
Fine	1.6
Coarse-ground	0.8
Medium-ground	0.4
Fine-ground	0.2
Super-fine	0.1

- ✓ **Table 25.2** shows what is typically achievable with different processes. Thus, sand casting produces a much rougher surface than die casting; hot rolling produces a rougher surface than cold rolling; sawing produces a much rougher surface than milling.

Table 25.2 Roughness values for different processes

Process	Roughness R_a μm
Sand casting	25 - 12.5
Hot rolling	25 - 12.5
Sawing	25 - 3.2
Planing, shaping	25 - 0.8
Forging	12.5 - 3.2
Milling	6.3 - 0.8
Boring, turning	6.3 - 0.4
Investment casting	3.2 - 1.6
Extruding	3.2 - 0.8
Cold rolling	3.2 - 0.8
Drawing	3.2 - 0.8
Die casting	1.6 - 0.8
Grinding	1.6 - 0.1
Honing	0.8 - 0.1

Lecture # 9:

3.3 Metal-forming processes

The following is a discussion of the characteristics of the various processes used for metal forming and the types of products that can be obtained from them.

3.3.1 Casting of Metals

Casting can be used for components from masses of about 10^{-3} kg to 10^4 kg with wall thicknesses from about 0.5 mm to 1 m. Castings need to have rounded corners, no abrupt changes in section and gradual sloping surfaces. Casting is likely to be the optimum method in the circumstances listed below but not for components that are simple enough to be extruded or deep drawn.

The casting process is selected when:

1. The part has a large internal cavity

There would be a considerable amount of metal to be removed if machining was used.

2. The part has a complex internal cavity

Machining might be impossible; by casting, however, very complex internal cavities can be produced.

3. The part is made of a material which is difficult to machine

The hardness of a material may make machining very difficult, e.g. **white cast iron**.

4. The metal used is expensive and so there is to be little waste

Machining is likely to produce more waste than occurs with casting.

5. The directional properties of a material are to be minimized

Metals subject to a manipulative process often have properties which differ in different directions.

6. The component has a complex shape

Casting may be more economical than assembling a number of individual parts.

7. The tooling cost for making the moulds

When many identical castings are required; the mould cost (used many times) will be spread over many items and make the process economic.

8. The mould type and cost for single product

Where just a single product is required, the mould used must be as cheap as possible.

- Each casting method has important characteristics which determine its appropriateness in a particular situation.

Table 25.3 illustrates some of the key differences between the casting methods.

Table 25.3 *Casting processes*

Process	Usual materials	Section thickness mm	Size kg	Roughness R_a μm	Production rate, items per hour
Sand casting	Most	> 4	0.1 – 200 000	25 - 12.5	1 - 60
Gravity die casting	Non-ferrous	3 to 50	0.1 - 200	3.2 - 1.6	5 - 100
Investment casting	All	1 - 75	0.005 - 700	3.2 – 1.6	Up to 1000
Centrifugal casting	Most	3 - 100	25mm – 1.8m diameter	25 - 12.5	Up to 50
Pressure die casting: high pressure	Non-ferrous	1 - 8	0.0001 - 5	1.6 - 0.8	Up to 200
Pressure die casting: low pressure	Non-ferrous	2 - 10	0.1 -200	1.6 – 0.8	Up to 200

✚ **Factors determine the type of casting process used:**

1. Large heavy casting

Sand casting can be used for very large castings.

2. Complex designs

Sand casting is the most flexible method and can be used for very complex castings.

3. Thin walls

Investment casting or pressure die casting can cope with walls as thin as 1mm. Sand casting cannot cope with such thin walls.

4. Good reproduction of detail

Pressure die casting or investment casting gives good reproduction of detail, sand casting is being the worst.

5. Good surface finishes

Pressure die casting or investment casting gives the best finish, sand casting being the worst.

6. High melting point alloys

Sand casting or investment casting can be used.

7. Tooling cost

- This is **highest** with pressure die casting.
- Sand casting is cheapest.
- With large number production, the tooling costs for metal moulds can be paid over a large number of castings,
- Whereas, the cost of the mould for sand casting is the same no matter how many castings are made since a new mould is required for each casting.

3.3.2 Manipulation of Metals

Manipulative methods involve the shaping of a material by means of **plastic deformation methods**. Such methods include forging, extruding, rolling, and drawing. Depending on the method, components can be produced from as small as about 10^{-5} kg to 100 kg, with wall thicknesses from about 0.1 mm to 1m.

- **Table 25.4** shows some of the characteristics of the different processes

Table 25.4 Manipulative processes

Process	Usual materials	Section thickness mm	Minimum size	Maximum size	Roughness R_a μm	Production rate, items per hour
Closed-die forging	Steels, Al, Cu, Mg alloys	3 upwards			3.2 – 12.5	Up to 300
Roll forming	Any ductile material	0.2 – 6			0.8 – 3.2	
Drawing	Any ductile material	0.1 – 25	3 mm diameter	6 mm diameter	0.8 – 3.2	Up to 3000
Impact extrusion	Any ductile material	0.1 – 20	6 mm diameter	0.15 m diameter	0.8 – 3.2	Up to 2000
Hot extrusion	Most ductile materials	1 – 100	8 mm diameter	500 mm diameter	0.8 – 3.2	Up to 720
Cold extrusion	Most ductile materials	1 – 100	8 mm diameter	4 m long	0.8 – 3.2	Up to 720

Note: ductile materials are commonly aluminium copper and magnesium alloys and to a lesser extent carbon steels and titanium alloys.

