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Chapter 1: Introduction to Material Science and Engineering Materials

Introduction

- Historical perspective:
  - Materials found everywhere around us and effects the quality of our life.
  - The development and advancement of societies are tied to their members ability to produce and manipulate material to fit their needs.

- Materials drive our society
  - **Stone Age**
  - **Bronze Age**
  - **Iron Age**
  - **Now?**
    - Silicon Age? → **Electronic components and semiconductors**
    - Polymer Age? → **Biotechnology and Energy applications**
    - Smart materials and Nano-materials Age → **Electronics**

Designation is based on the level of material development

Introduction

- **Naturally occur materials**: stone, skin, bone, wood.
- **Synthetic materials:** discover techniques (heat treatment, and addition of other substances) to produce materials that have superior properties to the natural ones, i.e. metals.
- **Advanced materials:** knowledge acquired over approximately the past 100 years after understanding relationship between material structure and its properties.

Why do we study materials science and engineering?

- Many engineers will at one time or another exposed to a design problem involving materials. Properties of materials; Cost and availability; Performance; Processing technique.
- Examples

Mechanical Engineer: Transmission gear design.

Chemical Engineer: Oil refinery component.

Electrical Engineer: Integrated circuit chip.

Civil Engineer: Superstructure of building.

Mechatronics engineer: Developing Sensors and ICs, dealing with Microelectronics and semiconductors

Materials Science and Engineering

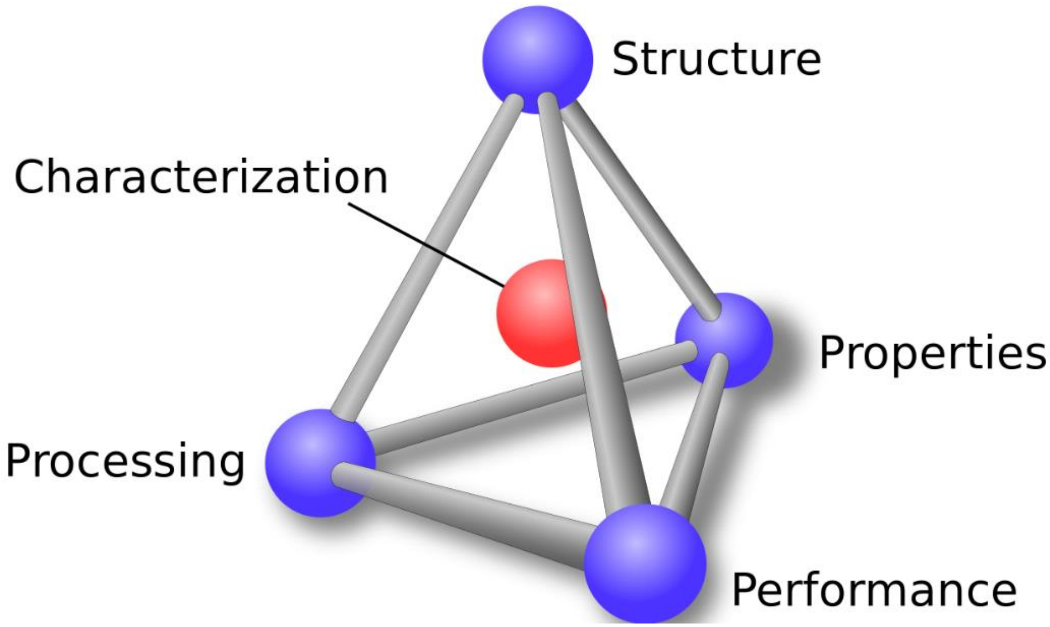
- What is material science? Materials science is a fundamental science concerned with the relationship between the structure and properties of materials. [Fundamental science (or basic science, pure science) … fundamentals and knowledge.]

- What is material engineering? Materials Engineering takes those materials and applies them to real world problems, by knowing the properties of a particular material engineers design or fabricate that material for desired applications. [Applied science: the application of scientific knowledge transferred into real-world problems.]

- What are the basic components of the materials science and engineering? (material tetrahedral)

Materials Science and Engineering Elements

1) Structure
2) Properties
3) Processing
4) Performance



Materials Tetrahedron

OPTICAL

- Transmittance: Aluminum oxide may be transparent, translucent, or opaque depending on the material structure.

1) Structure
2) Properties
3) Processing
4) Performance

Polycrystalline materials are solids that are composed of many crystallites of varying size and orientation.

Adapted from Fig. 1.2, *Callister 7e.* (Specimen preparation, P.A. Lessing; photo by S. Tanner.)

Material Property

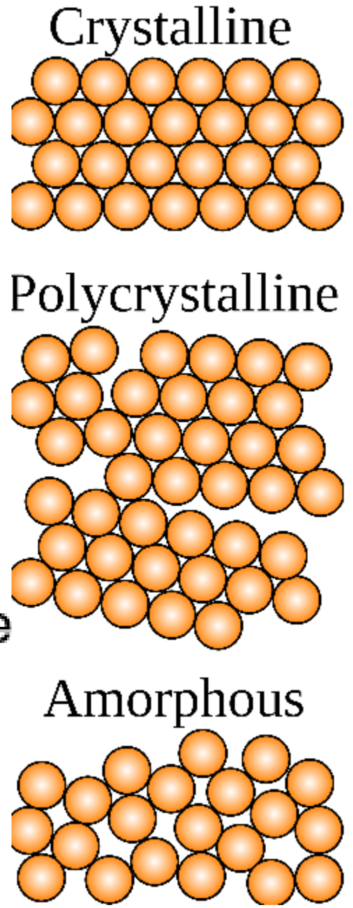
- Definition: it is the material attribute in terms of kind and magnitude of response to a specific imposed stimulus.
- The properties of solid materials can be grouped into different categories:
  - Mechanical
  - Electrical
  - Thermal
  - Magnetic
  - Optical
  - Deteriorative: The act or process of becoming worse.

Table 1 Material properties and qualities

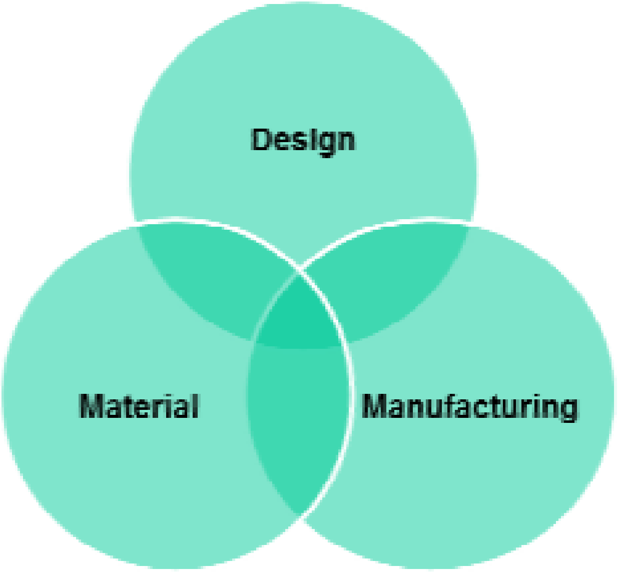
Properties	Qualities
Physical properties	Density, melting point, damping capacity
Mechanical properties	Yield, tensile, compressive and torsional strengths, ductility, fatigue strength, creep strength, fracture toughness
Manufacturing properties	Ability to be shaped by molding, casting, plastic deformation, powder processing, machining. Ability to be joined by adhesives, welding, and other process
Chemical properties	Resistance to oxidation, corrosion, solvents, and environmental factors
Other non-mechanical properties	Electrical, magnetic, optical and thermal properties
Economic properties	Raw material and processing cost. Availability
Aesthetic properties	Appearance, texture and ability to accept special finishes

Material Structure

- **Definition:** Arrangement of its internal component.
- Bottom-up study approach:
  - **Subatomic level:** involves electrons within individual atoms and interactions with their nuclei.
  - **Atomic level:** encompasses the organization of atoms or molecules relative to one another.
  - **Microscopic level:** contains large group of atoms that are normally agglomerated together. (Microscopic means it can be observed by some type of microscope).
  - **Macroscopic level:** involves the structural elements that may be viewed with the naked eye.



Design, materials and manufacture?



Interrelationships: **Design** problem involving materials...selecting the right **materials**...**manufacturing** processes

"The more familiar an engineer with the various characteristics and structure-properties relationship, and processing techniques; the more proficient and confident she/he will be to make good choices based on the selection criteria's."

Points to be consider upon material selection?

- **Does the material have the necessary properties?**

  Ex. Strength and ductility...range of materials suitable for the job
  In-service conditions...stability.
  Ex. Reduction in mechanical strength / high temperature / corrosive environments)

- **Can the material be formed to the desired design and shape?**

  Manufacturability; ...manufacturing process. Processing techniques...will effect the properties

- **Will the material be adversely affected by environmental conditions and environmental interaction?** Will the properties of the material alter with time during service? Will the material resist corrosion and other form of attack?

- **Will the material be acceptable on aesthetic grounds?**

- **Can the product be made at an acceptable cost?**

- **Environmental and social factors**...Safe

The Materials Selection Process

1. Application ⟶ Determine required Properties

   Properties: mechanical, electrical, thermal, magnetic, optical, deteriorative.

2. Properties ⟶ Identify candidate Material(s)

   Material: structure, composition.

3. Material ⟶ Identify required Processing

   Processing: changes *structure* and overall *shape*
   ex: casting, sintering, vapor deposition, doping
   forming, joining, annealing.

Classification of materials*

- Metals
- Ceramics
- Polymers
- Composites
- Semiconductors
- Biomaterials
- Nanomaterials
- Smart materials

Metals, Ceramics, Polymers: Main classes of materials

Semiconductors, Biomaterials, Nanomaterials, Smart materials: Advanced materials

* Classification criterion: chemical make up and atomic structure

Metals*

Composed of one or more metallic elements, and often nonmetallic element in a relatively small amount.

Structure:

Atoms arranged in a very orderly manner. Relatively dense. Large number of non-localized electrons.

Properties:

Strong, Stiff, ductile. High thermal & electrical conductivity. Opaque, reflective.

Application examples

*The term metal alloy is used to refer to a metallic substance that is composed of two or more elements.

Ceramics

Compounds between metallic and nonmetallic elements.

Common ceramics: Oxides, carbides, nitrides, clay minerals (porcelain), cement, and glass.

Properties:

Strong, stiff, very hard, brittle. Insulator (low electrical conductivity). Resistance to high temperature and harsh environments. Optical behavior: transparent, translucent, or opaque.

Application examples

Polymers

Organic compounds that are chemically based on C, H, and other nonmetallic element (O, N, Si).

Structure:

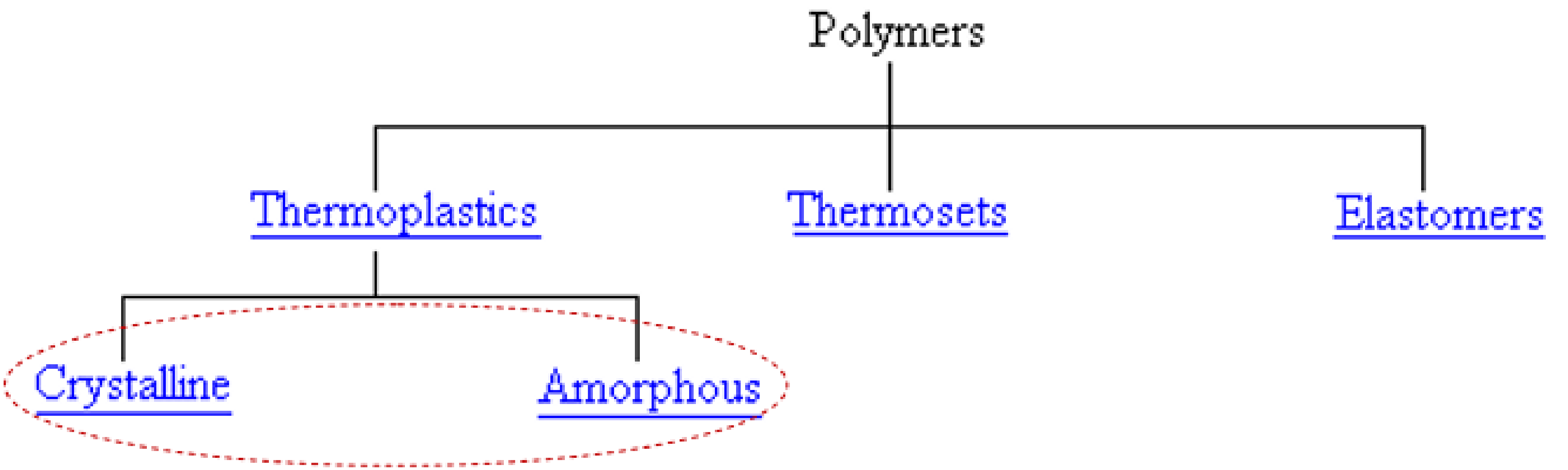
Large molecular structure chain-like in nature, have backbone of C atoms

Properties:

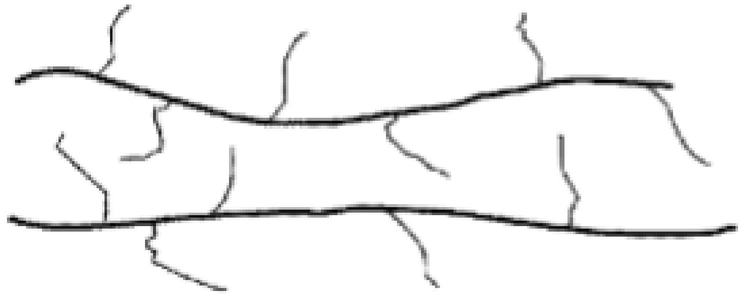
Low density. Non strong, not stiff (strength/mass is good), ductile, and pliable. Inert chemically and unreactive. Tend to soft/decompose at high temperatures. Low conductivity, nonmagnetic.

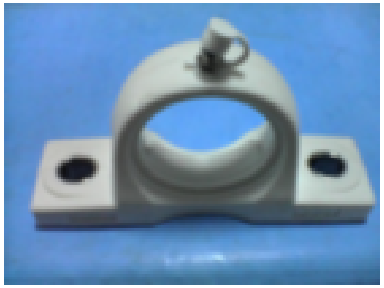
Application examples

Classification of Polymers



- **Thermoplastic (TP)** – Polymers that can be shaped when heated and regain original hardness & strength upon cooling, in other words, a polymer that becomes pliable or moldable above a specific temperature, and returns to it's original solid state upon cooling.
  - Have a linear or branched structure.
  - Most thermoplastics have a high molecular weight, whose chains associate through intermolecular forces; this property allows thermoplastics to be remolded because the intermolecular interactions spontaneously reform upon cooling.
  - Process is reversible.
  - Example: Cellulosics, nylons, polyethylenes, polyvinyl chloride…etc

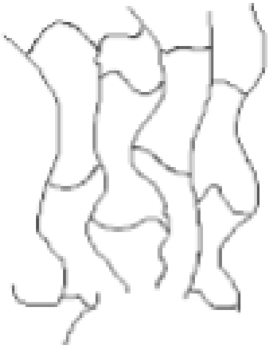




- **Thermoset (TS)** – is polymer material that irreversibly cures.

  Have a three-dimensional networked (strong secondary bonds), in which there is a high degree of cross-linking between polymer chains. The cross-linking restricts the motion of the chains and leads to a rigid material.

  - Process is irreversible.
  - Thermosets cannot be reshaped by heating.
  - Example: Epoxy, polyester, urethane, phenolics, silicones



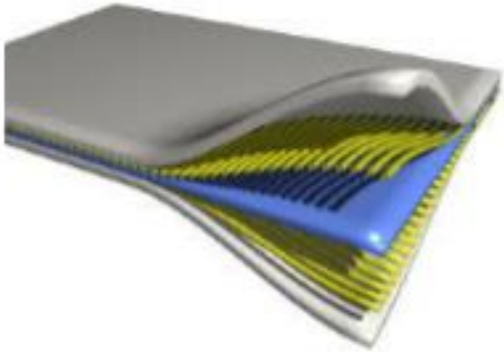
Curing is a term in polymer chemistry and process engineering that refers to the toughening or hardening of a polymer material by cross-linking of polymer chains, brought about by chemical additives, ultraviolet radiation, electron beam or heat. In rubber, the curing process is also called vulcanization

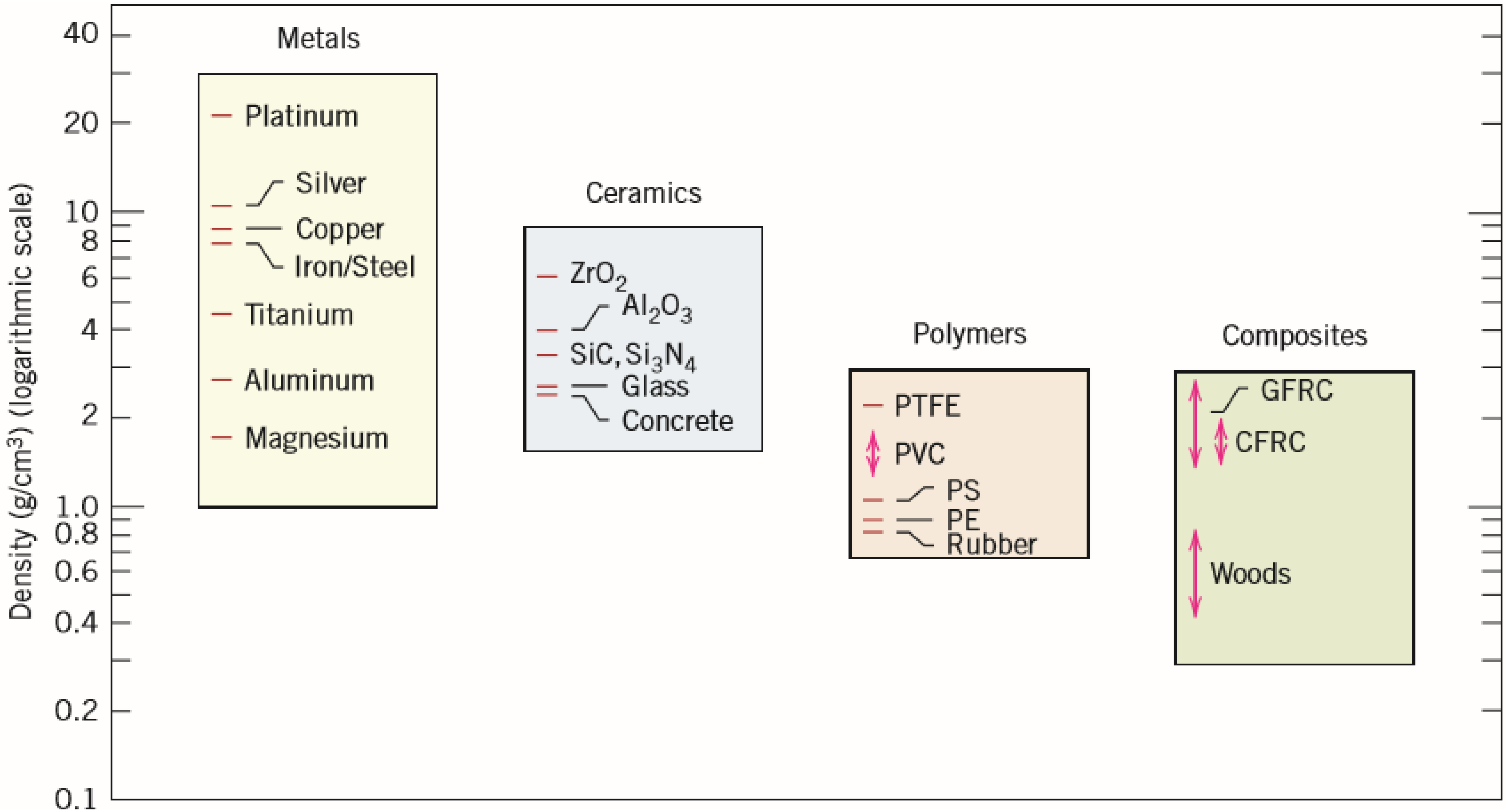
- **Elastomer (Rubber)** –are rubbery polymers that can be stretched easily to several times their un-stretched length and which rapidly return to their original dimensions when the applied stress is released.
- Elastomers are cross-linked, but have a low cross-link density. The polymer chains still have some freedom to move, but are prevented from permanently moving relative to each other by the cross-links.