- Compared with casting, wrought products tend to have a greater degree of uniformity and reliability of mechanical properties.
- The manipulative processes do, however, tend to give a directionality of properties which is not the case with casting.
- Manipulative processes are likely to be the optimum method for product production when:
 - 1. The part is to be formed from sheet metal**
Depending on the form required, **shearing, bending or drawing** may be appropriate if the components are not too large.
 - 2. Long lengths of constant cross-section are required**
Extrusion or rolling is the optimum methods for long lengths of quite complex cross-section. It can be produced without any need for machining.

3. The part has no internal cavities

i. Forging can be used when there are no internal cavities, particularly if better toughness and impact strength is required than are obtainable with casting.

ii. Directional properties can be obtained to the material to improve its performance in service.

4. Seamless cup-shaped objects or cans are required

Deep drawing or impact extrusion would be optimum methods.

5. The component is to be made from material in wire or bar form

Bending or upsetting can be used.

3.3.3 Metal Powder Processes (Metallurgy)

Include the production of "green" parts by compaction followed by sintering. Powder processes enables:

1. Large numbers of small items (components) to be made at high rates of production; with little, if any, finishing machining required.
2. It enables components to be made with all metals and in particular with those which otherwise cannot easily processed, e.g. the high melting point metals of molybdenum, tantalum and tungsten.
3. Production of parts with specific degree of porosity, e.g. porous bearings to be oil filled.
4. The mechanical compaction of powders only, however, permits two-dimensional shapes to be produced, unlike casting and forging.
5. The shapes are restricted to those that are capable of being ejected from the die. Thus, for example, reverse tapers, undercuts and holes at right angles to the pressing direction have to be avoided.
6. Powdered metals are more expensive than metals for use in manipulative or casting processes; however, this higher cost may be compensated by the absence of scrap, the elimination of finishing machining and the high rates of production.

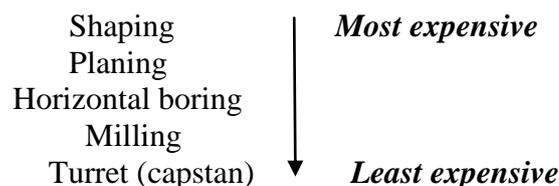
3.3.4 Machining of Metals

It is a cutting process, like planing, shaping, boring and turning.

The following factors are relevant in determining the optimum process or processes:

1. Operations should be designed so that the minimum amount of material is removed. This reduces material costs, energy costs involved in the machining and costs due to tool wear.
 2. The time spent on the operation should be kept to a minimum to keep labor costs low.
 3. The skills required affect the labor costs.
 4. The properties of the material being machined should be considered; in particular the **hardness**:
 - i.) In general, the harder a material the longer it will take to cut. The hardness also, however, affects the choice of tool material that can be used,
 - ii.) In the case of very hard materials, grinding is a process that can be used because the tool material and the abrasive particles can be very hard.
 - iii.) Where a considerable amount of machining occurs, the use of free machining grades of materials (machinable materials) should be considered as a means of minimizing cutting times.
 5. The process, or processes, chosen should take into account the quantity of products required and the required rate of production.
 6. The geomantic form of the product should be considered in choosing the most appropriate process or processes.
 7. The required surface finish and dimensional accuracy also affect the choice of process or processes.
- Machining operations vary quite significantly in cost, especially when a particular tolerances to be achieved.

For example, to achieve a tolerance of 0.10mm, the rank order of the processes is:



- The cost of all processes increases as the required tolerance is decreased. At high tolerances, grinding is one of the cheapest processes.
- Different machining operations produce different surface finishes, see **Table 25.5**.

Table 25.5 Surface finishes

Machining process	R _a μm	
Planing and shaping	25 - 0.8	Least smooth
Drilling	8 - 1.6	
Milling	6.3 - 0.8	
Turning	6.3 - 0.4	
Grinding	1.6 - 0.1	Most smooth

- The choice of process will also depend on the geometric form required for the product. **Table 25.6** indicates the processes that can be used for different geometric forms.

Table 25.6 Machining processes for particular geometric forms

Type of surface	
Plane surface	Shaping, planing, face milling, surface grinding
Externally cylindrical surface	Turning, grinding
Internally cylindrical surface	Drilling, boring, grinding
Flat and contoured surfaces and slots	Milling, grinding

- In general, machining process is:
 - A relatively expensive process when compared with many other methods of forming materials.
 - The machining process is, however, a very flexible process which allows the generation of a wide variety of forms.
 - A significant part of the total machining cost of a product is due to setting-up times when there is a change from one machining step to another.
 - By reducing the number of machining steps and hence the number of setting-up times a significant saving becomes possible. Thus, the careful sequencing of machining operations and the choice of machine to be used is important.

3.3.5 Joining processes with Metals

- Fabrication involves the joining of materials and enables very large structures to be assembled, much larger than can be obtained by other methods such as *casting* or *forging*.
- The main joining processes are essentially ***adhesive bonding, soldering and brazing, welding and fastening*** systems.
- The ***factors*** that determine the joining process are:
 - The materials involved,
 - The shape of the components being joined,
 - Whether the joint is to be permanent or temporary,
 - Limitations imposed by the environment,
 - Cost.
- Welded, brazed and adhesive joints, and some fastening joints, e.g. *riveted*, are generally meant to be ***permanent joints***.
- Soldered joints and bolted joints are readily taken apart and ***rejoined***.

Lecture # 10:

3.4 Polymer forming processes

Injection molding and extrusion are the most widely used processes:

- Injection molding is generally used for the mass production of small items, often with intricate (complex) shapes.
- Extrusion is used for products which are required in continuous lengths or which are fabricated from materials of constant cross-section.

The following are some of the *factors* involved in *selecting* a process:

1- Rate of production

Cycle times are typically:

Injection molding and Blow 10-60 s,

Compression molding 20-600 s,

Rotational molding 70- 1200 s,

Thermo-forming 10-60 s

2- Capital investments required

- Injection molding requires the highest capital investment with extrusion and blow molding requiring less capital.
- Rotational molding, compression molding, transfer molding, thermoforming and casting require the least capital investment

3- Most economic production rate

- Injection molding, extrusion and blow molding are economic only with large production runs.
- Thermoforming, rotational molding and machining are used with small production runs.

- **Table 25.7** indicates the minimum output that is likely to be required to make the processes economic.

Table 25.7 Minimum output

Process	Economic output number
Machining	1 – 100 items
Rotational molding	100 – 1000 items
Sheet forming	100 – 1000 items
Extrusion	300 – 3000 m length
Blow molding	1000 – 10 000 items
Injection molding	10 000 – 100 000 items

4- Surface finishes

- Injection, blow and rotational molding, thermoforming, transfer and compression molding, and casting all give very good surface finishes.

- Extrusion gives only a fairly good surface finish.

5- Metals inserts during the process

These are possible with injection molding, rotational molding, transfer molding and casting.

6- Dimensional accuracy

Injection molding and transfer molding are very good. Compression molding and casting are good, extrusion is fairly poor.

7- Item size

Injection molding and machining are the best for very small items. Section thicknesses of the order of 1mm can be obtained with injection molding, forming and extrusion.

8- Enclosed hollow shapes

Blow molding and rotational molding can be used

9- Intricate, complex shapes

Injection molding, blow molding, transfer molding and casting can be used.

10- Threads

Threads can be produced with injection molding, blow molding, casting and machining.

11- Large formed sheets

Thermoforming can be used.

12- The assembly processes that can be used with plastics are welding, adhesive bonding, riveting, press and snap-fits, and thread systems.

- **Table 25.8** shows the processing methods that are used for some commonly used thermoplastics and **Table 25.9** for thermosets.

Table 25.8 Processing methods for thermoplastics

Polymer	Extrusion	Injection moulding	Extrusion blow moulding	Rotational moulding	Thermo-forming	Casting	Bending and joining	As film
ABS	X	X		X	X		X	
Acrylic	X	X			X	X	X	
Cellulosics	X	X			X			
Polyacetal	X	X	X					
Polyamide	X	X		X		X		
Polycarbonate	X	X	X		X		X	
Polyester	X	X						
Polyethylene HD	X	X	X	X			X	X
Polyethylene LD	X	X	X	X			X	X
Polyethylene	X	X	X					X
Terephthalate								
Polypropylene	X	X	X		X		X	X
Polystyrene	X	X	X	X	X		X	X
Polysulphone	X	X			X			
PYFE	X							
PVC	X	X	X	X	X		X	X

Table 25.9 Processing methods for thermosets

Polymer	Compression moulding	Transfer moulding	Casting	Laminate	Foam	Film
Epoxy			X	X	X	
Melamine formaldehyde	X	X		X		
Phenol formaldehyde	X	X	X	X	X	
Polyester	X	X	X	X		X
Urea formaldehyde	X	X		X		

Lecture # 11:

3.5 Powder Forming Processes

- Powder Technology used for :metals, alloys, ceramic and polymers.
- *Powder Technology = Powder Processes + Heat Treatments (e.g. Sintering, pre-Sintering...etc),*
- *The selection of a collection of Powder Processes + Heat Treatments = **The Powder Technological Root***

Powder Technology Processes

1. Crushing, Grinding and Milling

Crushers and grinders (or millers) are chosen according to the type of the starting materials and the desired final particle size.

2. Classification of Powders

The starting powders are classified utilizing standard sieve set. The resultant powder batches are differing in average particle size and distribution according to the sieve number. In addition, the powder batches can be mixed with designed average particle size and distribution. The classification step has a significant effect on the properties of the final product. Like physical, mechanical and thermal properties.

3. Mixing of powders

Homogeneity in chemical composition and particle size distribution is essential in powder technology. Homogeneity can be achieved through good mixing of powder batches; utilizing particular equipments like:

- **Mixers:** like Paddle mixers, Blade mixers and Tube mixers.
- **Millers:** like Ball millers, Rod millers...etc. Usually, the miller is a metallic or ceramic cylinder partially filled with hard balls or rods.

4. Forming

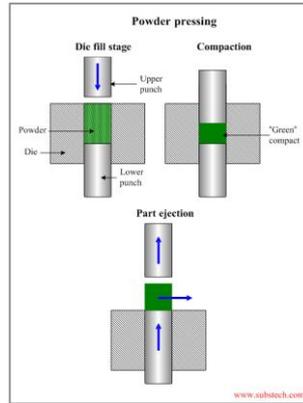
- Forming is the manufacturing of green bodies that have enough strength to handle, i.e. for transportation to the furnace.
- Forming is achieved via different procedures which depend on the type of the powder. The processed powder can be dry powder, have some sort of plasticity, a paste or slurry.
- Usually, these powders are formed via compaction with different types of dies. The compaction of powders aimed to pack the powder particle and the green body have its shape and strength.
- The main types of compaction of powders are: *Dry, Semi Dry and Isostatic Compression*.
- The main type of compaction of powder pastes is: *Extrusion, Injection Molding*.
- The forming of Slurry is via special technique called *Slip Casting*.

The following are some techniques that involved in forming ceramic powders into a desired shape:

- ❖ Die Compaction.
- ❖ Isostatical Pressing
- ❖ Injection Molding
- ❖ Extrusion
- ❖ Slip Casting
- ❖ Tape Casting

❖ **Die Compaction :**

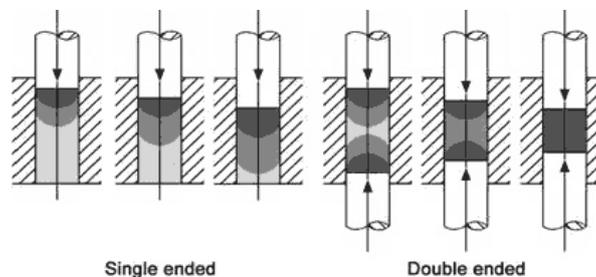
- A technique used extensively for forming of ceramic powder.
- It is the powder compaction method involving uniaxial pressure applied to the powder placed in a die between two rigid punches (as shown below).