– Tires, foot wear, gaskets,..

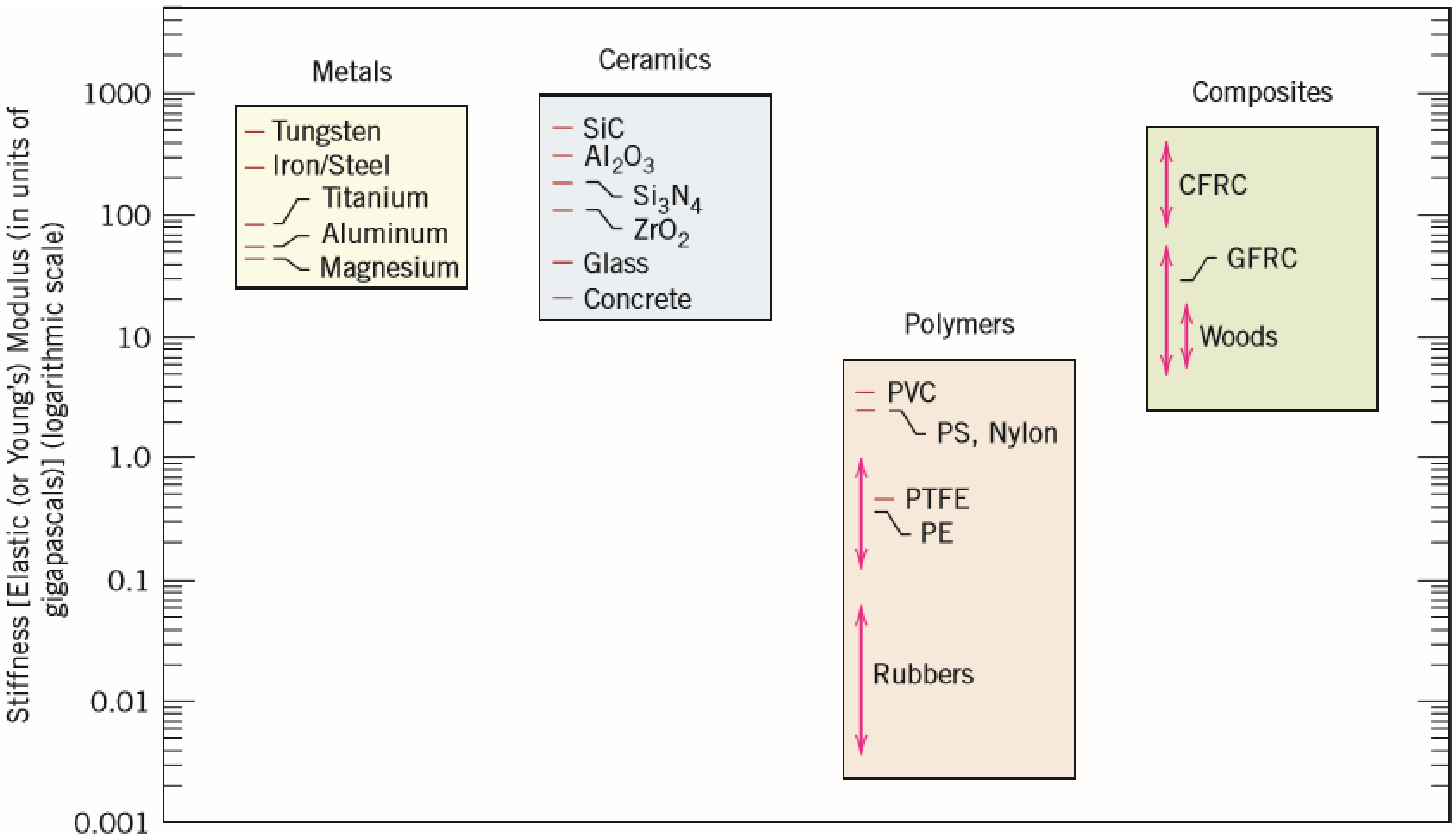
Composites

- Combination of more than one material it could be naturally-occurring or synthetic (man-made).
- Designed to display (incorporate) a combination of the best characteristics (properties) of each one of the component materials.
- Example: Fiber glass embedded within a polymeric material.
    - Fiber glass: strong and stiff (but also brittle)
    - Polymer: ductile , low density (but also weak and flexible)
    - Composite: stiff, strong, flexible, and ductile.
- Example: Polyte-tra-flouro-ethylene (PTFE) is a composite material of polymer and metal, used as bearing material.

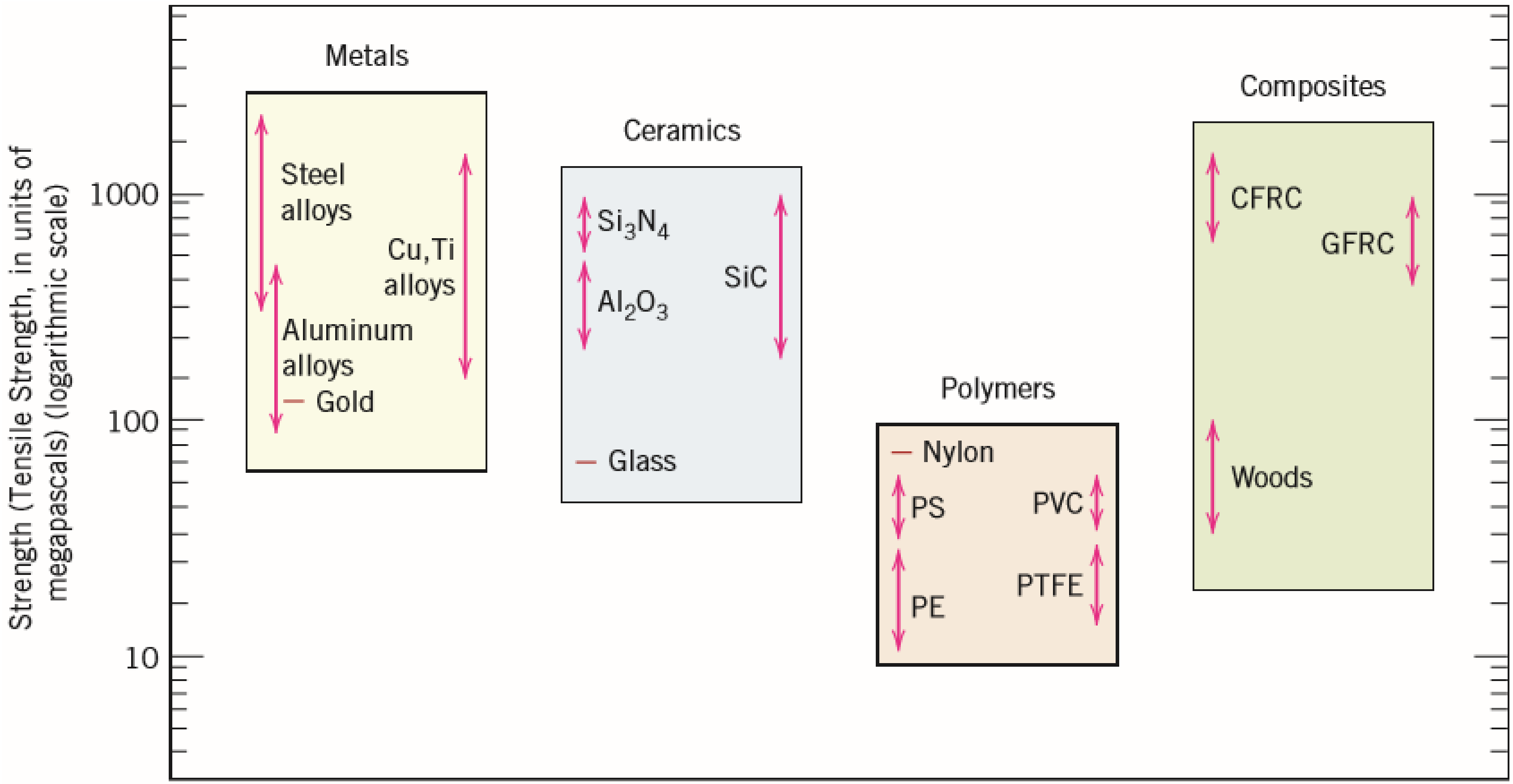



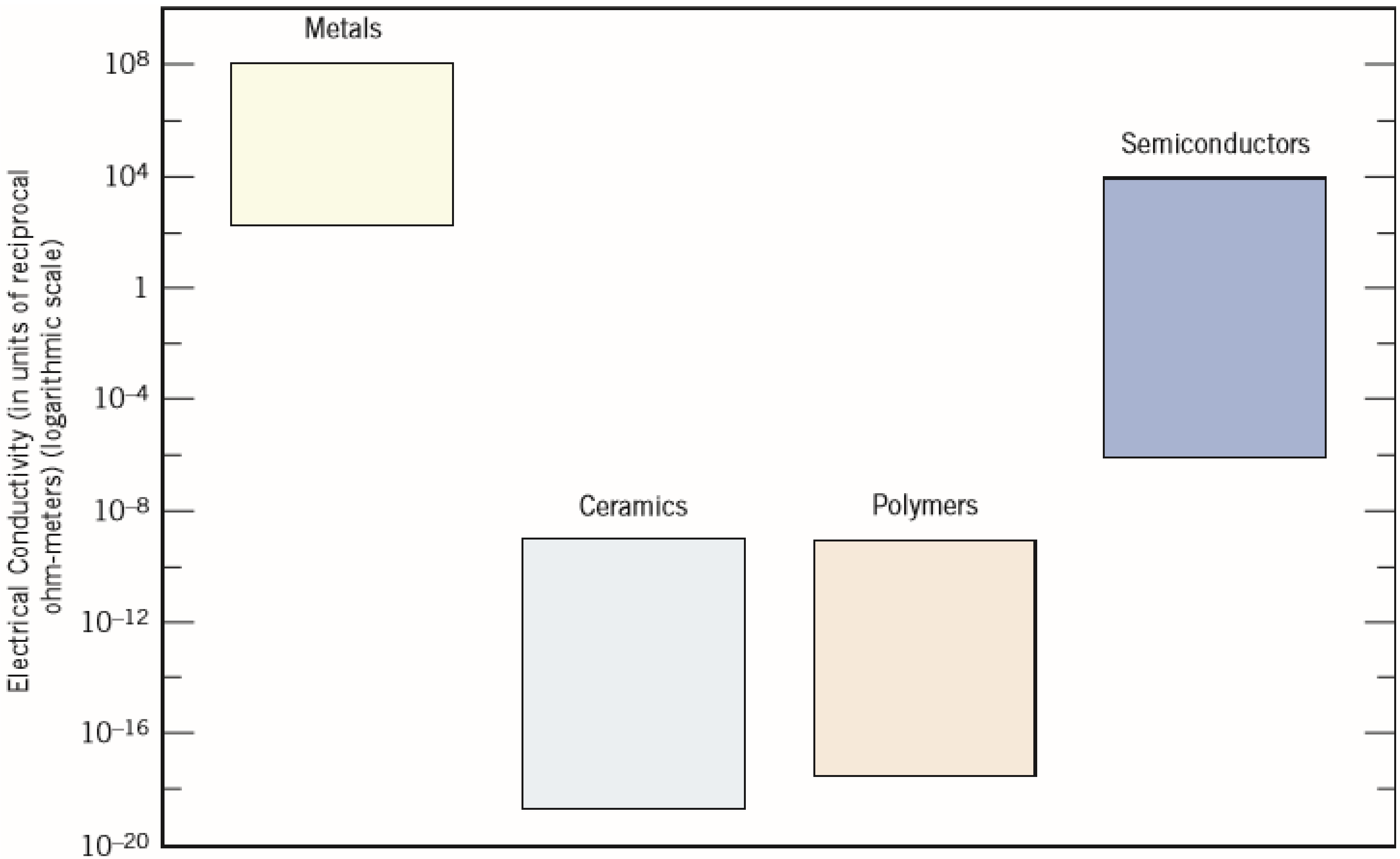



Density (g/cm3) (logarithmic scale)
40
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.2
0.1
Metals
Platinum
Silver
Copper
Iron/Steel
Titanium
Aluminum
Magnesium
Ceramics
ZrO2
Al2O3
SiC, Si3N4
Glass
Concrete
Polymers
PTFE
PVC
PS
PE
Rubber
Composites
GFRC
CFRC
Woods



Stiffness [Elastic (or Young's) Modulus (in units of gigapascals)] (logarithmic scale)
1000
100
10
1.0
0.1
0.01
0.001
Metals
Tungsten
Iron/Steel
Titanium
Aluminum
Magnesium
Ceramics
SiC
Al_2O_3
Si_3N_4
ZrO_2
Glass
Concrete
Polymers
PVC
PS, Nylon
PTFE
PE
Rubbers
Composites
CFRC
GFRC
Woods


Strength (Tensile Strength, in units of megapascals) (logarithmic scale)
1000
100
10
Metals
Steel alloys
Cu,Ti alloys
Aluminum alloys
Gold
Ceramics
Si_3N_4
Al_2O_3
SiC
Glass
Polymers
Nylon
PS
PVC
PE
PTFE
Composites
CFRC
GFRC
Woods


Electrical Conductivity (in units of reciprocal ohm-meters) (logarithmic scale)
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
Metals
Ceramics
Polymers
Semiconductors

Global Material Issues

- **Challenges**
  - Non-efficient use of energy resources.
  - The reserves of many economical minerals are diminishing. Copper (Cu), lead (Pb); Silver (Ag), Zinc (Zn) and Tin (Sn)...resources could be exhausted in our lifetime...
  - Pollution and global warming (Environmental and Sociological issues).
- **Solutions**
  - Create designs that utilize materials in the most effective and efficient manner.
  - Create materials that can be recycled; when the product has reached the end of its useful life.
  - Search for other alternative renewable energy resources.

Cost and availability

- Cost and availability are very important factors which affect the selection and use of materials.
- For a product to be succeed in the market, it has to be made at an acceptable cost (the price that the buyer are willing to pay for the product or the service).
- The final cost of the finished product is influenced by many factors; including:
  - Raw material cost
  - Processing cost
  - Availability

Cost of the raw material

- The cost of the raw material (accounts for about 50% of the total cost.
- The use of cheaper material have a significant effect on the final product cost.
- The cost of the raw material may change with time (for some materials, it is relatively unchanged over fairly long period of time but others are subjected to fluctuations).
- It is usual to see the cost of raw materials quoted per unit mass. However, in some occasions, the cost per volume may be used.

Processing cost

- The processing cost (in general, every process and heat treatment will give added value and increase the cost)
- Examples: The cost of alloys will be higher than the cost of unalloyed metals, for example, bronze (Cu-Sn) alloy is more expensive than pure copper.
- The cost of processed metal products such as sheets, plate, sections, and forging will be higher than those of ingot metal.

Cost of raw material

Processing cost

Availability

- The choice of a material for a particular application can be influenced by its availability.
- Example: In the major growth of railways in the 19th century most railway bridges in Britain were constructed of wrought iron.
- The principle is to use a material close to the source of material supply.

Example: Material selection for a tennis racquet frame?

<u>**Required properties:**</u> High strength, high stiffness, good damping characteristics and low weight.

Up to 1970s: racquet was made from laminated wood. (Drawback: it can absorb water which can lead to variations in performance and also can cause warping the frame).

In 1970s: frame was made from aluminum and steel (In spite of their good strength/weight ratio, they have low damping characteristics).

In 1980s: frame was made from composite construction using glass or carbon fiber in a polyester or epoxy resin matrix. The new material has a high strength to weight ratio and good damping characteristics.

Example: Material selection for overhead electrical transmission wires

Required: high electrical conductivity

Metal candidate: silver, copper, gold and aluminum

Design concern: metal should have high purity, as impurities cause a reduction in the electrical conductivity

<u>How do we filter/select among the candidates?</u>

List the advantages and disadvantages for each.

Gold and silver are very expensive for this application.

Copper is relatively more expensive than aluminum

Our choice: aluminum (drawback: very low tensile strength; this problem was solved by creating aluminum wires braided around a steel wire core to give strength).

Braided wire

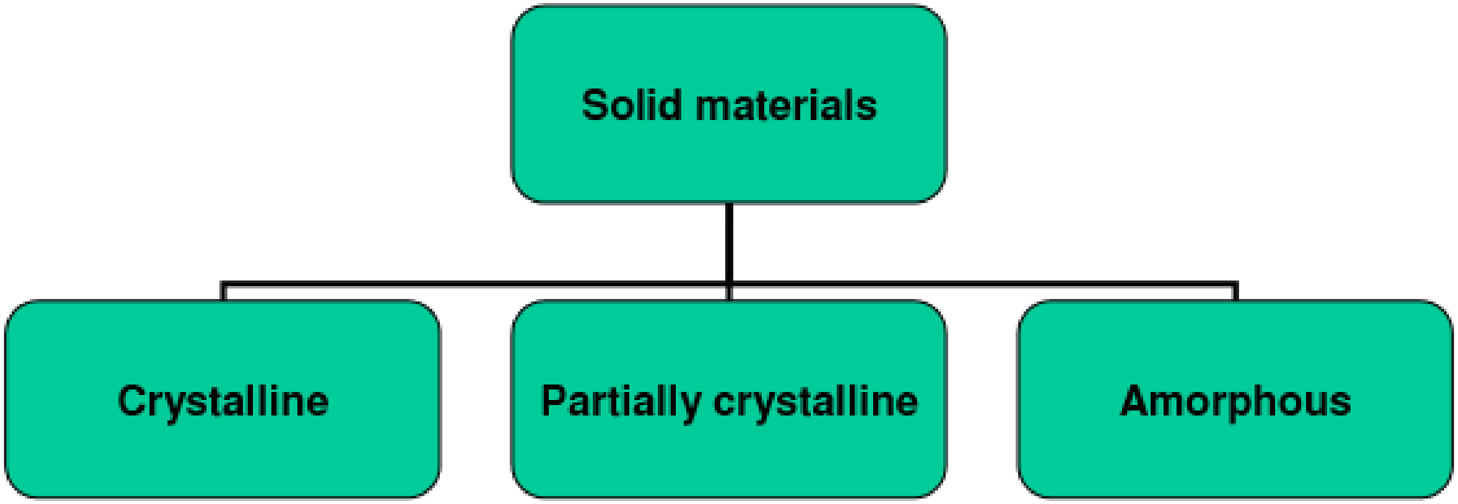
Chapter 2: Crystalline structure

Introduction

Issues To Address...

- How do atoms assemble into solid structures?
- Know the difference between crystalline and amorphous solids.
- Know the name and definitions of the seven crystal system.
- How does material properties vary with the its crystal structure?
- Understand Miller notations and be able to derive the Miller indices for planes and directions within crystal unit cells.
- Understand the concept of the unit cell and be able to sketch the unit cells of the body centered cubic, and face centered cubic.

Introduction



The classification is based upon the arrangement of the constituent atoms or molecules of the substance after solidification.