- Effectively used for mass production of simple parts (alternative method is isostatical pressing).
- Suitable for both simple and complex geometries.
- The die compaction can be categorized into two types: (see figure below)

✚ Single Die Compaction; where the pressing is carried out via the upper (top) punch only.

✚ Double Die Compaction; where the pressing is carried out via both upper and lower (bottom) punch. The double die compaction produces green compacts with more uniform density compared with single die compaction.

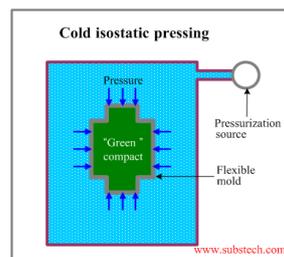


❖ Isostatic Pressing

It is suitable for the manufacture of uniformly compressed blanks and large parts that are appropriate for machining in the green state.

➤ *Cold Isostatic Press (CIP) :*

- It is the powder compaction method involving applying pressure from multiple directions through a liquid or gaseous medium surrounding the compacted part.
- High degree of homogeneity of green density is achieved via this technique.
- The cold isostatic pressing (CIP) method has the following advantages as compared to the die cold pressing method:
 - better uniformity of compaction;
 - more complex forms (for example long thin-walled tubes) may be compacted

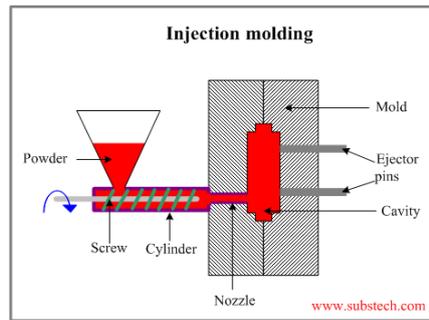


➤ *Hot Isostatic Press (HIP)*

- It involves isostatic pressing conducted at increased temperature.
- This technique is the best known so far that produce high and uniform sintered products.
- Cans made of stainless steel, or mild steel are used in the method.
- The method may be used without a mold.
- In this case the part is first compacted by cold isostatic pressing method, and then it is sintered in order to close the interconnecting porosity. The sintered (but still porous) part is then pressed isostatically at high temperature without any can (mold).

❖ Injection Molding

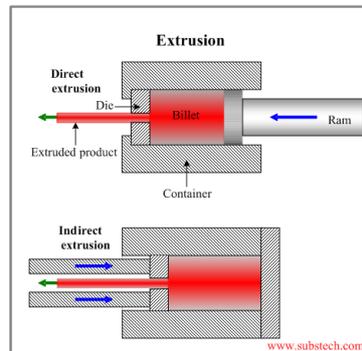
- A method of compaction of ceramic powder fed and injected into a mold cavity by means of a screw rotating in cylinder.
- The principal scheme of the injection molding method is shown in the picture:



- Injection molding method is widely used for manufacturing small parts having complex shapes.
- The method permits to produce part with close tolerance, due to the consistent shrinkage.

❖ **Extrusion**

- Extrusion of powder pastes can be done when a sufficient amount of moisture content and plasticizers are present.
- The two possible schemes of extrusion are presented in the picture:

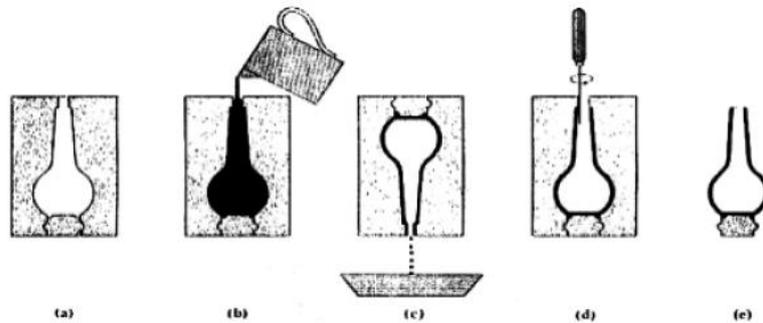


- Extrusion ram forces the ceramic paste through a die, resulting in a long product (rods, bars, long plates, pipes) of regular cross-section, which may be cut into pieces of required length.
- Extrusion is used for manufacturing furnace tubes, thermocouple components, heat exchanger tubes.

❖ **Slip Casting**

- This technique is used for materials which can produce suspension in liquids like water.

- It is a simple method for the manufacture of prototypes, parts with complex geometries and relatively large items. It can be used to manufacture both thin-walled and solid objects.
- Slip casting is used for manufacturing fine china, sinks, sanitary ware, thermal insulation parts.

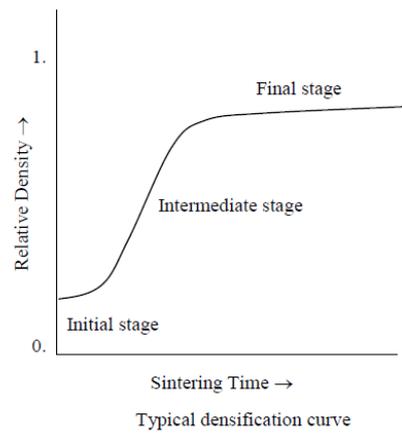


❖ **Tape Casting**

- It is a process of forming a thin film of ceramic slurry spread over a flat surface.
- Used for manufacturing multilayer ceramics for capacitors and dielectric insulators.