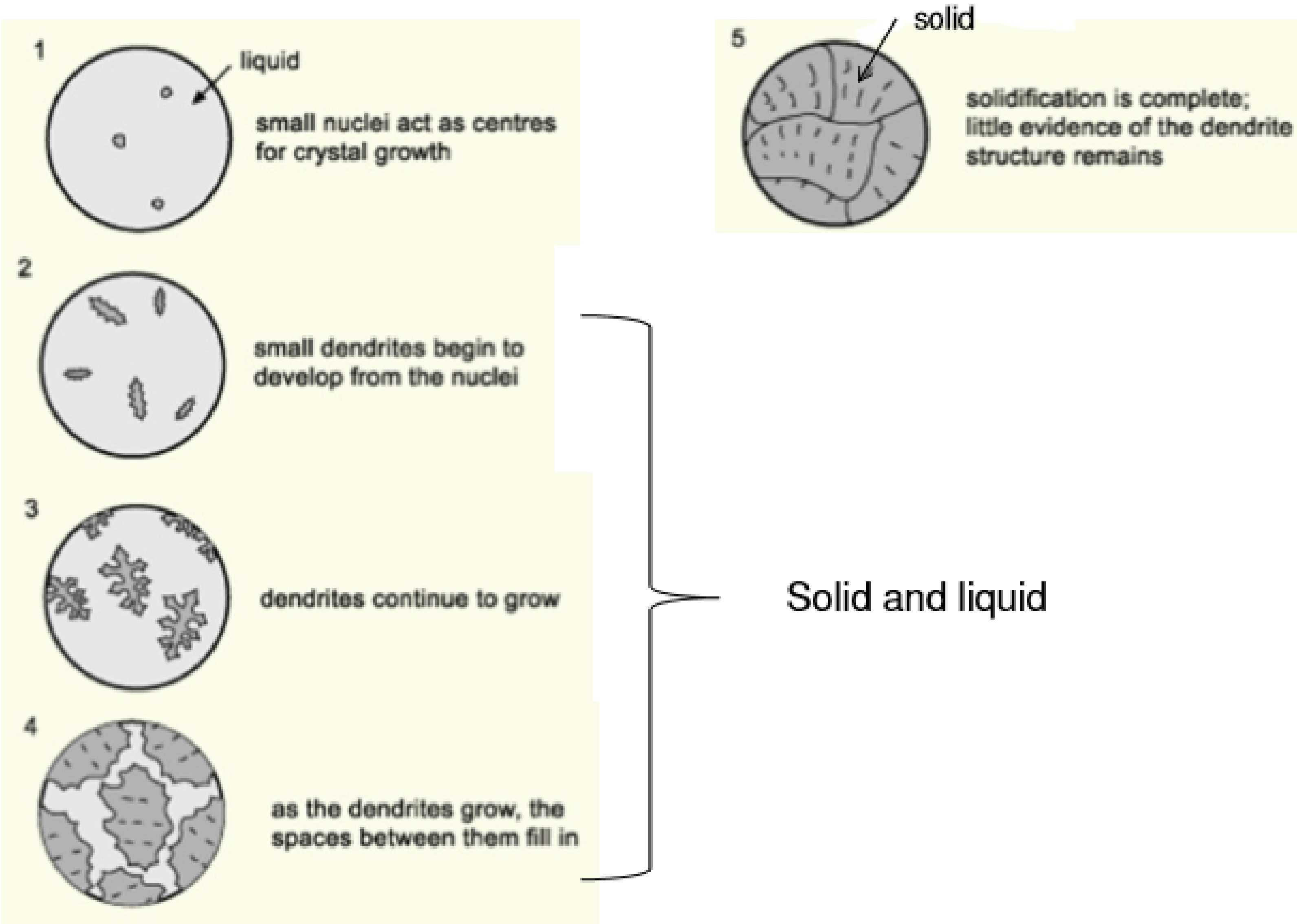
Does they form a regular pattern?
Is this pattern repetitive or symmetrical?

Why study crystal structure?

- **Crystalline structure:** The constituent atoms or ions are arranged in regular, repetitive and symmetrical array.
- Many solid materials are crystalline in nature.
- The properties of a material are determined by the type of the crystal structure. This is particularly true for metals.

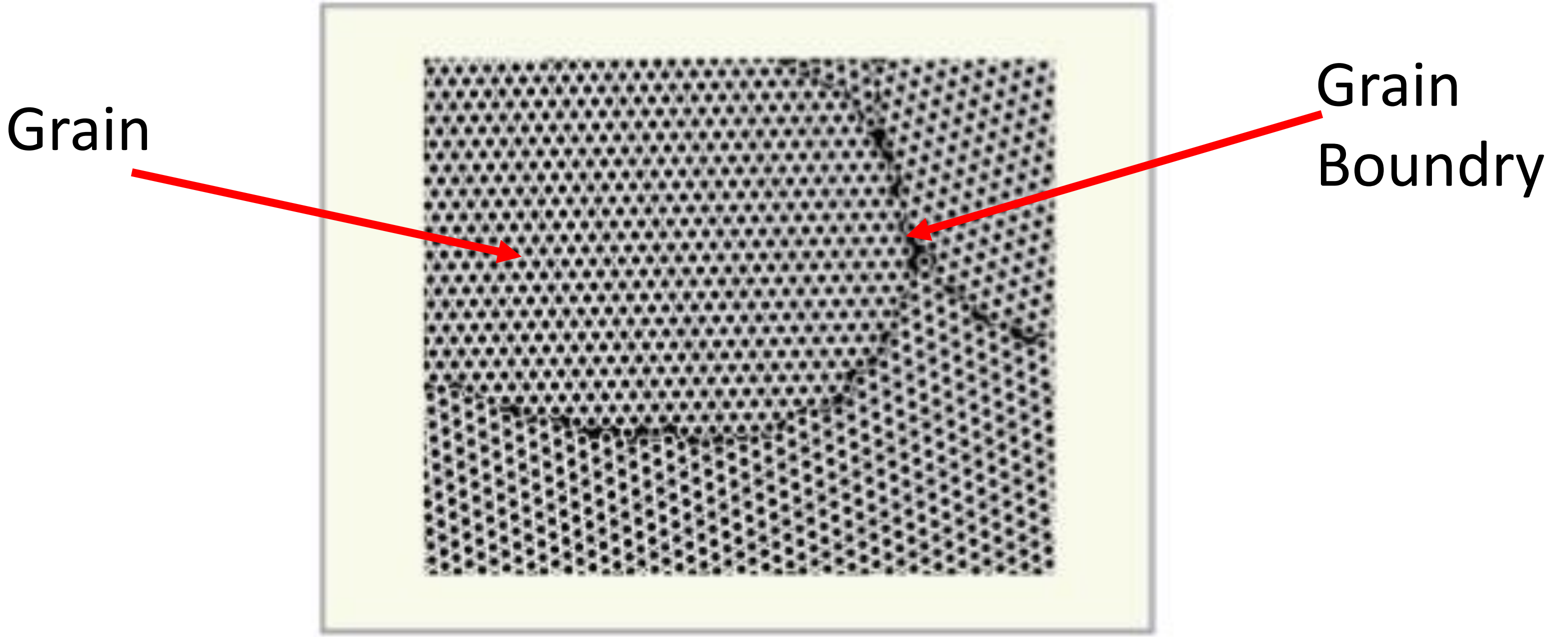
Chemical
Electrical
Thermal
Optical
...

Solidification of a molten metal



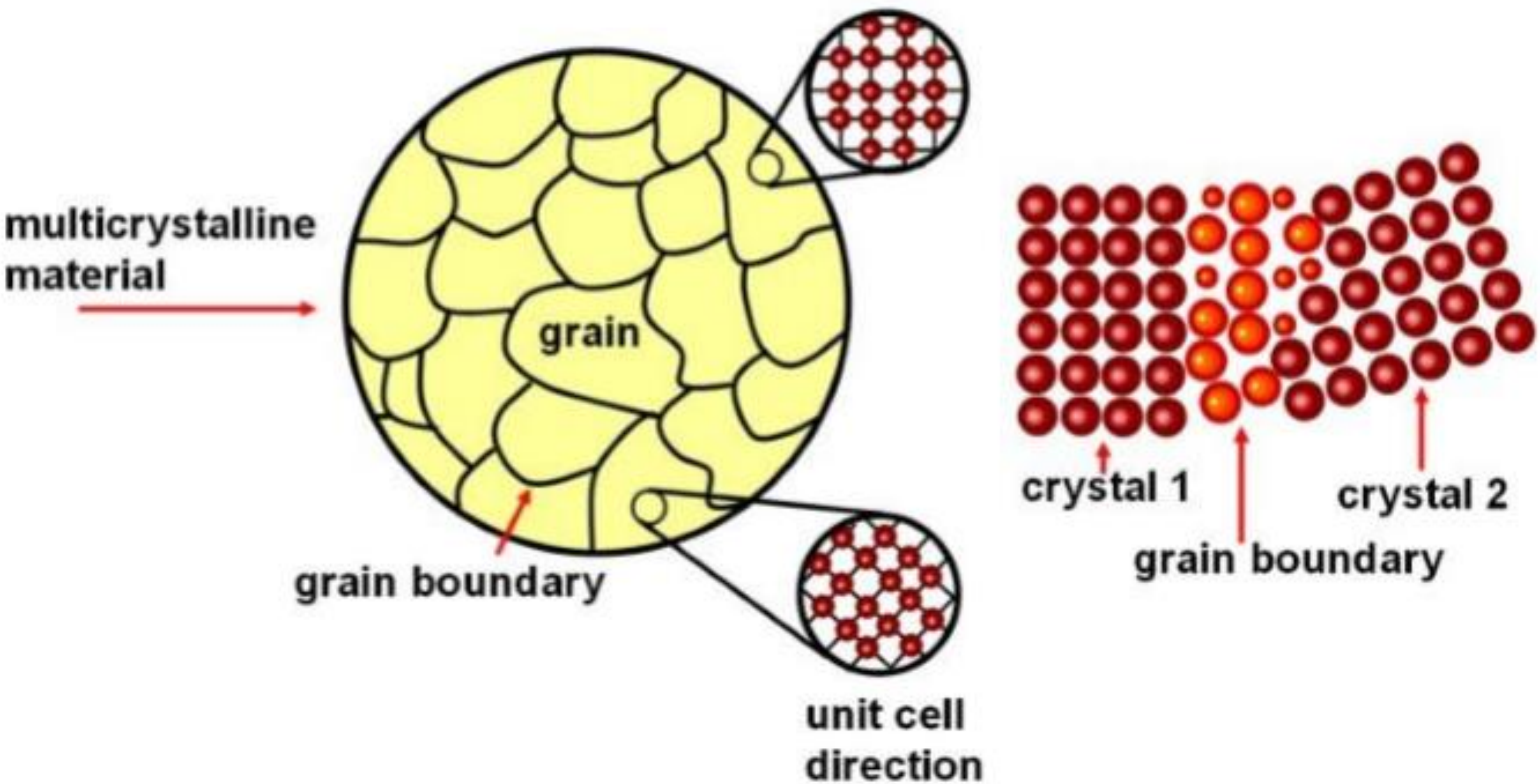
Stages of metal solidification and formation of polycrystalline material

Solidification of molten metal



- The atoms pack together in an orderly and repetitive manner.
- At the boundaries between the grains, the regular pattern breaks down, as the pattern changes from the orderly pattern of one grain to that of the next.

Polycrystalline material



Polycrystalline : many **crystallites** of varying size and orientation
Most inorganic solids are polycrystalline, including all common metals and many ceramics.

Crystalline structure

- **Crystalline structure:**

The constituent atoms or ions are arranged in regular, repetitive and symmetrical array. The regularity of the structure may be termed as long range order, or short range order.

- **Long range order:**

  The same symmetrical pattern of atoms or ions exist over large distances within the material.

- **Short range order**:

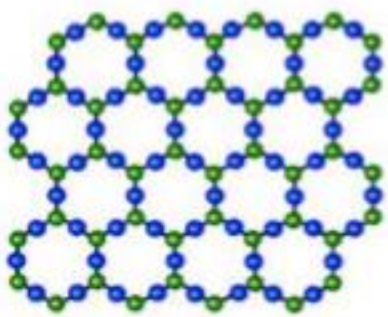
  –Repetition is only over a range 10-20 atoms.

  –Local groups of atoms or ions may be in a symmetrical pattern.

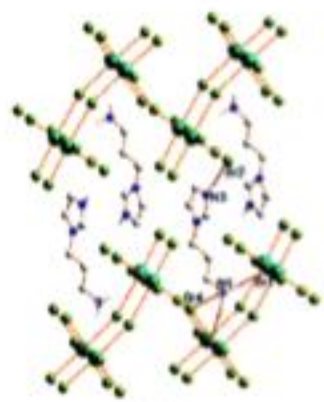
  –The relationship between these local groups may not be regular.

Amorphous structure

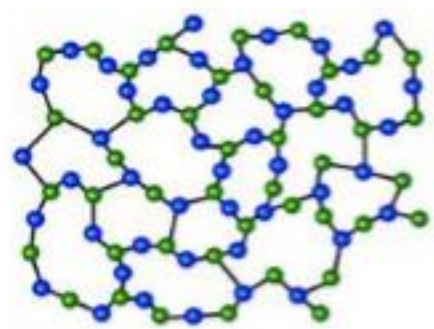
- **Amorphous**, meaning literally **without form**, is the term used to describe non crystalline structures, even they may have a short range order (Short range order is found in many inorganic glasses).



Crystalline structures



Short range order



Non crystalline structures

Structure of solid materials

- Metals and ceramics are crystalline solids.
- In many polycrystalline ceramics there is a frequently a glassy phase in the space between crystal grains.
- Many polymer materials show a greater or lesser degree of crystallinity but others are amorphous.
- Inorganic glasses have amorphous structure, even though they have the same composition as ceramics.

Solidification and crystallization

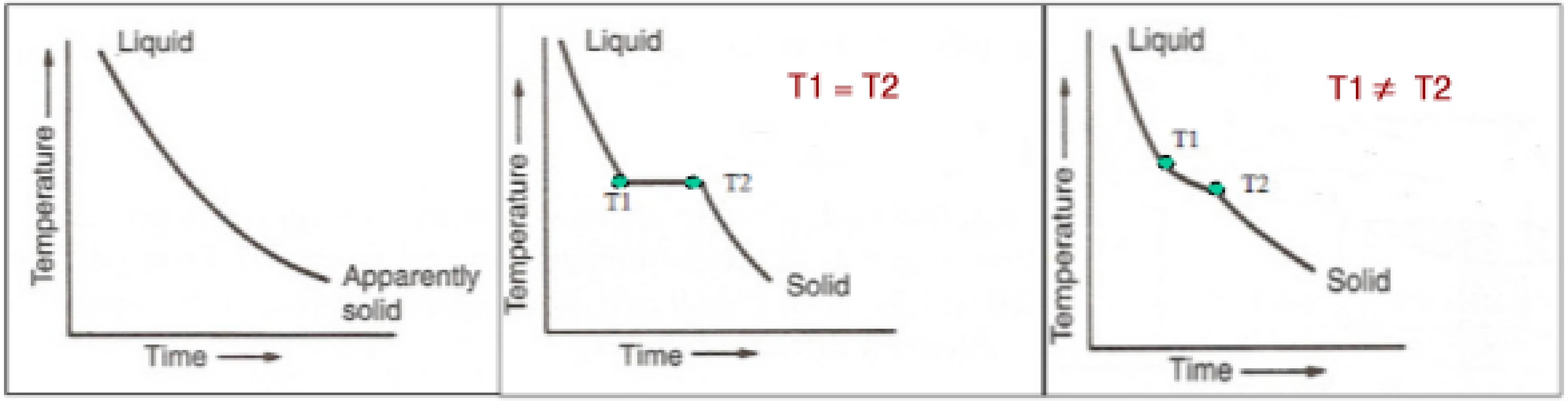
Once the material is allowed to cool slowly from the liquid state , the cooling curve (Temp. Vs Time) obtained can be:

Continuous cooling curve: (glassy material)

- No definite solidification temperature.

Discontinuous cooling curve: (crystalline material)

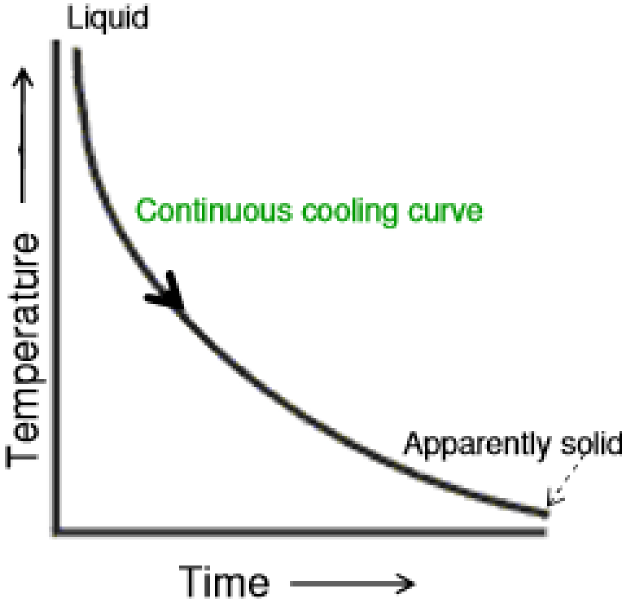
- Definite unique solidification temperature for pure metal.
- Solidification occurs over a range of temperatures for alloys.



Cooling curve for a glassy material

As the <u>temperature falls</u> upon cooling:

- A steady **decrease in the kinetic energy** of the atoms or molecules that make up the liquid.
- A steady **increase in the viscosity** of the fluid.
- The atoms or molecules present still have the same type of **random arrangement** that existed in the true fluid state.



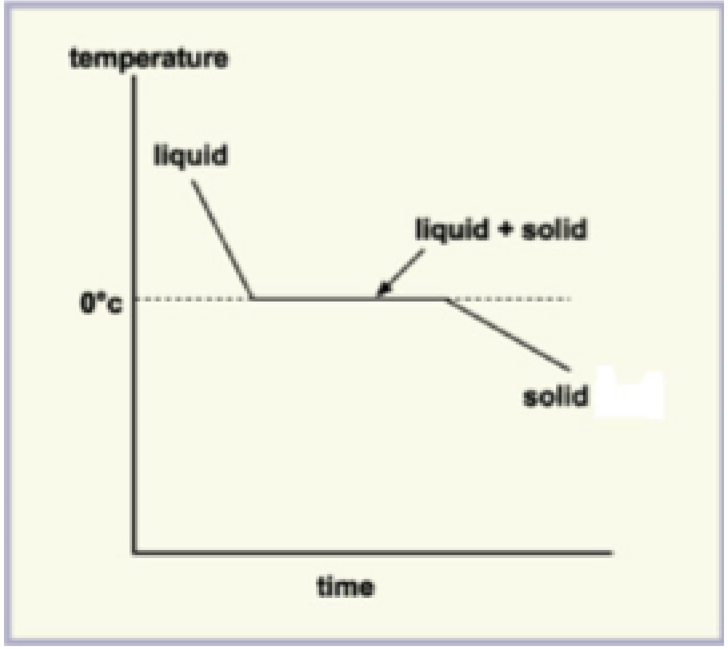
What are the changes occur in material during cooling?

True fluid → Viscous fluid → Apparent solid
(Amorphous solids or glasses)

Cooling curve for a pure crystalline material

As the temperature falls upon cooling:

- There is a definite freezing or solidification point.
- At the freezing temperature:
  - The atoms cease their random movement.
  - They tend to 'stick' together in relatively fixed positions in a regular pattern.
- The atomic motion does not cease abruptly upon solidification.
- The atoms or molecules in a crystalline structure vibrate about fixed positions.



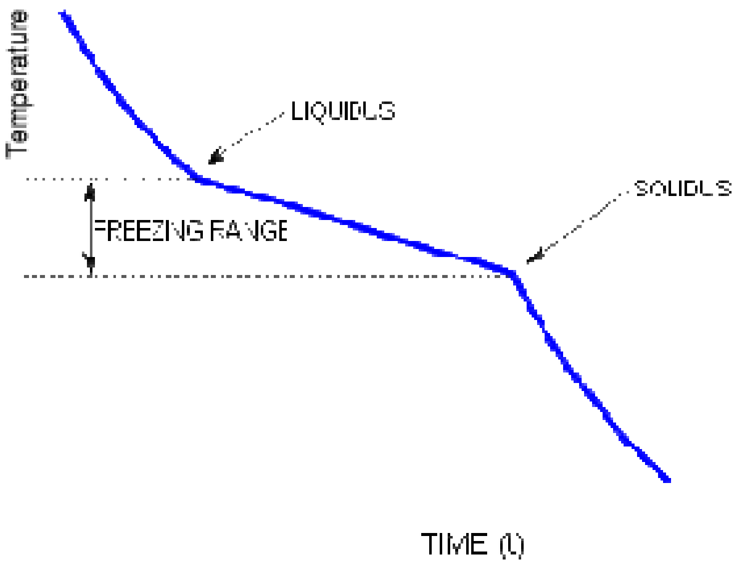
Cooling curve for pure water

In crystalline material, atoms or molecules are arranged in a definite symmetrical pattern.

Cooling curve of a crystalline material (alloy)

As the temperature falls upon cooling:

1) There is no specific freezing temperature.
2) Material freeze or solidify upon a range of temperatures.
3) The resultant structure is crystalline solid.
4) The same mechanism of pure solid solidification applies.



Cooling curve for an alloy

In crystalline material, atoms or molecules are arranged in a definite symmetrical pattern.

Latent heat

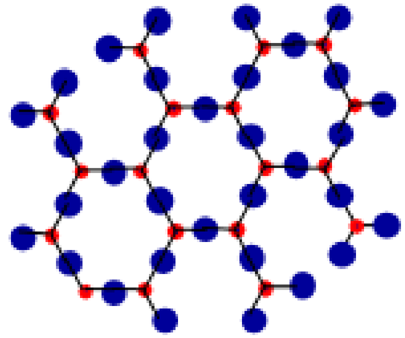
As the liquid solidify, the material changes from a **high energy state** (random motion of atoms or molecules) to a much **lower energy state** (and vibrate about a point within a crystal).

Latent heat is the difference between the high energy state and the low energy state, it is the energy emitted from the material at the freezing temperature.

Materials and Packing

Crystalline materials...

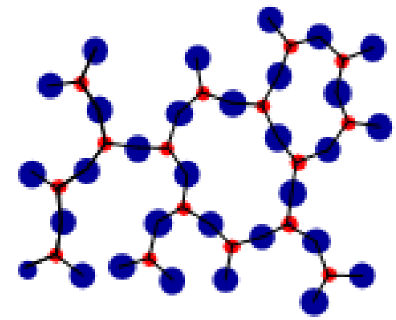
- Atoms pack in periodic, 3D arrays
- Typical of: -metals
  -many ceramics
  -some polymers



crystalline SiO_2

Noncrystalline materials...

- Atoms have no periodic packing
- Occurs for: -complex structures
  -rapid cooling



noncrystalline SiO_2

• Si • Oxygen

Silicon dioxide

"Amorphous" = Noncrystalline

Adapted from Fig. 3.22(a), *Callister 7e.*

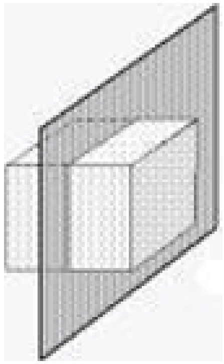
Adapted from Fig. 3.22(b), *Callister 7e.*

Symmetrical structure

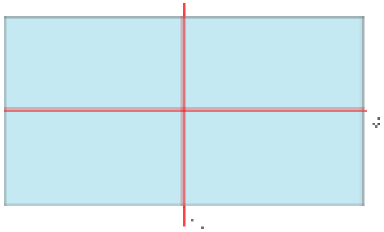
- A shape is said to be symmetrical if it posses one or more elements of symmetry.
- Some of the elements of symmetry: planes, axes of symmetry.
- The degree of symmetry in a shape depends on the number of symmetrical elements that exist in that shape.
- A shape of low symmetry may has only one plane of symmetry.
- A highly symmetrical shape, such as the cube, will contain several planes and axes of symmetry.

Plane of symmetry and axis of symmetry

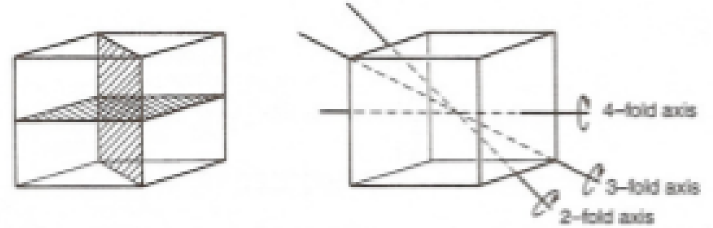
- **Plane of symmetry:**
  - A shape is said to be symmetrical about a plane if the plane divides the shape into either two identical halves, or into two halves that are mirror images of one another.
- **Axis of symmetry:**
  - If the shape can be rotated about an axis so that the shape occupies the same relative position in space more than once in a complete revolution then such an axis is termed an axis of symmetry.
  - The line in a plane divides the figure into two such parts that one part, when folded over along the axis, shall coincide with the other part.



Plane of symmetry

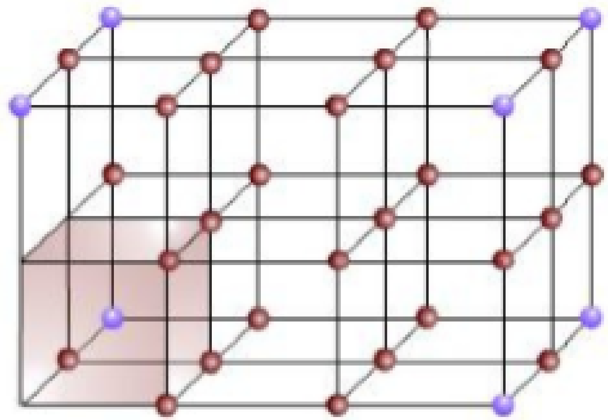


Axis of symmetry

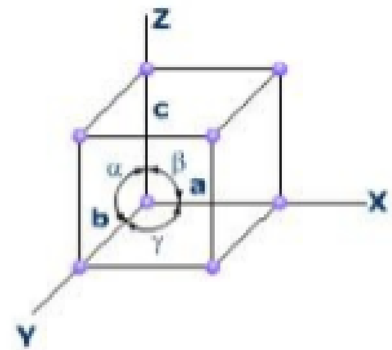


Elements of cubic symmetry: (a) planes; (b) axes.

Space lattice and unit cell



Representation of space lattice and unit cell



Representation of dimensions of a unit cell

Unit cell: the smallest building block of atoms that are arranged in three-dimensional space (unit cell describes the spatial arrangement of atoms).

When the unit cell is repeated in different directions, it will form what is called crystal lattice or space lattice.

Crystal lattice or space lattice is a regular arrangement of the constituent particles of a crystal in a three dimensional space.

Crystal Systems

Unit cell: smallest repetitive volume which contains the complete lattice pattern of a crystal. The unit cell geometry is completely defined in term of six parameters (Lattice Parameters): three edge lengths, and three inter-axial angles.

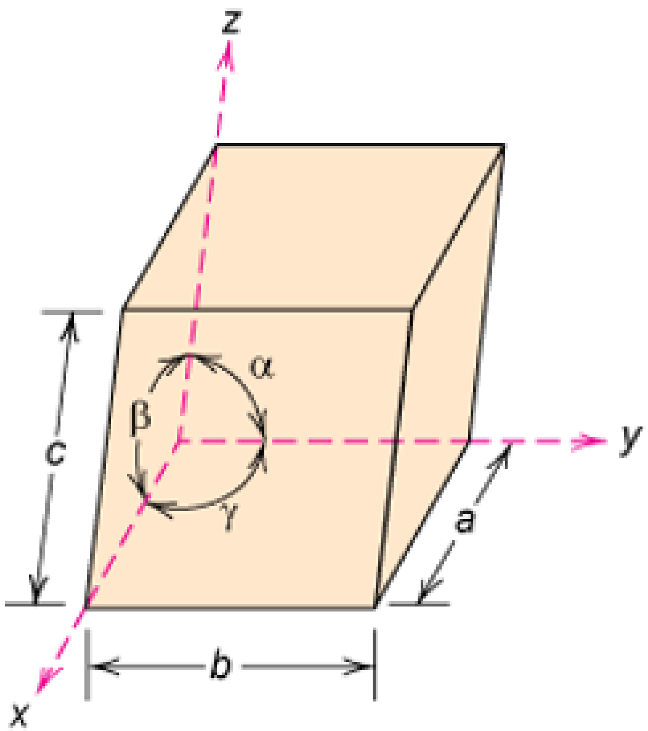


Fig. 3.4, *Callister 7e.*

a, *b*, and *c* are the lattice constants

7 crystal systems

Crystal systems

There are seven crystal systems. These are:

(1) Triclinic

(2) Monoclinic

(3) Rhombohedral

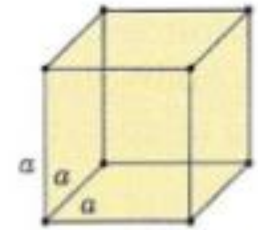
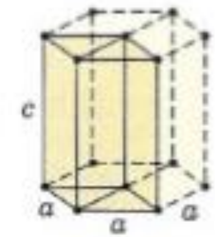
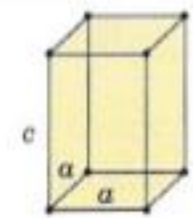
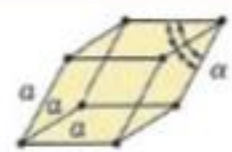
(4) Hexagonal

(5) Orthohombic

(6) Tetragonal

(7) Cubic

Crystal systems

Crystal System	*Axial Relationships*	*Interaxial Angles*	*Unit Cell Geometry*
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°,\ \gamma = 60°$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	
Rhombohedral (Trigonal)	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	

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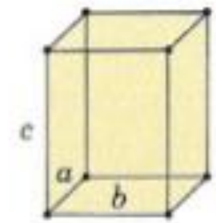
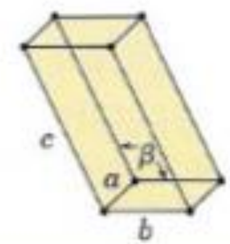
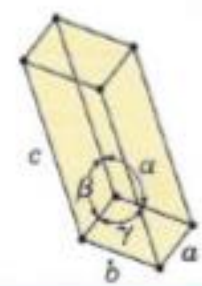
Crystal systems

Crystal System	*Axial Relationships*	*Interaxial Angles*	*Unit Cell Geometry*
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90^\circ \neq \beta$	
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	

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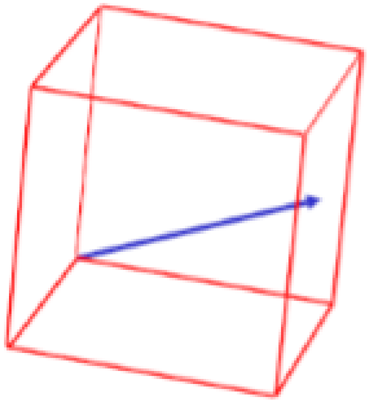
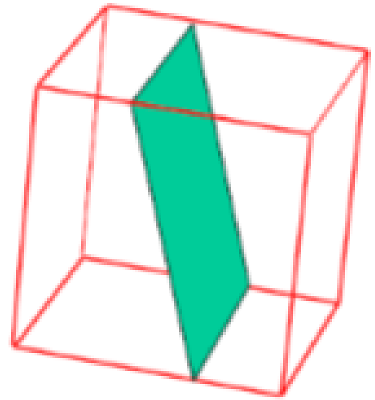
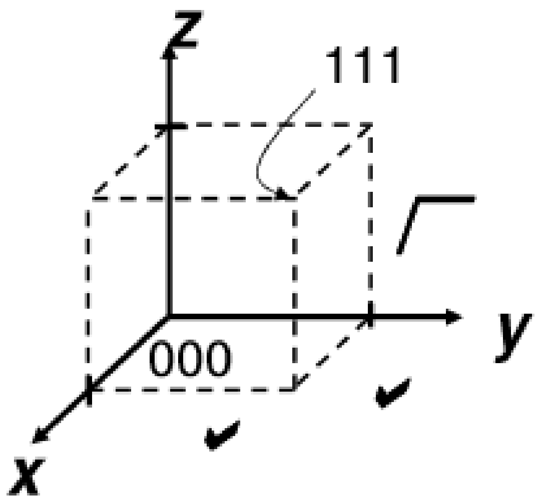
Crystallographic planes and directions



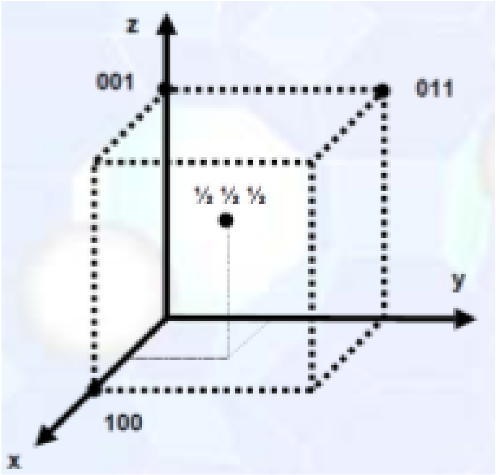


- It is often necessary to be able to specify certain directions and planes in crystals.
- Many material properties and processes vary with direction in the crystal.
- Directions and planes are described using three integers, Miller indices.

Point Coordinates



Point coordinates for unit cell corner are (111)

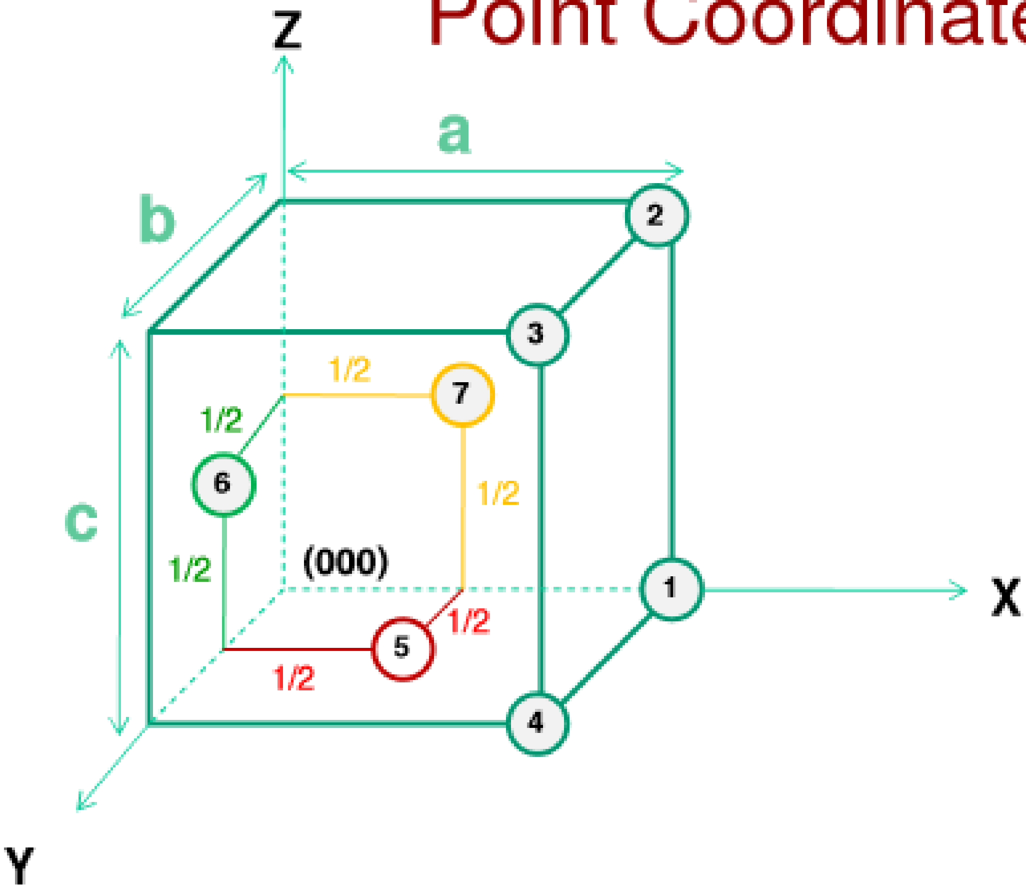


Point coordinates for unit cell center are:

a/2, *b*/2, *c*/2 (½ ½ ½)

Translation: integer multiple of lattice constants → identical position in another unit cell

Point Coordinates



Give the coordinate for the atoms 1, 2, 3, 4, 5, 6 and 7 within the unit cell (for this unit cell a = b = c = 1 unit).

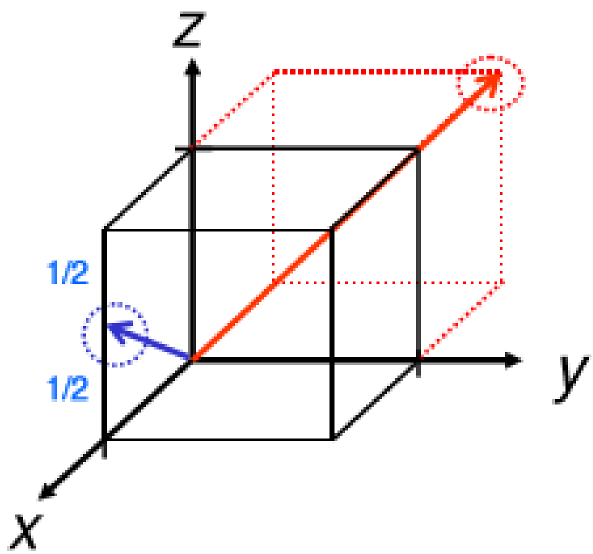
General Rules for Lattice Directions, Planes & Miller Indices

- Miller indices used to express lattice *planes* and *directions*
- x, y, z are the axes (on arbitrarily positioned origin)
- a, b, c are lattice parameters (*length of unit cell along a side*)
- h, k, l are the Miller indices for planes and directions - expressed as planes: (hkl) and directions: [hkl]

- Conventions for naming
  - There are NO COMMAS between numbers
  - Negative values are expressed with a bar over the number
    - *Example: -2 is expressed* $\bar{2}$

- Crystallographic direction:
  - [123]
  - [100]
  - … etc.