5. Sintering

- Sintering is critical step in fabricating and developing ceramic and metallic materials.
- It is a high-temperature process during which a powder compact generally shrinks, decreasing its pore volume, and increases its bulk density.
- The solid state sintering process during which shrinkage occurs can be divided into initial, intermediate, and final stages as shown in figure below.
- Sintering is a process of consolidation of particles under the temperature below the melting point and caused, therefore, mostly by solid state reactions. Sintering forms solid bonds reducing the free surface. Thus, the total interfacial free energy of an assembly of particles is reduced.



The sintering phenomena can be categorized as follows:

- *Solid State Sintering*
- *Liquid Phase Sintering*
- *Activated Sintering*

Comparison between different forming processes:

The choice of the forming process to be used in any particular case depends, from a technical point of view, on the geometry and size of the part and the needs of the application. The piece count, raw material consumption and process costs determine the most economic choice. Further extensions to the forming processes initially introduced here are possible.

Forming process	<i>Advantageously</i> permits	<i>Disadvantageously</i> associated with
Slip casting	<ul style="list-style-type: none"> Complex geometries (thin walls, asymmetric) Low material consumption 	<ul style="list-style-type: none"> Complex rheology Rough surfaces Difficult mould manufacture Limited form tolerance High dimensional tolerance
Pressure casting (in comparison to slip casting)	<ul style="list-style-type: none"> Fast build up of the body Very low drying shrinkage Good dimensional accuracy No necessity to dry forms Low space requirement 	<ul style="list-style-type: none"> Expensive tools Large lot sizes are necessary Problematic organic solvents
Tape casting	<ul style="list-style-type: none"> Continuous production Thin layers Good dimensional accuracy High manufacturing capacity 	<ul style="list-style-type: none"> Limited part geometries Drying is necessary
Injection moulding	<ul style="list-style-type: none"> Complex geometries Close tolerances Good reproducibility High surface quality Accurate contours High lot sizes 	<ul style="list-style-type: none"> Expensive tools High die wear Limited part size Expensive debinding Noticeable density gradients
Extrusion	<ul style="list-style-type: none"> Continuous production High manufacturing capacity High part lengths Economical manufacture 	<ul style="list-style-type: none"> Distinct textures Drying is necessary
Dry pressing	<ul style="list-style-type: none"> Process can be automated Good reproducibility Good dimensional accuracy Limited drying Economically large lot sizes 	<ul style="list-style-type: none"> Limitations in the part geometries Density gradients possible Expensive moulding tools Expensive powder preparation
Wet pressing/ moist pressing (in comparison to dry pressing)	<ul style="list-style-type: none"> Complex part geometries Uniform density distribution 	<ul style="list-style-type: none"> Drying is necessary Lower compaction Higher tolerances
Isostatic pressing	<ul style="list-style-type: none"> High density without textures No density gradients 	<ul style="list-style-type: none"> Low cycle times

Lecture # 12:

3.6 The cost aspects of process selection

The manufacturing cost, for any process, can be considered to be made up of two elements; fixed costs and variable costs; for example;

- (a) Low fixed cost but high variable cost per item, e.g. *sand casting*,
- (b) High fixed cost but low variable cost per item, e.g. *die casting*.

✚ The Cost elements are made up as follows:

1- Fixed costs

- Capital costs for installations, e.g. the cost of a machine ...etc. However, in any one year there will be depreciation (decrease) of the assessment and this is the capital cost that is paid against the output of the product in that year.
- Another element of fixed costs is the cost of dies or tools needed specifically for the product concerned.
- Other factors we could include in the fixed costs are plant maintenance and tool, die overhaul.

2- Variable costs

The variable costs are:

- Material costs,
- Labour costs,
- Power costs,
- Any finishing costs required.

The questions to be asked when costing a product are:

1. Is the installation to be used solely for the product concerned?

The purpose of this question is to determine whether the entire capital cost has to be written off against the product or whether it can be spread over a number of products.

2. Is the tooling to be used solely for the product concerned?

If specific tooling has to be developed for a particular product the the entire cost will have to be put against the product.

3. What are the direct labour costs per item?

Direct labour costs are those of the labour directly concerned with the production process.

4. What are other labour costs involved?

These, termed indirect labour costs, include such costs as those incurred in supervision, inspection, etc.

5. What is the power cost?

6. Are there any finishing processes required and, if so, what are their costs?

7. What are the materials costs?

8. Are there any overhead costs to be included?

Overhead costs are those costs which a company cannot specifically allocate to any particular job or product but are part of the overhead company costs, *e.g.* telephone costs, rent for factory, management salaries.

Lecture # 13:

Examples :

Cement Forming Processes:

Cement : is a fine, soft, powdery-type substance. It is made from a mixture of elements that are found in natural materials such as limestone, clay, sand and/or shale. When cement is mixed with water, it can bind sand and gravel into a hard, solid mass called concrete.



Manufacturing of Portland cement:

- The raw materials for manufacturing of Portland cement are :
 1. Calcareous material – limestone or chalk
 2. Argillaceous material – Shale or clay.

- **Methods of production of Portland cement:** There are different methods of production of Portland cement: dry process, semi-dry process and wet process. The method of manufacturing cement depends on hardness, homogeneity and moisture content of raw materials.