Crystallographic Directions



Algorithm

1. Vector repositioned (if necessary) to pass through origin.
2. Read off projections in terms of unit cell dimensions *a*, *b*, and *c*
3. Adjust to smallest integer values
4. Enclose in square brackets, no commas [*uvw*]

ex: 1, 0, ½ => 2, 0, 1 => [201]

-1, 1, 1 => [$\bar{1}$11] where over-bar represents a negative index

Families of directions <*uvw* >

Crystallographic direction, [uvw]

Vector 1:

Start: 1, 0, 1

End :0, 0 ,0

End – start = (0 -1), (0 – 0), (0 -1)

End – start = -1, 0 , -1

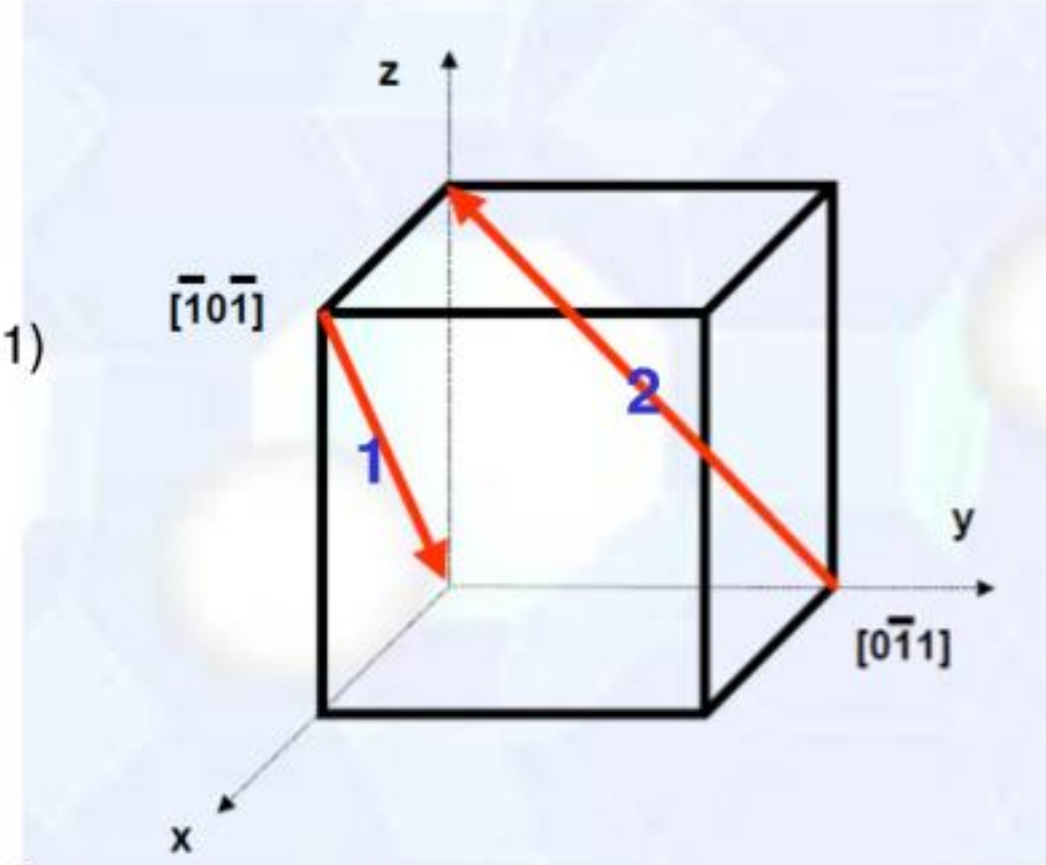
Vector 2:

Start: 0, 1, 0

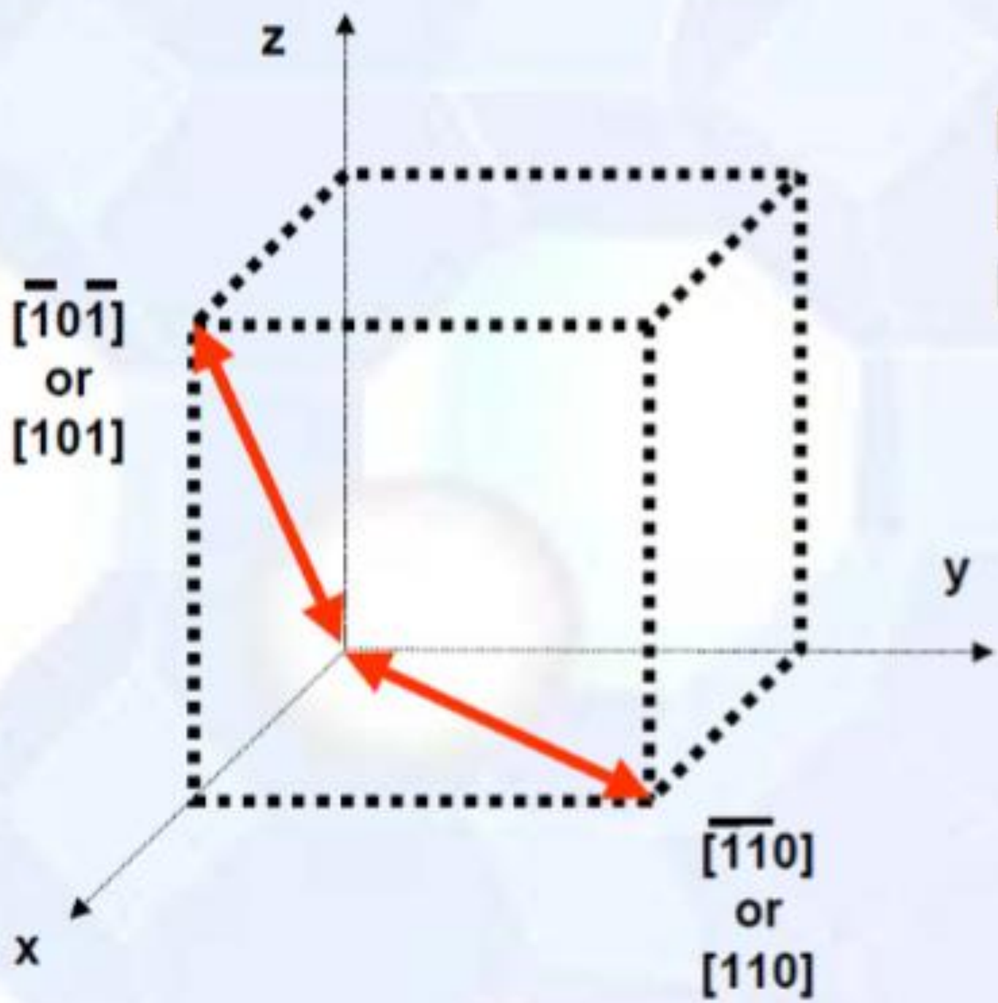
End :0, 0 ,1

End – start = (0 -0), (0 – 1), (1 -0)

End –start = 0, -1, 1



Family of crystallographic directions <uvw>



<110>

[110],[$\bar{1}$10],[1$\bar{1}$0],[$\bar{1}\bar{1}$0]

[101],[$\bar{1}$01],[10$\bar{1}$],[$\bar{1}$0$\bar{1}$]

[011],[0$\bar{1}$1],[01$\bar{1}$],[0$\bar{1}\bar{1}$]

Crystallographic directions

Vector 1:

Start: 0, 0, 0

End: ½, 1, ½

End – Start = ½, 1, ½

[121]

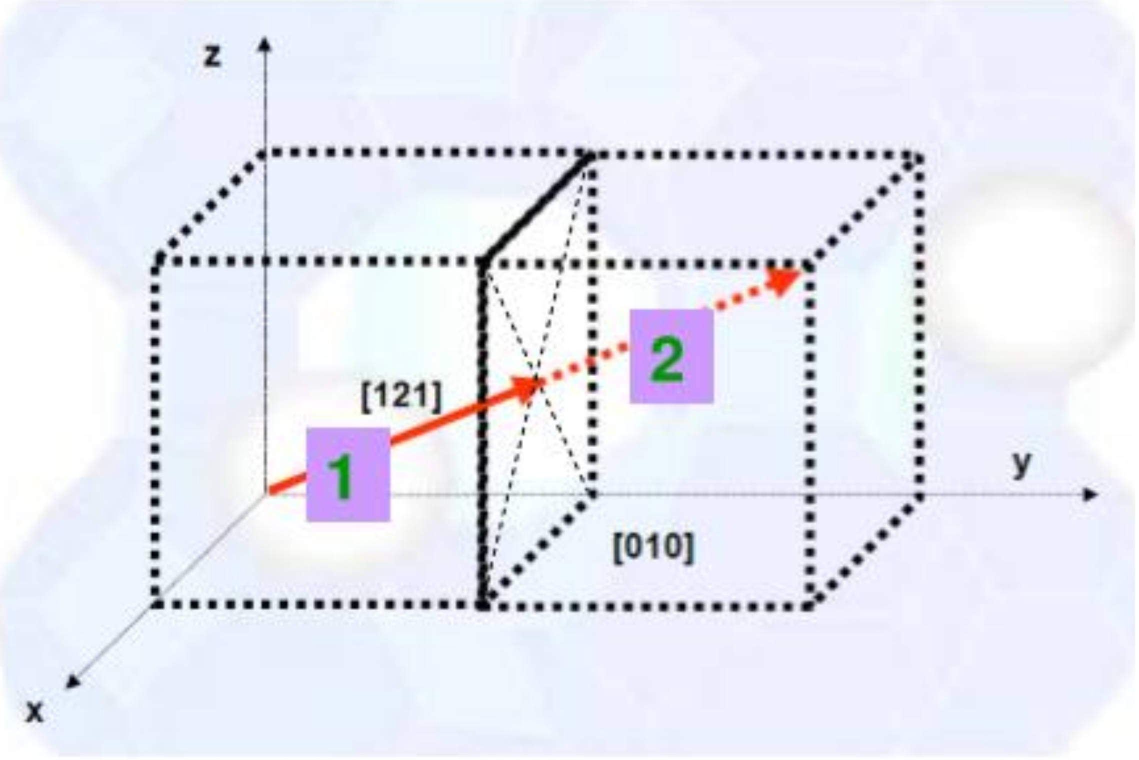
Vector 2:

Start: ½, 1, ½

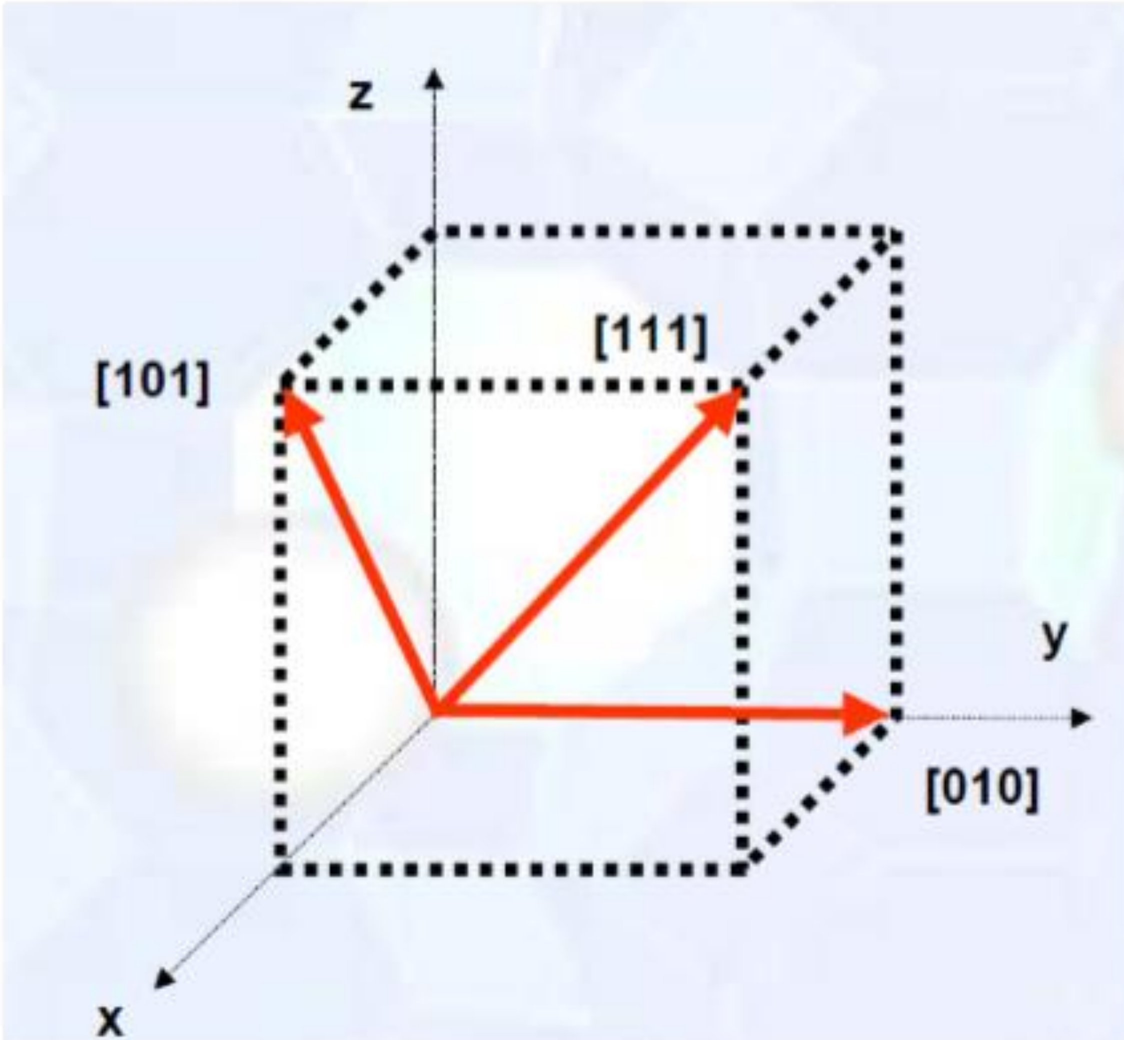
End: 1, 2, 1

End – Start =½, 1, ½

[121]

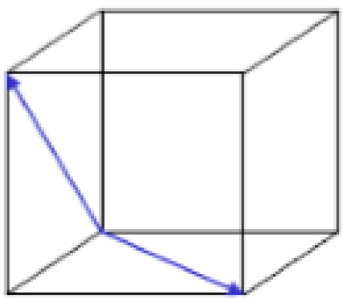


Crystallographic Directions



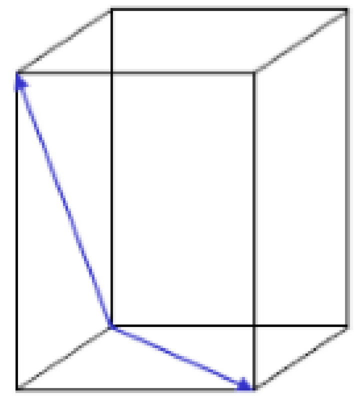
Families of directions

- Equivalence of directions



[101] = [110]

cubic



[101] ≠ [110]

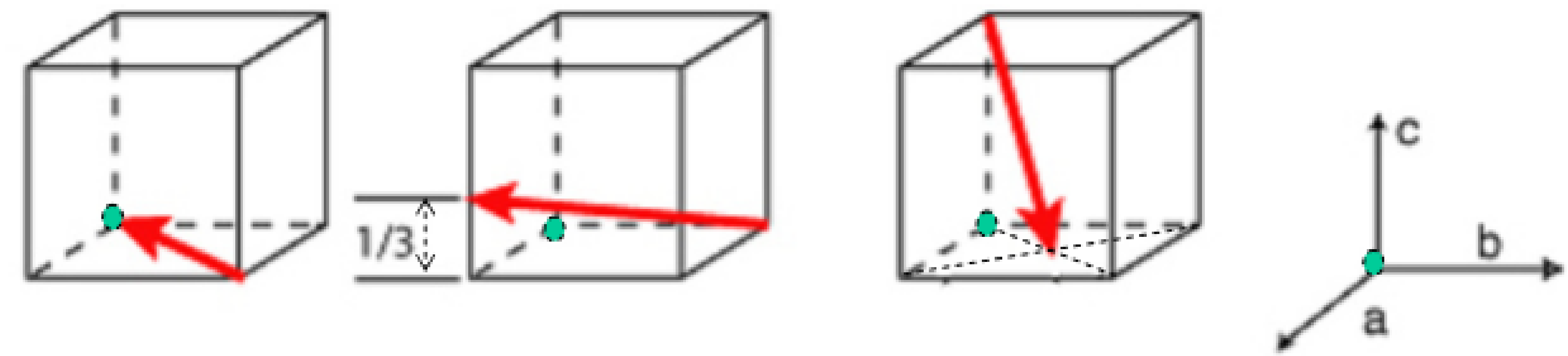
tetragonal

- <123> Family of directions
  - [123], [213], [312], [132], [231], [321]
    - *– only in a cubic crystal*

In the cubic system directions having the same indices regardless of ***order*** *or* ***sign*** *are equivalent.*

Crystallographic direction, [uvw]

Example: (a,b,c) ….. [hkl]



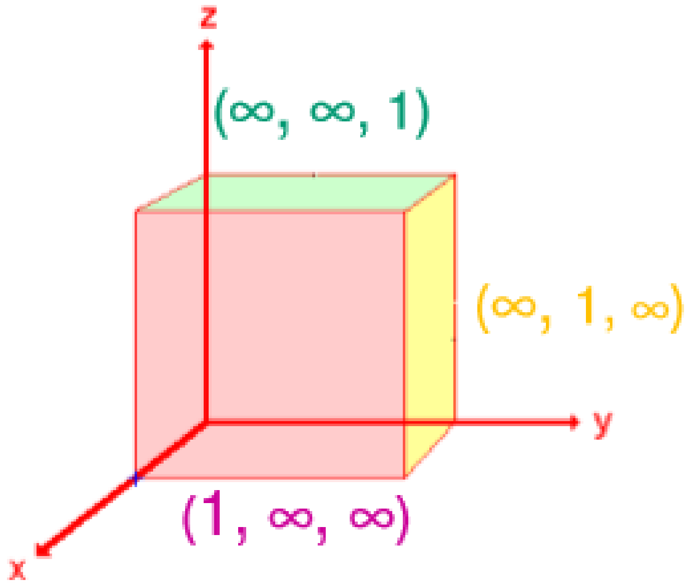
$[\bar{1}\;\bar{1}\;0]$ $[3\;\bar{3}\;1]$ $[1\;1\;\bar{2}]$

Crystallographic Planes

- Miller Indices: Reciprocals of the (three) axial intercepts for a plane, cleared of fractions & common multiples.
- All parallel planes have same Miller indices.

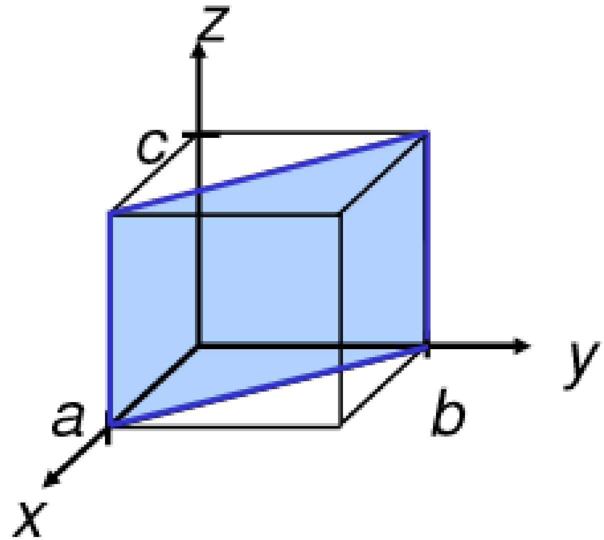
- Algorithm

1. Read off intercepts of plane with axes in terms of *a*, *b*, *c*
2. Take reciprocals of intercepts
3. Reduce to smallest integer values
4. Enclose in parentheses, no commas i.e., (*hkl*)

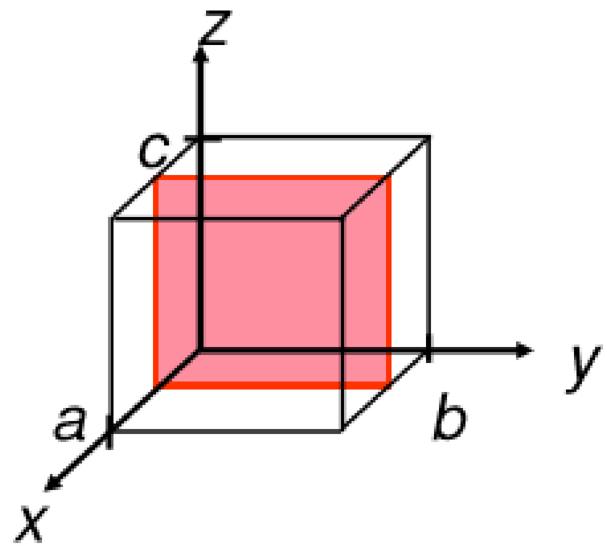


Crystallographic Planes

Example:		a	b	c
1.	Intercepts	1	1	∞
2.	Reciprocals	1/1	1/1	1/∞
	--------------------	1	1	0
3.	Reduction	1	1	0
4.	Miller Indices	**(110)**		



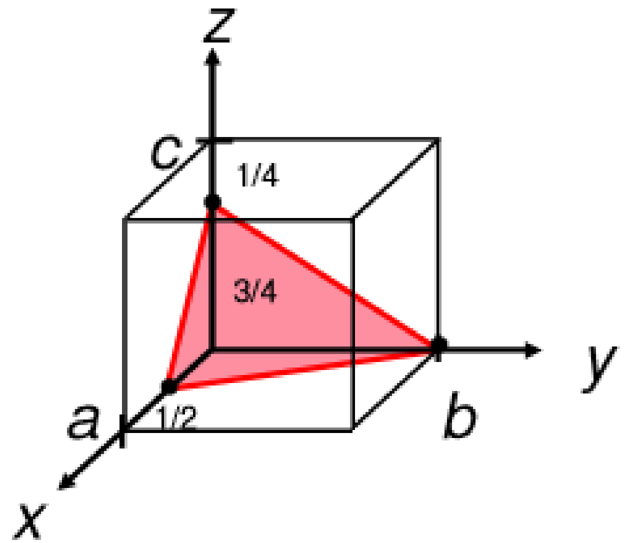
Example:		a	b	c
1.	Intercepts	1/2	∞	∞
2.	Reciprocals	1/½	1/∞	1/∞
	--------------------	2	0	0
3.	Reduction	2	0	0
4.	Miller Indices	**(200)**		



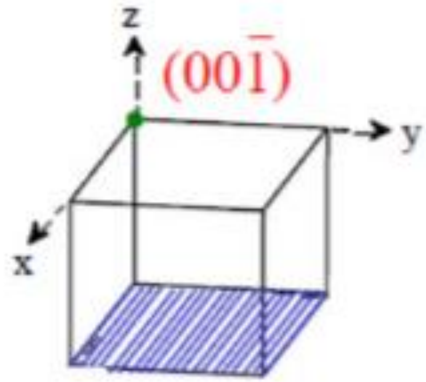
Crystallographic Planes

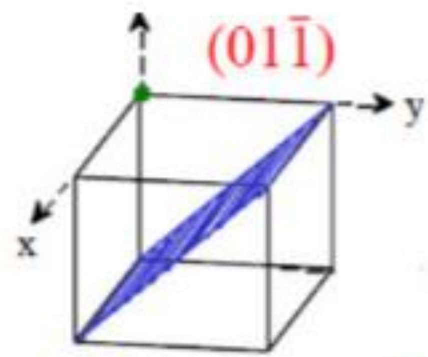
Example:

		a	b	c
1.	Intercepts	1/2	1	3/4
2.	Reciprocals	1/½	1/1	1/¾
	--------------------	2	1	4/3
3.	Reduction	6	3	4
4.	Miller Indices	**(634)**		

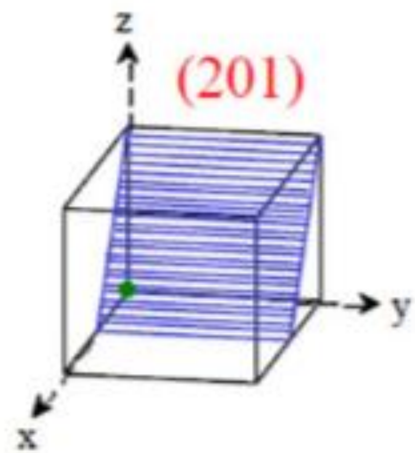


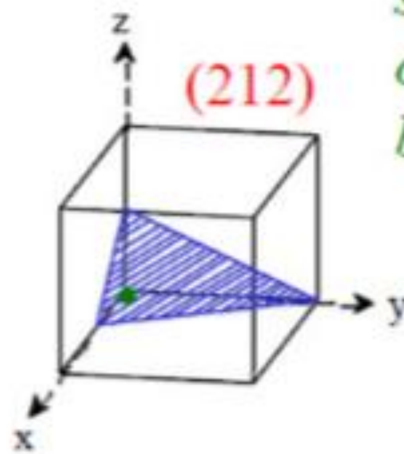
Crystallographic planes



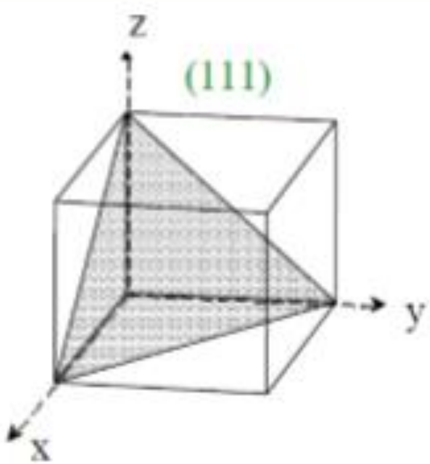


Green circles show where the origins have been placed.



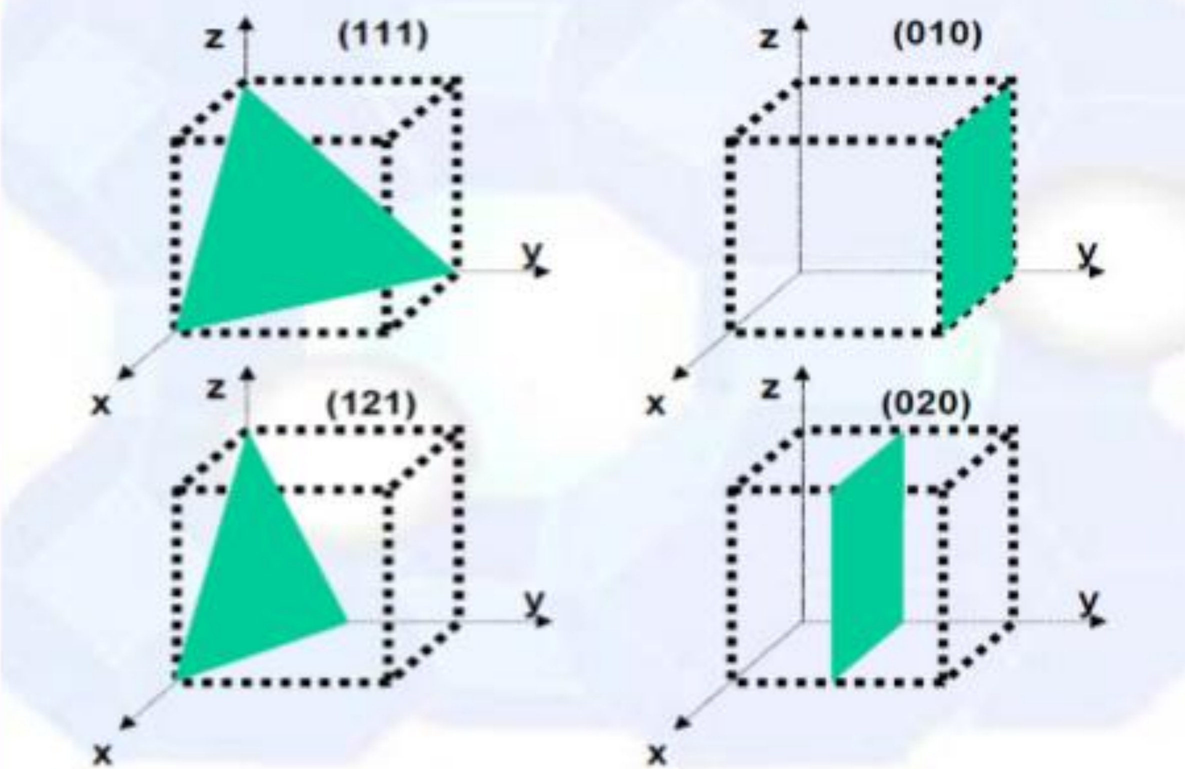


Crystallographic planes



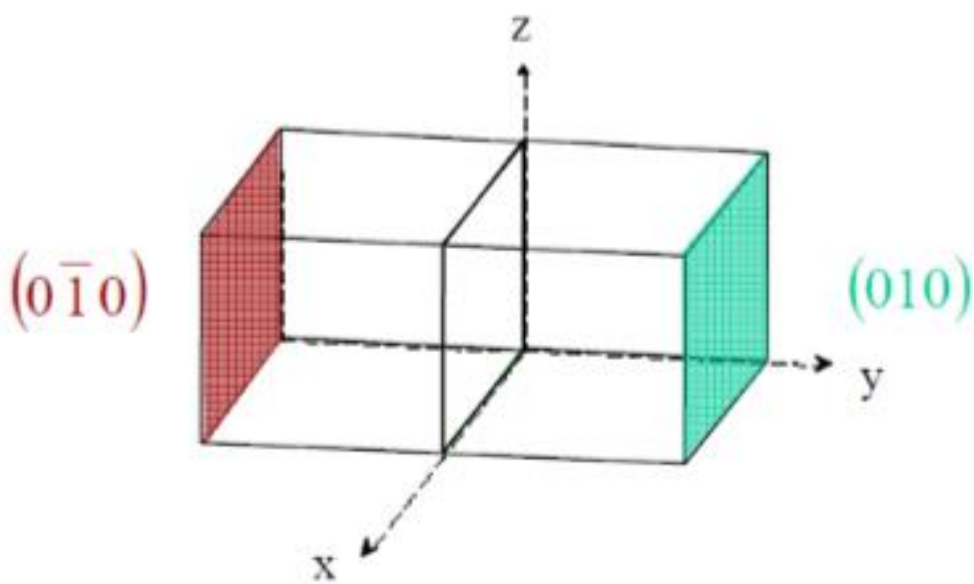
	x	y	z
Intercepts	1	1	1
Reciprocals	1	1	1

Crystallographic Planes: Miller Indices (hkl)



Crystallographic planes

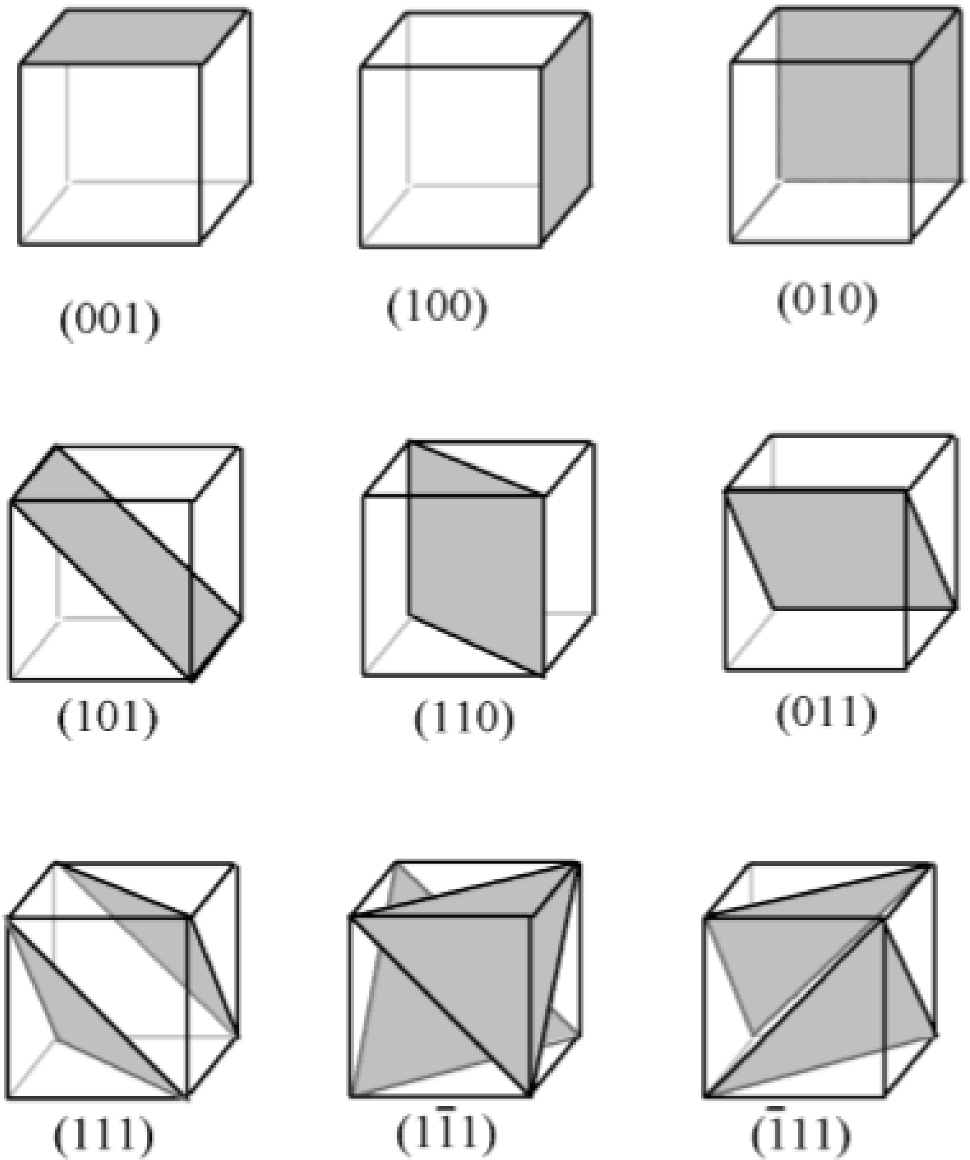
Planes and their negatives are equivalent



Family of Planes $\{hkl\}$

Ex: $\{100\} = (100), (010), (001), (\bar{1}00), (0\bar{1}0), (00\bar{1})$

Crystallographic planes



In the cubic lattice, (100) is equivalent to five other planes, (010), (001), (100), (010), (001)

Equivalent plans

Equivalent plans

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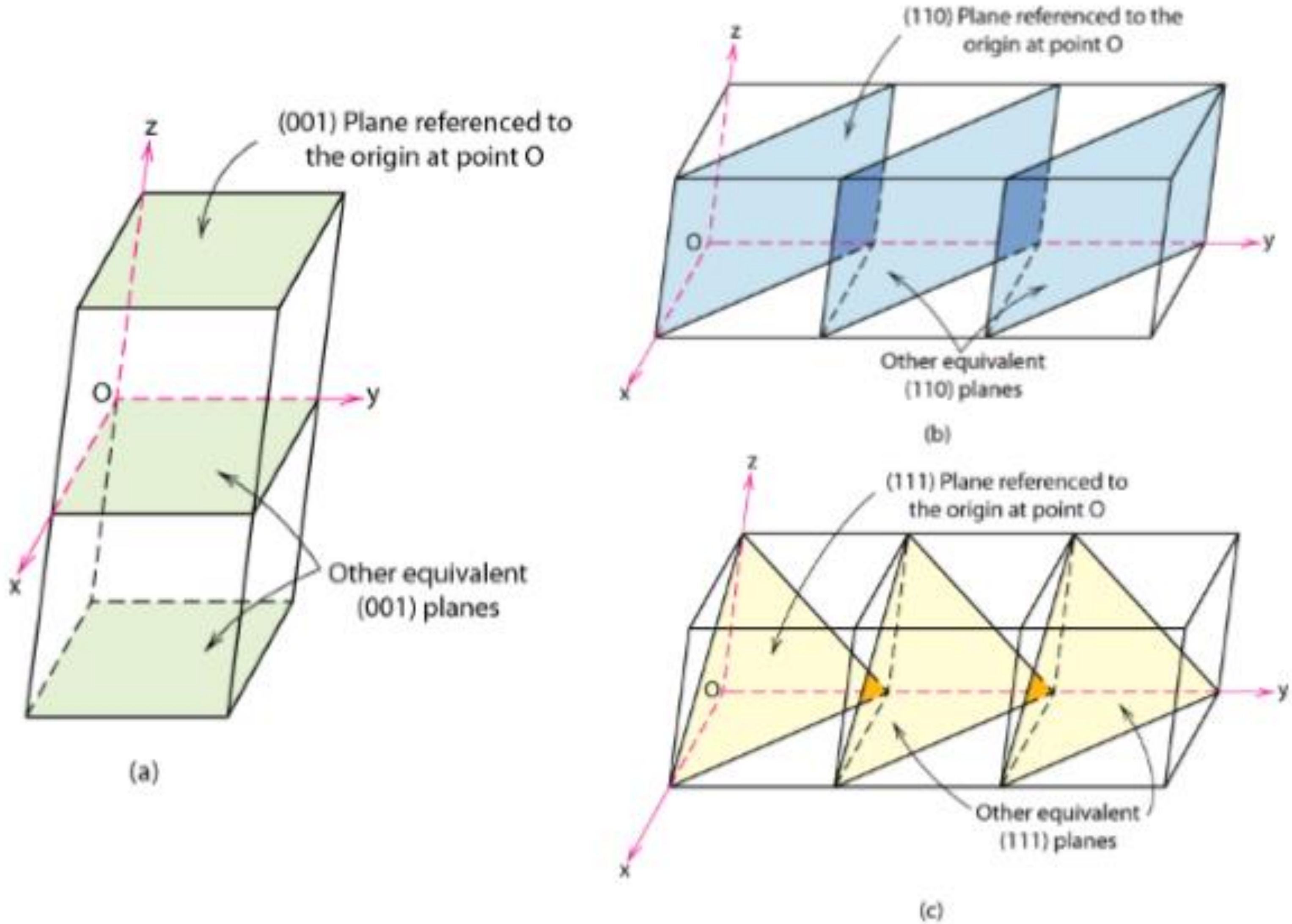
Crystallographic Planes



Adapted from Fig. 3.9, *Callister 7e.*

Miller indices for planes

- (hkl) Crystallographic plane
- {hkl} Family of crystallographic planes

  e.g. (hkl), (lhk), (hlk)…..etc

- In the *cubic* system planes having the same indices regardless of ***order*** or ***sign*** are equivalent.

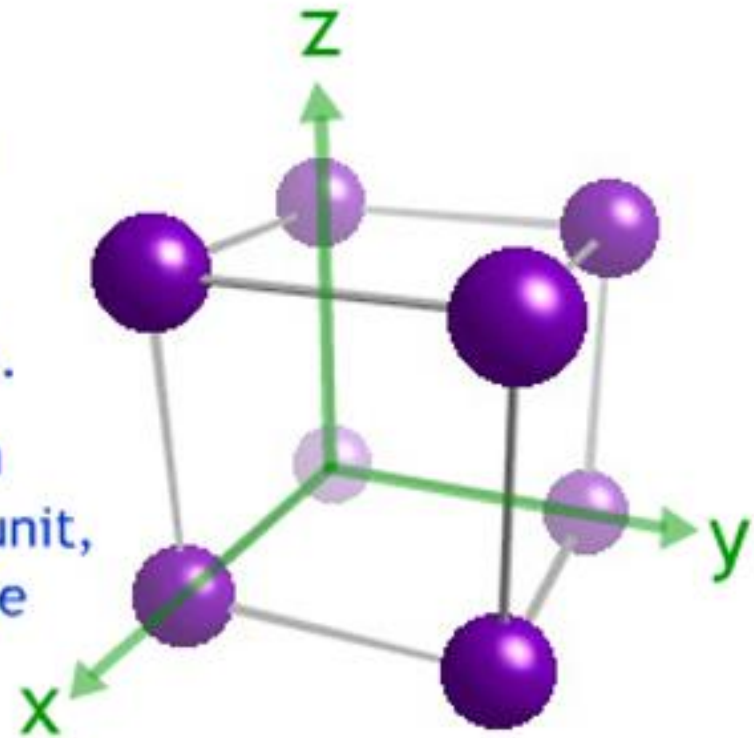
(001) (100) (010)

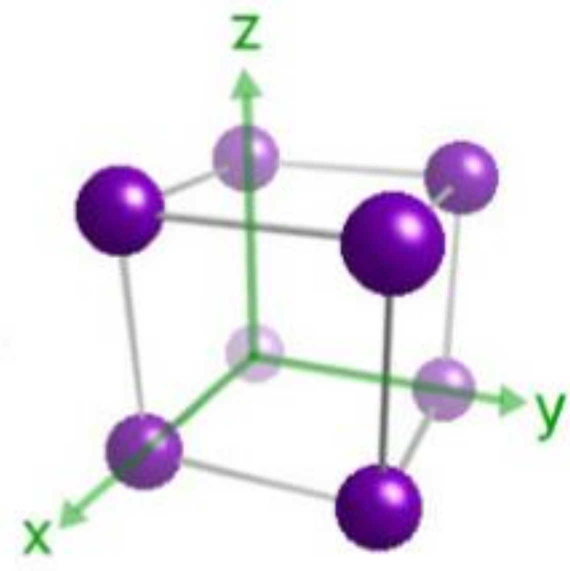
(hkl) **(lhk)** **(hlk)…etc.**

How to draw a lattice plane

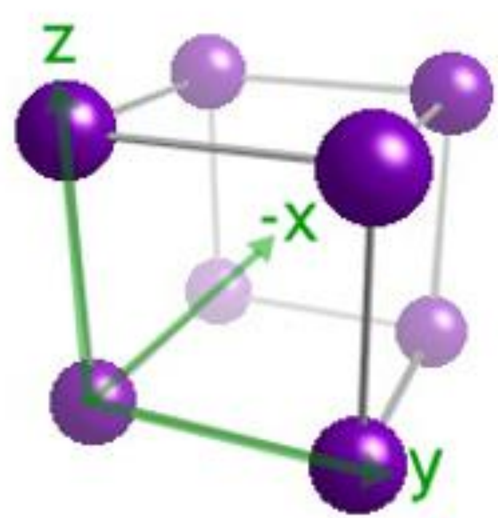
Just as you do when indexing a plane, it is necessary to choose the correct point of reference from which to work.

Taking the conventional origin at the far bottom left of the unit, we can then move along to the next lattice point in the x, y, or z directions.