A comparison between wet and dry processes in the cement production process is shown below:

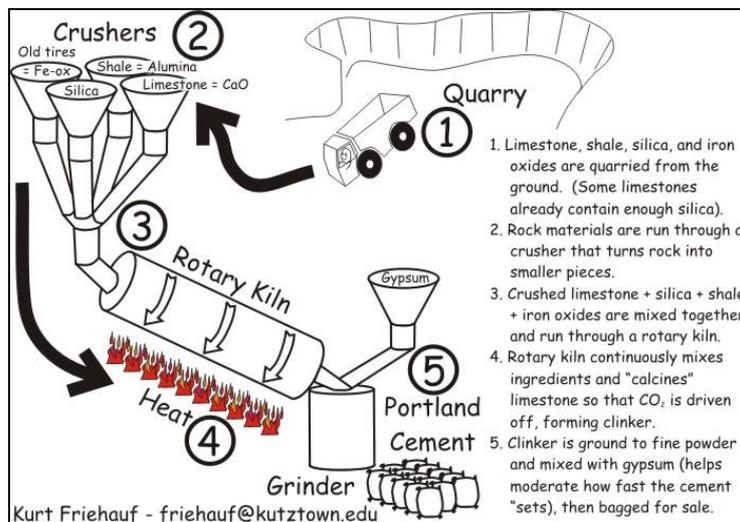
<i>Wet process</i>	<i>Dry process</i>
Moisture content of the slurry is 35-50%	moisture content of the pellets is 12%
Size of the kiln needed to manufacture the cement is bigger	Size of the kiln needed to manufacture the cement is smaller
Less economically	More economically
The amount of heat required is higher, so the required fuel amount is higher	The amount of heat required is lower, so the required fuel amount is lower
The raw materials can be mix easily, so a better homogeneous material can be obtained	Difficult to control the mixing of raw materials process, so it is difficult to obtain homogeneous material
The machinery and equipment do not need	The machinery and equipment need more

much maintenance

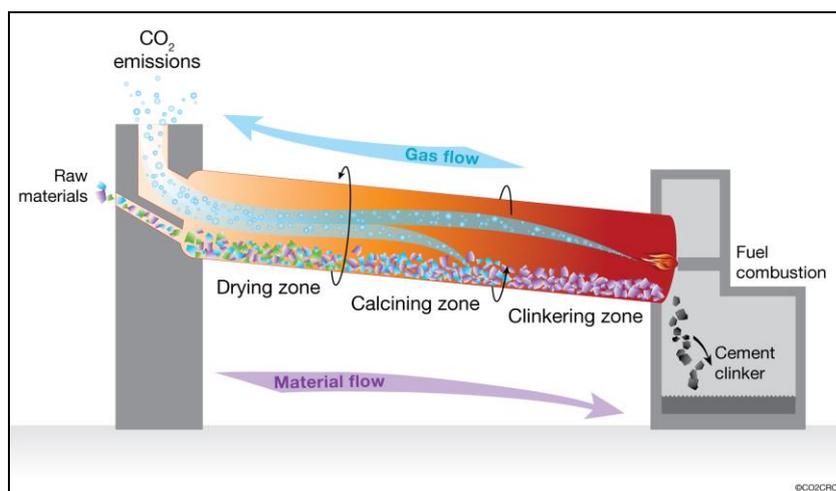
maintenance

➤ The process of manufacture of cement consists of :

- (a) Grinding of raw materials
- (b) Mixing them intimately in certain proportion, depending on their purity and composition.
- (c) Burning them in a kiln at temperatures of 1330°C to 1500°C, at which the material sinters and partially fuses to form modular shaped clinkers.
- (d) Cooling of clinker and grinding it to fine powder with addition of 2 to 3% of gypsum.



Cement Manufacturing Process



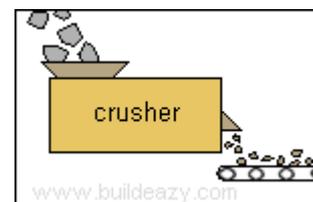
Rotary Kiln

The following steps summarized manufacturing process of Portland Cement:

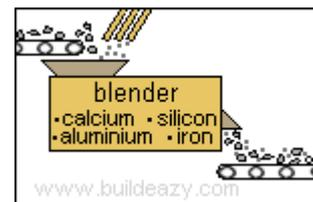
1.) Limestone is taken from a quarry. It is the major ingredient needed for making cement. Smaller quantities of sand and clay are also needed. Limestone, sand and clay contain the four essential elements required to make cement. *The four essential elements are calcium, silicon, aluminum and iron.*



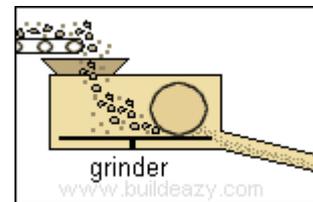
2.) Boulder-size limestone rocks are transported from the quarry to the cement plant and fed into a crusher which crushes the boulders into marble-size pieces.



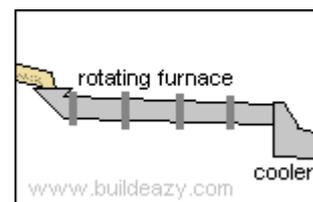
3.) The limestone pieces then go through a blender where they are added to the other raw materials in the right proportion.



4.) The raw materials are ground to a powder. This is sometimes done with rollers that crush the materials against a rotating platform.



5.) Everything then goes into a huge, extremely hot, rotating furnace to undergo a process called "**sintering**". Raw materials become sort of partially molten. The raw materials reach about 1480°C inside the furnace. This causes chemical and physical changes to the raw materials and they come out of the furnace as large, glassy, red-hot cinders called "clinker".



6.) The clinker is cooled and ground into a fine gray powder. A small amount of gypsum is also added during the final grinding. The cement is then stored in silos (large holding tanks) where it awaits distribution.