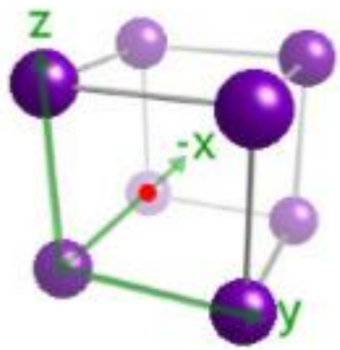




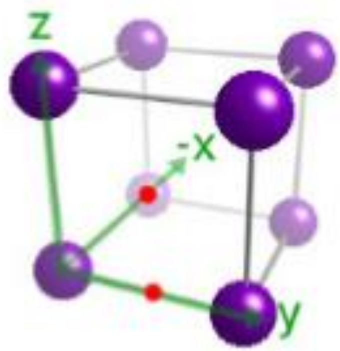
If you have a negative h index, move the point of reference along the x-axis to the other side of the unit cell, so that you can then go back in the negative x direction to find your intercept. Do the same for negative k and l indices.



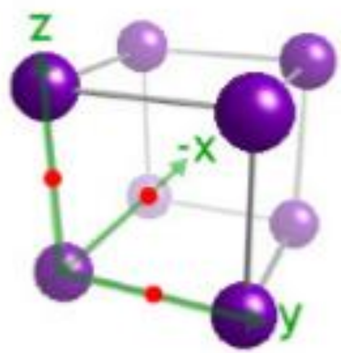
To draw the $(\bar{1}22)$ plane, go back to -a on the x-axis,



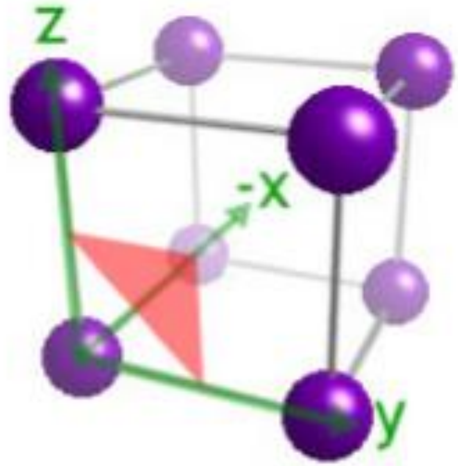
go along to b/2 on the y-axis,



and go up to c/2 on the z-axis.



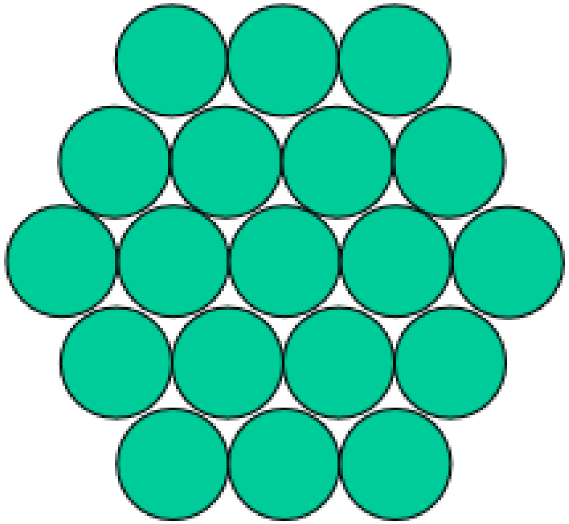
We can join these points to mark the trace of the plane on the unit cell surface, and then fill the plane.



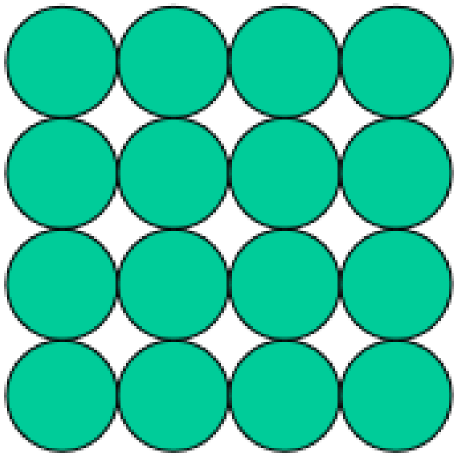
Metallic Crystal Structures

- How can we stack metal atoms to minimize empty space?
- Two possible packing arrangement for spheres in a plane:

2-dimensions



vs.



Hexagonal packing **Square packing**

This is the closest possible packing for uniform spheres

Now stack these 2-D layers to make 3-D structures

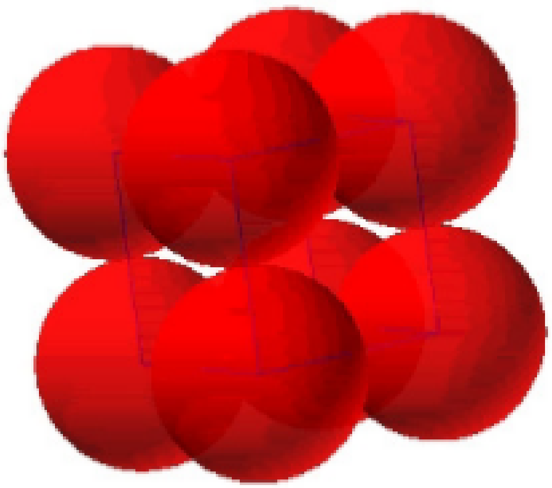
Metallic Crystal Structures

- Tend to be densely packed.
- Reasons for dense packing:
  - Typically, only one element is present, so all atomic radii are the same.
  - Metallic bonding is not directional.
- Have the simplest crystal structures.

We will examine three such structures...

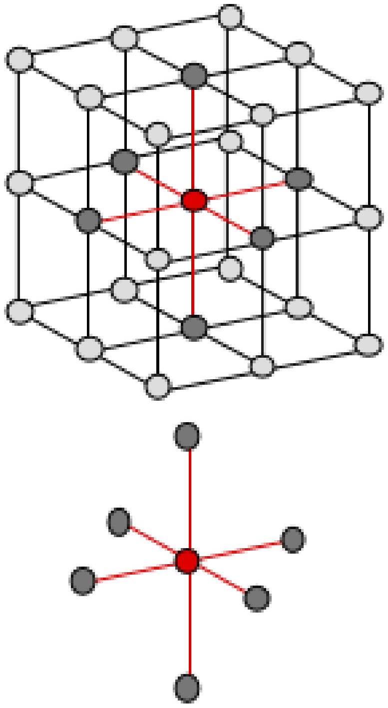
Simple Cubic Structure (SC)

- Rare due to low packing density, only Po (Polonium) has this structure.
- Close-packed directions are cube edges.



(Courtesy P.M. Anderson)

- Coordination # = 6 (# nearest neighbors)

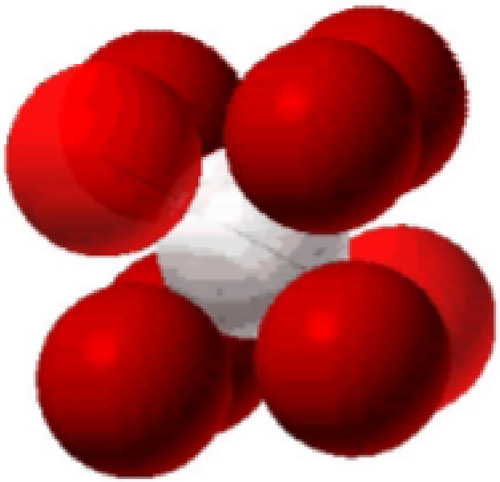


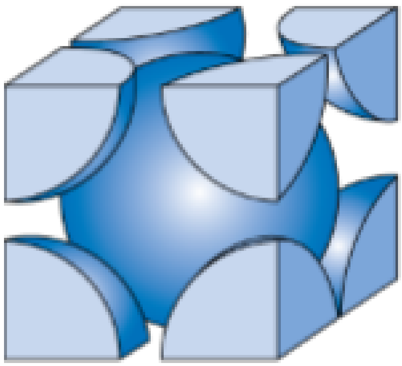
Body Centered Cubic Structure (BCC)

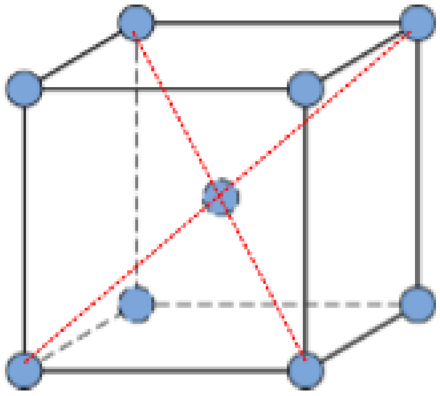
- Atoms touch each other along cube diagonals.

  Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.

ex: Cr (chromium), W (Tungsten), Fe (α), (Ta) Tantalum, (Mo) Molybdenum







2 atoms/unit cell: 1 center + 8 corners x 1/8

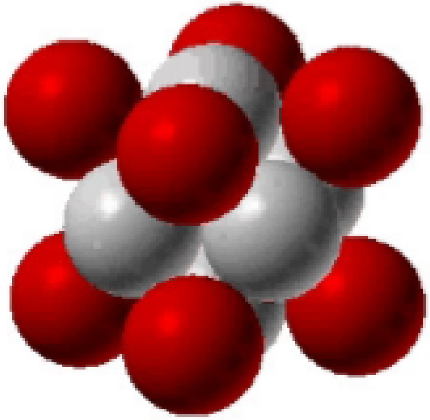
- Coordination # = 8

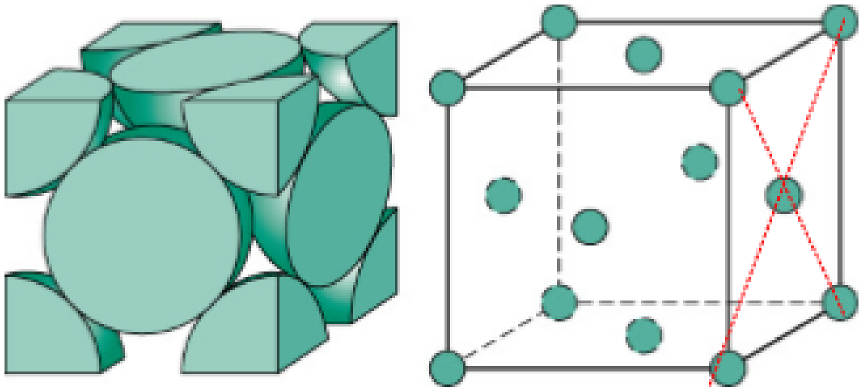
(Courtesy P.M. Anderson) Adapted from Fig. 3.2, *Callister 7e.*

Face Centered Cubic Structure (FCC)

- Atoms touch each other along face diagonals.
  - --Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

ex: Al (Aluminium), Cu (Copper), Au (Gold), Pb (Lead), Ni (Nickel), Pt (Platinum), Ag (Silver)





4 atoms/unit cell: 6 face x 1/2 + 8 corners x 1/8

(Courtesy P.M. Anderson)   Adapted from Fig. 3.1, *Callister 7e.*

- Coordination # = 12

Video

Crystal structure

To find the number of the atoms are contained within the 3-Dimensional unit cell, the following rules are applied:

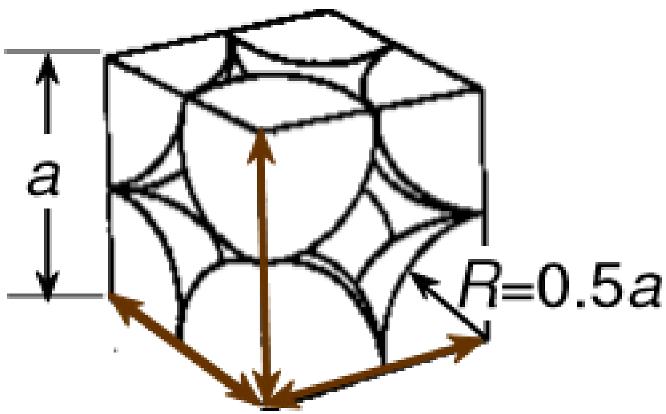
- Eight unit cells meet at the corner of a unit cell
- Each face of the unit cell is common between 2 cells
- The corner atom will be shared between 8 unit cells that meet at that point
- The atom positioned in the cell face will be shared between 2 cells.

Atomic Packing Factor (APF)

$$APF = \frac{\text{Volume of atoms in unit cell*}}{\text{Volume of unit cell}}$$

*assume hard spheres

- APF for **a simple cubic structure** = 0.52



close-packed directions

contains 8 x 1/8 = 1

1 atom/unit cell

$$APF = \frac{1 \quad \frac{4}{3}\pi(0.5a)^3}{a^3}$$

atoms / unit cell → 1

volume / atom → $\frac{4}{3}\pi(0.5a)^3$

volume / unit cell → a^3

$$APF = \frac{1*\left(\frac{4}{3}\pi\left(\frac{a}{2}\right)^3\right)}{a^3} = \frac{4}{3}\pi\frac{a^3}{8}\frac{1}{a^3}$$

$$APF = \frac{\pi}{6} = 0.52$$

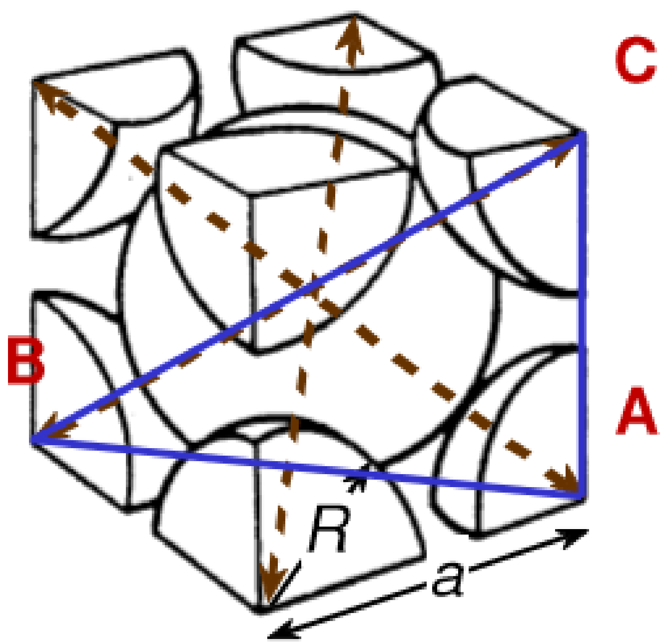
Adapted from Fig. 3.23, *Callister 7e.*

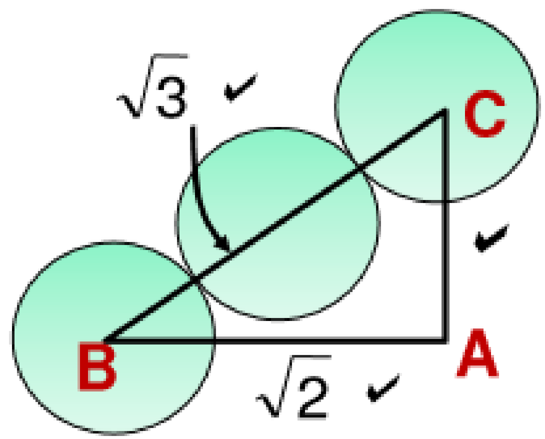
Atomic Packing Factor: BCC

$$APF = \frac{\text{Volume of atoms in unit cell*}}{\text{Volume of unit cell}}$$

*assume hard spheres

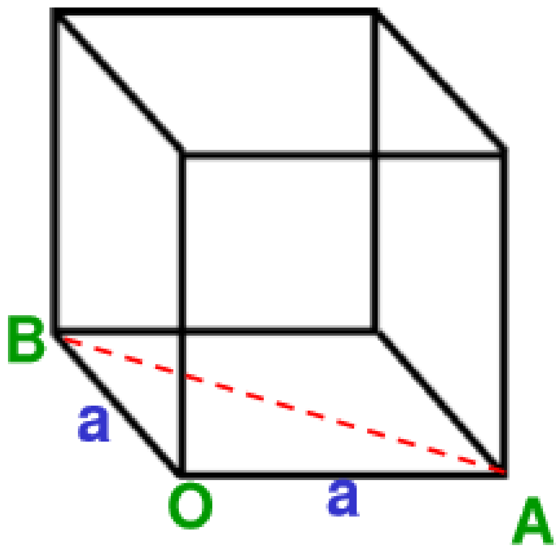
- To find volume of an atom, we need to find r = f(a); where r: atom radius, a: lattice constant





Close-packed directions:
Length= $4R = \sqrt{3}\,a$

Atomic Packing Factor: BCC



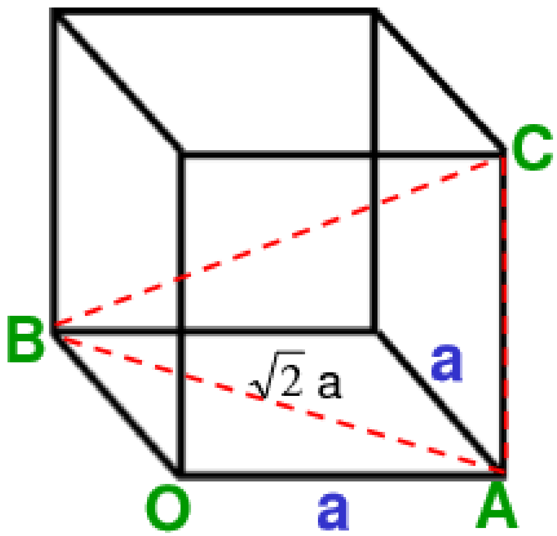
Triangle OAB

$$AB^2 = OA^2 + OB^2$$

$$AB^2 = a^2 + a^2$$

$$AB^2 = 2a^2$$

$$AB = \sqrt{2}a$$



Triangle ABC

$$BC^2 = AB^2 + AC^2$$

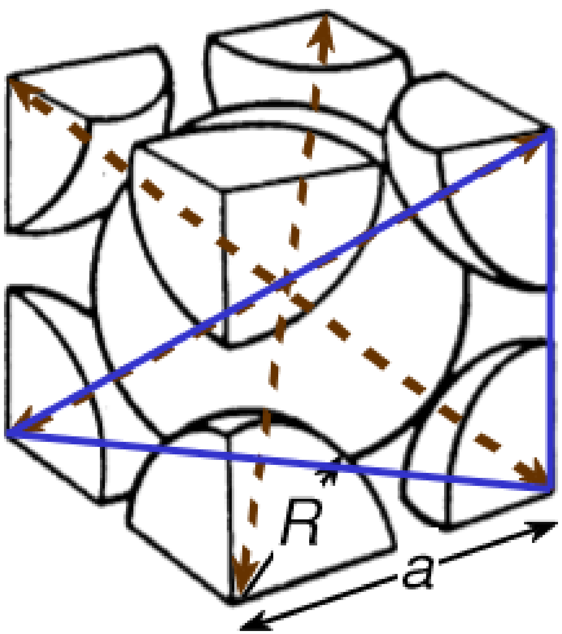
$$BC^2 = \left(\sqrt{2}a\right)^2 + a^2$$

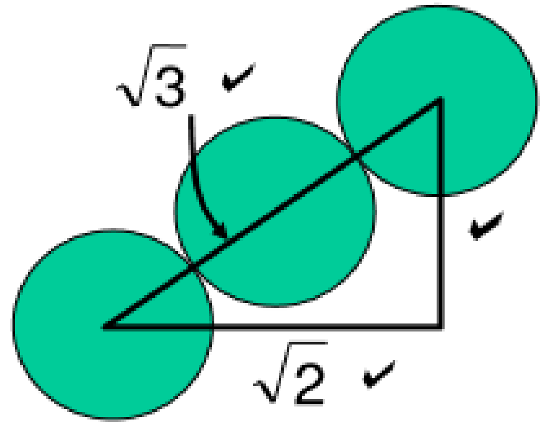
$$BC^2 = 2a^2 + a^2 = 3a^2$$

$$BC = \sqrt{3}a$$

Atomic Packing Factor: BCC

- APF for a body-centered cubic structure = 0.68





Close-packed directions:
length = $4R = \sqrt{3}\,a$

$$\text{APF} = \frac{2 \cdot \frac{4}{3}\pi\left(\sqrt{3}a/4\right)^3}{a^3}$$

atoms / unit cell → 2

volume / atom → $\frac{4}{3}\pi\left(\sqrt{3}a/4\right)^3$

volume / unit cell → a^3

Adapted from
Fig. 3.2(a), *Callister 7e.*

Atomic Packing Factor: BCC

$$APF = \frac{\text{Volume of atoms in unit cell*}}{\text{Volume of unit cell}}$$