Major compounds of Portland Cement:

Name of compound	Oxide composition	Abbreviation
Tricalcium Silicate	$3\text{CaO} \cdot \text{SiO}_3$	C_3S
Dicalcium Silicate	$2\text{CaO} \cdot \text{SiO}_2$	C_2S
Tricalcium Aluminate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	C_3A
Tetra calcium Alumina Ferrite	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	C_4AF

Types of Cement:

Some of cement types are shown below:

1. Ordinary Portland Cement (O.P.C) (Type I)
2. White Cement
3. Colored Cement
4. Modified Portland Cement (Type II)
5. Rapid Hardening Portland Cement (R.H.P.C) (Type III)
6. Low Heat Portland Cement (L.H.P.C) (Type IV)
7. Sulphate Resistant Portland Cement (S.R.P.C) (Type V)
8. Air Entraining Cement.
9. Supersulphated Cement
10. Oil-well Cement

1. Ordinary Portland Cement (OPC) (Type I)

It is used in general construction works. All other varieties of Cement are derived from this Cement.

2. White Cement

- OPC with pure white color produced with white chalk or clay free from iron oxide.
- Instead of coal, oil fuel is used for burning.
- White cement manufacture needs higher firing temperature (up to 1650°C) because of the absence of iron element that works as a flux in the formation process of the clinker.
- Contamination of the cement with iron during grinding of clinker has also to be avoided. For this reason, instead of the usual ball mill, the expensive nickel and molybdenum alloy balls are used in a stone or ceramic-lined mill.
- Much expensive than OPC.

3. Modified Portland Cement (Type II)

- This cement on setting develops less heat of generation than OPC.
- It is recommended for use in structures where:
 - ✓ moderately low heat generation is desirable
 - ✓ moderate sulfate attack may occur.

4. Colored Cement

- Suitable pigments used to impart desired color.
- Pigments used should be chemically inert and durable under light, sun or weather.

5. Low Heat Cement (L.H.P.C) (Type IV)

- Low percentage of (C₃A) and (C₃S) and high (C₂S) to keep heat generation low.
- It has low lime content and less compressive strength.
- Very slow rate of developing strength.
- Not suitable for ordinary structures.
- **Uses:** L.H.P.C is used in large concrete mass. The interior faces of the concrete mass has a high temperature due to the heat development by the hydration of cement, coupled with a low thermal conductivity of concrete while the exterior faces has dissipated the heat of hydration thus serious cracking occurred.

6. Rapid Hardening Portland Cement (R.H.P.C) (Type III)

- R.H.P.C develops strength more rapidly.
- Setting time for R.H.P.C is similar for that of O.P.C.
- Higher content of C_3S and C_3A .
- R.H.P.C has higher fineness.
- The higher fineness increases the strength at 10- 20 hrs up to about 28 days.
- Rate of heat evolution is higher than in O.P.C due to the increase in C_3S and C_3A , and due to its higher fineness.
- **Uses:**
 - 1) R.H.P.C is used when rapid strength development is desired (to develop high early strength :3 days strength of R.H.P.C = 7 days strength of O.P.C), for example:
 - a) when formwork is to be removed for re-use.
 - b) where sufficient strength for further construction is wanted as quickly as practicable, such as:
 - ✓ concrete blocks manufacturing.
 - ✓ Sidewalks.
 - ✓ places that can not be closed for a long time.
 - ✓ repair works needed to construct quickly.
 - 2) For construction at low temperatures, to prevent the frost damage of the capillary water.
 - 3) R.H.P.C does not use at mass concrete constructions.

7. Sulphate Resistant Portland Cement (S.R.P.C) (Type V)

- Lower percentage of C_3A and C_4AF .
- Higher percentage of silicates in comparison with O.P.C.
- Heat developed is almost same as L.H.P.C
- Theoretically ideal cement. Costly manufacturing because of stringent composition requirements.
- Used for structures likely to be damaged by severe alkaline conditions like bridges, culverts, canal lining, siphons, etc.

8. Air Entraining Cement

- OPC with small quantity of air entraining materials (resins, oils, fats, fatty acids) ground together.
- Air is entrained in the form of tiny air bubbles during chemical reaction.
- Uses
 - ✓ Air en-trained cement is ideal for use in structures subjected to freezing and thawing.
 - ✓ Its use in improving work ability of cement needs to be practiced increasingly.

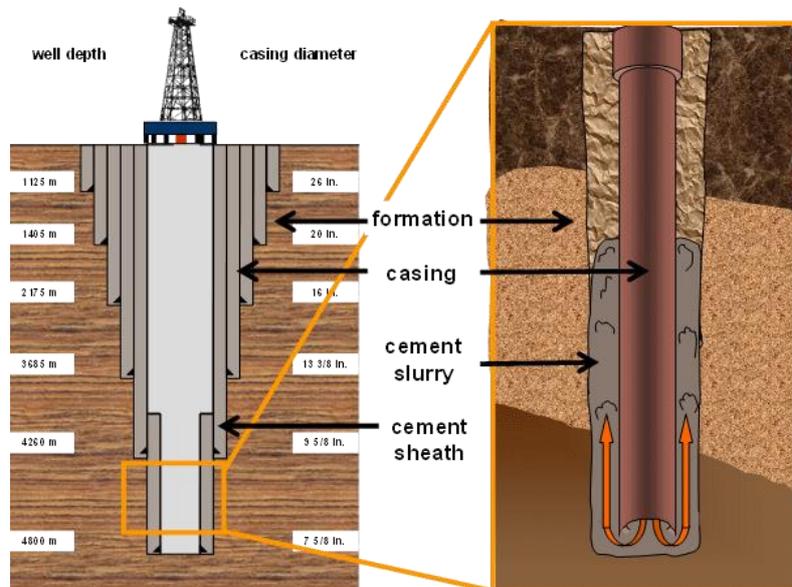
9. Supersulphated Cement

- Initially, not less than 70 % finely ground blast furnace slag, Calcium Sulphate and a small quantity of OPC or Portland cement clinker.
- It is finer than O.P.C.
- Its physical and other properties are almost same as are of O.P.C except the heat of hydration which is considerably lower.
- It is a slag cement and is resistant to majority of chemicals found in construction industry. It is also resistant to Sulphate attack.
- It is used in:
 - ✓ Marine Structures.
 - ✓ Mass concrete works subjected to aggressive waters.
 - ✓ Reinforced concrete pipes in ground water.
 - ✓ Concrete construction in Sulphate bearing soils.
 - ✓ In factories where concrete is exposed to highly concentrated Sulphates.
 - ✓ Construction of concrete sewers carrying industrial effluents.
 - ✓ Underside of railway bridges.
 - ✓ Under tropical conditions, its use is recommended only below 40°C.
 - ✓ Can be used as a general purpose cement with adequate precautions.
 - ✓ It should never be used for casting 'steam cured concrete' products.

10. Oil-Well Cement

Oil wells are drilled through stratified sedimentary rocks through great depths. Oil when struck, could escape together with gas, through the space between the steel casing and the rock formation. To prevent this, cement slurry is used. The cement slurry has to be pumped in position at considerable depth where the prevailing temperature may be 175°C , coupled with pressures up to 1300 kg/cm^2 . The slurry should remain sufficiently mobile to be able to flow under such conditions for several hours and then harden fairly and rapidly. In addition, it may have to resist corrosive actions because of sulphur gases or waters containing dissolved salts.

The type of cement suitable for such situations is called **oil well cement**. The desired properties are obtained either by adjusting the compound composition of cement or by adding retarders to the OPC. The most common agents are starches or cellulose products or acids. These retarding agents prevent quick setting and impart mobility to slurry to facilitate penetration of all fissures and cavities.



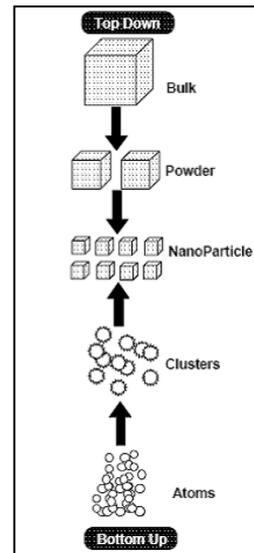
Lecture # 14:

Examples :

Nanomaterials Forming Processes:

The manufacture of nanomaterials can occur in one of two ways, or a mixture of both. These methods are known as:

- **Top-down approach:** which is the reduction of "bulk materials (top) into nanoparticles (down) by way of a physical, chemical or mechanical processes"
- **Bottom-up approach:** which "begin with atoms and molecules (bottom). These atoms or molecules react under chemical or physical circumstances to form nanomaterials (up) ".



Top-down vs. Bottom-up

Top-down vs. bottom-up

- **Top-down methods**
begin with a pattern generated on a larger scale, then reduced to nanoscale.
 - By nature, aren't cheap and quick to manufacture
 - Slow and not suitable for large scale production.
- **Bottom-up methods**
start with atoms or molecules and build up to nanostructures
 - Fabrication is much less expensive

3.7 Process Selection for Joining

Several joining processes can be used for a particular job. The major problem is to select the one that is most suitable in terms of fitness for service and cost.

Selection of a process can depend on a number of considerations, including:

- ✓ The number of components being fabricated.
- ✓ Capital equipment costs.
- ✓ Joint location.
- ✓ Structural mass.
- ✓ Desired performance of the product.

➤ **Table 1.1** below shows general guides for selecting a suitable joining process for different types of applications

Table 1.1 Comparison of joining process characteristics

Attribute	Welding	Brazing and soldering	Mechanical fastening	Adhesive bonding
Performance	Permanent joints	Usually permanent (soldering may be nonpermanent)	Threaded fasteners permit disassembly	Permanent joints
Stress distribution	Local stress points in structure	Fairly good stress distribution	Points of high stress at fasteners	Good uniform load distribution over joint area (except in peel)
Appearance	Joint appearance usually acceptable. Some dressing necessary for smooth surfaces	Good joint appearance	Surface discontinuities sometimes unacceptable	No surface marking. Joint almost invisible

(continued)

Table 1.1 (continued)

Attribute	Welding	Brazing and soldering	Mechanical fastening	Adhesive bonding
Materials joined	Generally limited to similar material groups	Some capability for joining dissimilar materials	Most forms and materials can be fastened	Ideal for joining most dissimilar materials. CTE difference a concern for elevated temperature bonds
Temperature resistance	Very high temperature resistance	Temperature resistance limited by filler metal	High temperature resistance	Poor resistance to elevated temperatures
Mechanical resistance	Special provisions often necessary to enhance fatigue resistance	Fairly good resistance to vibration	Special provisions for fatigue and resistance to loosening at joints	Excellent fatigue properties. Electrical isolation reduces corrosion.
Joint preparation	Little or none on thin material. Edge preparation for thick plates	Prefluxing usually required	Hole preparation and tapping for threaded fasteners	Stringent cleaning required
Postprocessing	Heat treatment sometimes necessary	Corrosive fluxes must be cleaned off	Usually none. Occasionally retightening in service	Not usually required
Equipment	Relatively expensive, bulky, heavy power supply often required	Manual equipment cheap. Special furnaces and automatic equipment expensive	Relatively cheap and portable for manual assembly. Automated equipment can be expensive.	Can be relatively cheap or expensive for tooling and presses or autoclaves
Consumables	Wire, rods fairly cheap	Some braze alloys expensive. Soft solders cheap	Quite expensive	Structural adhesives somewhat expensive
Production rate	Can be very fast	Automatic processes quite fast	Manual processes slow. Automated processes can be very fast.	Seconds to hours depending on type