*assume hard spheres

$$APF = \frac{2\left(\frac{4}{3}\pi r^3\right)}{a^3}, \quad r = \frac{\sqrt{3}}{4}a$$

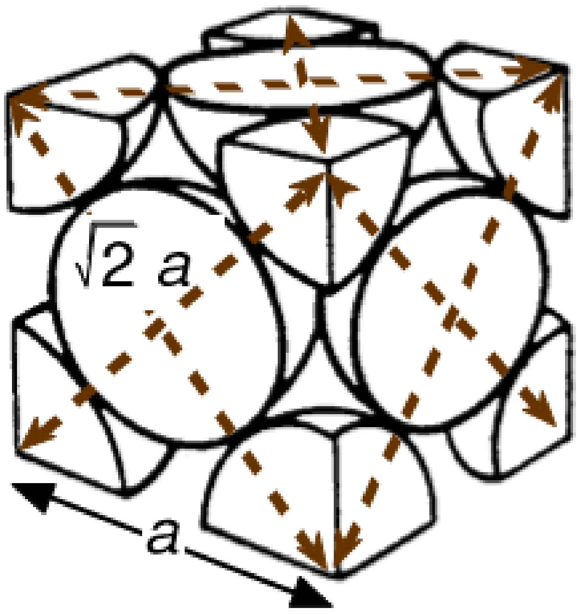
$$APF = \frac{2\left(\frac{4}{3}\pi\left(\frac{\sqrt{3}}{4}a\right)^3\right)}{a^3}$$

$$APF = 2\,\frac{4}{3}\pi\,\frac{3\sqrt{3}a^3}{64}$$

$$APF = \frac{\pi\sqrt{3}}{8}$$

$$APF = 0.68$$

Atomic Packing Factor: FCC



The atoms touch one another across a face-diagonal, the length of this is 4R

$$a^2 + a^2 = (4R)^2$$

$$2a^2 = 16R^2$$

$$a = 2\sqrt{2}R$$

Volume of the unit cell

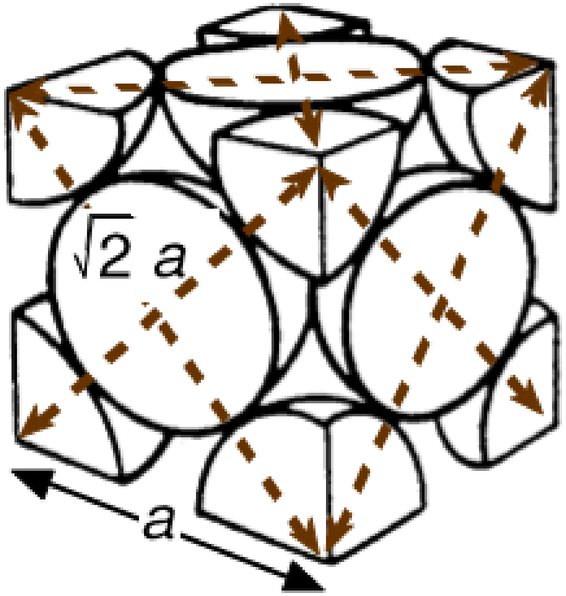
$$V_c = a^3 = \left(2\sqrt{2}R\right)^3 = 16\sqrt{2}R^3$$

Adapted from Fig. 3.1(a), *Callister 7e.*

Atomic Packing Factor: FCC

- APF for a face-centered cubic structure = 0.74

maximum achievable APF



Close-packed directions:

length = $4R = \sqrt{2}\,a$

Unit cell contains:

$6 \times 1/2 + 8 \times 1/8$

= 4 atoms/unit cell

$$\text{APF} = \frac{4 \;\; \frac{4}{3}\pi(\sqrt{2}a/4)^3}{a^3}$$

atoms / unit cell → 4

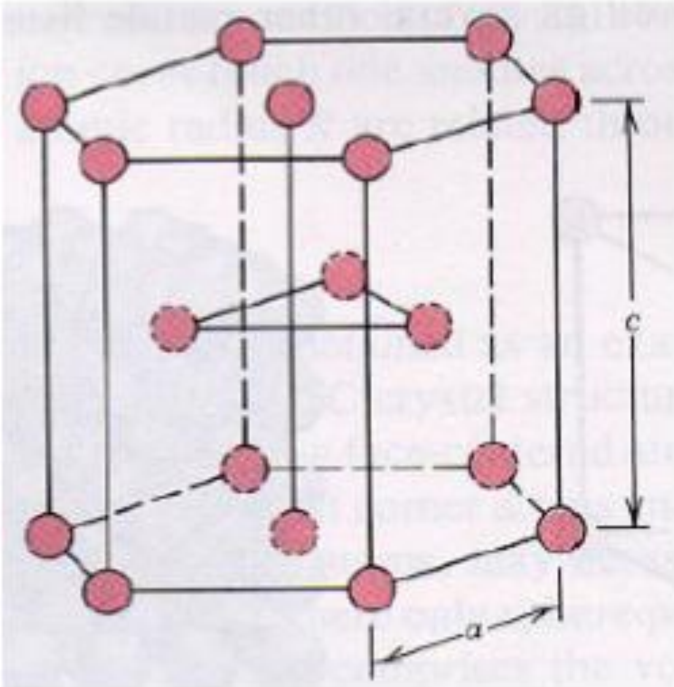
volume / atom → $\frac{4}{3}\pi(\sqrt{2}a/4)^3$

volume / unit cell → a^3

Adapted from Fig. 3.1(a), *Callister 7e.*

Hexagonal Closed Packed (HCP)

- Two lattice parameters: a and c, representing the basal and height parameters respectively.
- The ideal c/a ratio is 1.633.
- Number of atoms per unit cell (N) = 6 atoms.
- Atomic packing factor is 0.74
- Coordination number (CN) = 12.



N =# corner atoms +# central atoms +# face center atoms

$$N = 2\left(6x\frac{1}{6}\right) + 3x1 + \left(2x\frac{1}{2}\right)$$

N = 6 atoms / unit cell

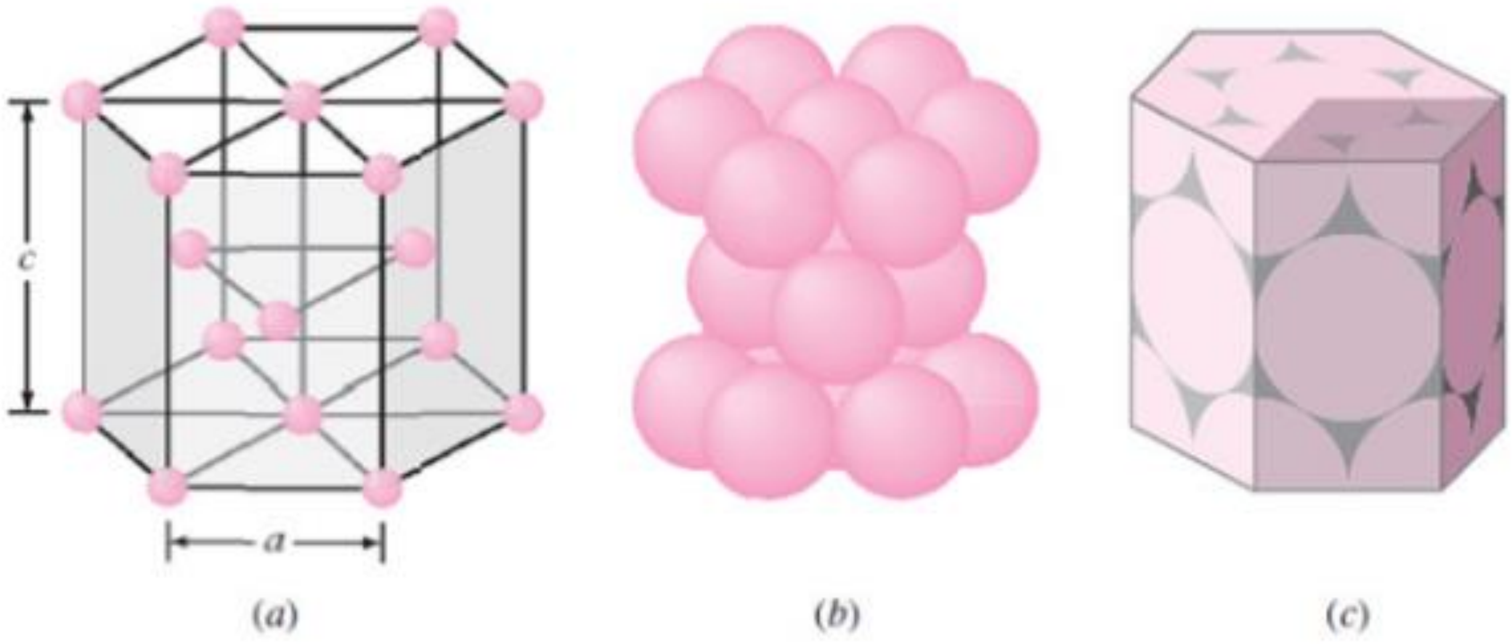


Figure 3.8
HCP unit cells: (*a*) atomic-site unit cell, (*b*) hard-sphere unit cell, and (*c*) isolated unit cell.
[*(b) and (c) After F. M. Miller, "Chemistry: Structure and Dynamics," McGraw-Hill, 1984, p. 296.*]

Video

Show how to calculate the APF for the HCP?

Hexagonal Closed Packed (HCP)

Table 3.4 Selected Metals That Have the HCP Crystal Structure at Room Temperature (20°C) and Their Lattice Constants, Atomic Radii, and *c/a* Ratios

Metal	Lattice constants (nm)		Atomic radius *R* (nm)	*c/a* ratio	% deviation from ideality
	a	*c*			
Cadmium	0.2973	0.5618	0.149	1.890	+15.7
Zinc	0.2665	0.4947	0.133	1.856	+13.6
Ideal HCP				1.633	0
Magnesium	0.3209	0.5209	0.160	1.623	−0.66
Cobalt	0.2507	0.4069	0.125	1.623	−0.66
Zirconium	0.3231	0.5148	0.160	1.593	−2.45
Titanium	0.2950	0.4683	0.147	1.587	−2.81
Beryllium	0.2286	0.3584	0.113	1.568	−3.98

Crystal structure

Atomic Radii and Crystal Structures for 16 Metals

Metal	*Crystal Structure*[a]	*Atomic Radius*[b] *(nm)*	*Metal*	*Crystal Structure*	*Atomic Radius (nm)*
Aluminum	FCC	0.1431	Molybdenum	BCC	0.1363
Cadmium	HCP	0.1490	Nickel	FCC	0.1246
Chromium	BCC	0.1249	Platinum	FCC	0.1387
Cobalt	HCP	0.1253	Silver	FCC	0.1445
Copper	FCC	0.1278	Tantalum	BCC	0.1430
Gold	FCC	0.1442	Titanium (α)	HCP	0.1445
Iron (α)	BCC	0.1241	Tungsten	BCC	0.1371
Lead	FCC	0.1750	Zinc	HCP	0.1332

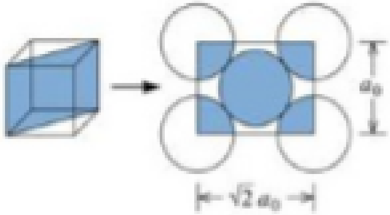
[a] FCC = face-centered cubic; HCP = hexagonal close-packed; BCC = body-centered cubic.

[b] A nanometer (nm) equals 10^{-9} m; to convert from nanometers to angstrom units (Å), multiply the nanometer value by 10.

Crystal structure

Unit cell	No. atoms / unit cell	Coordination number	A.P.F.	Stacking sequence	r = f(a)
Simple cubic , **SC**	1	6	0.52		0.5a
Body centered cubic, **BCC**	2	8	0.68	*	$\frac{\sqrt{3}}{4}a$
Face centered cubic , **FCC**	4	12	0.74	ABCABC..	$\frac{\sqrt{2}}{4}a$
Hex. closed packed , **HCP**	6	12	0.74	ABAB….	

*The 3-D build up of the crystal is formed by stacking a series of the (110) – the most dense packed plane



Crystal structure

The physical properties of single crystals of some substances depend on the crystallographic direction in which measurements are taken. For example, the elastic modulus and electrical conductivity have different values in the (100) and (111) directions.

	Modulus of Elasticity (GPa)		
Metal	*[100]*	*[110]*	*[111]*
Aluminum	63.7	72.6	76.1
Copper	66.7	130.3	191.1
Iron	125.0	210.5	272.7
Tungsten	384.6	384.6	384.6

Modulus of Elasticity Values for Several Metals at Various Crystallographic Orientations

Furthermore, the magnetic properties of some iron alloys used in transformer cores, magnetize in a (100) type direction easier than any other crystallographic directions. Energy losses in transformer cores are minimized by utilizing polycrystalline sheets of these alloys (most of the grains in each sheet have a (100) type); these sheets aligned in a direction parallel to the direction of the applied magnetic field.

 66

Crystalline structure

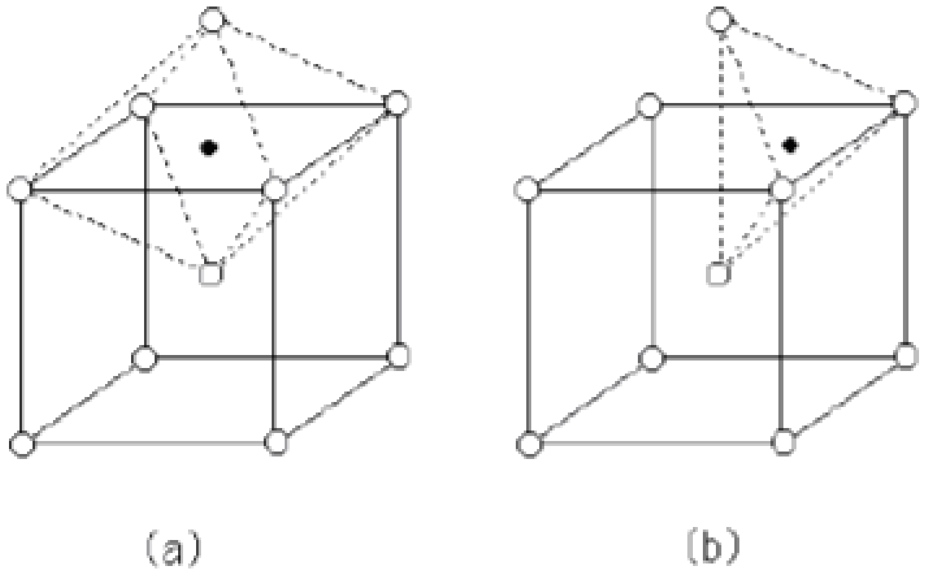
Interstitial sites

•In the study of the crystal structure of pure metal, we use the **hard sphere model**, all the atoms have been spheres of uniform diameter.

•In all crystal structure (SC, BCC, FCC) build up, there is a gap or interstics between the uniform spheres.

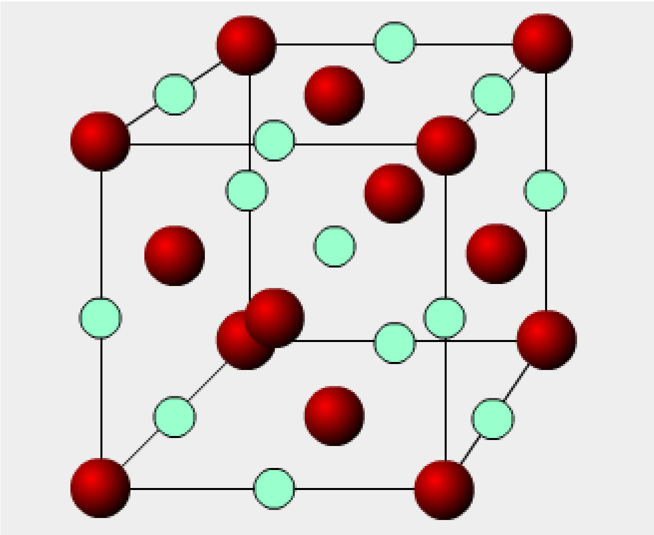
•Smaller diameter atoms or ions can fit in this gap.

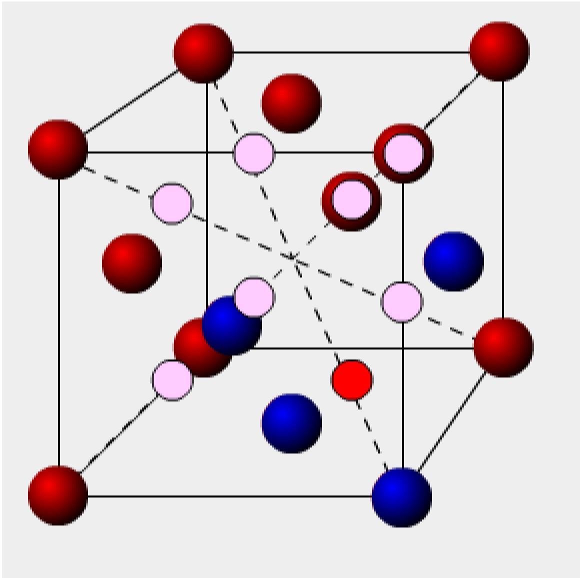
Interstitial sites



The two interstitial sites (a) octahedral and (b) tetrahedral

Interstitial sites in FCC





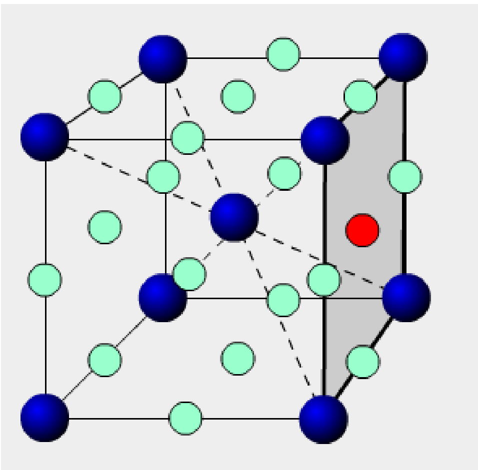
There is one octahedral site at the centre of the FCC cell (½,½,½) and one on each of the twelve cell edges (½,0,0).

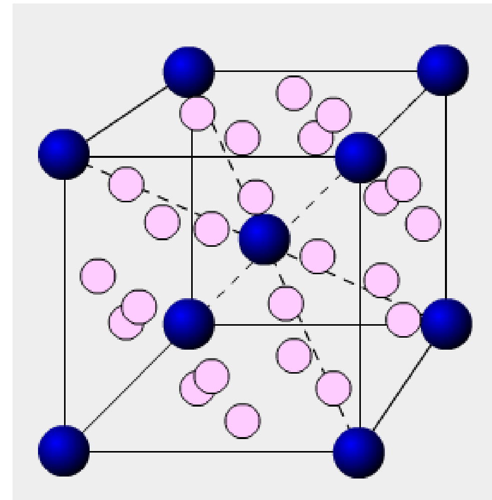
There are eight tetrahedral sites in the FCC unit cell.

13

8

Interstitial sites in BCC





There is one octahedral site on each of the six BCC cell faces and one on each of the twelve cell edges.

There are four tetrahedral sites on each of the six BCC cell faces.

18

24

Try to find the position of the interstitial sites for the HCP?

Answer: 6 octahedral
8 tetrahedral

Density Computation

- A knowledge of the crystal structure of a metallic solid permits computation of its theoretical density ρ through the relationship

$$\rho = \frac{nA}{V_c N_A}$$

Watch the units ↓

$$\rho = \frac{atom}{unit.cell}\frac{g}{mol}\frac{unit.cell}{volume}\frac{mol}{atom}$$

Where:

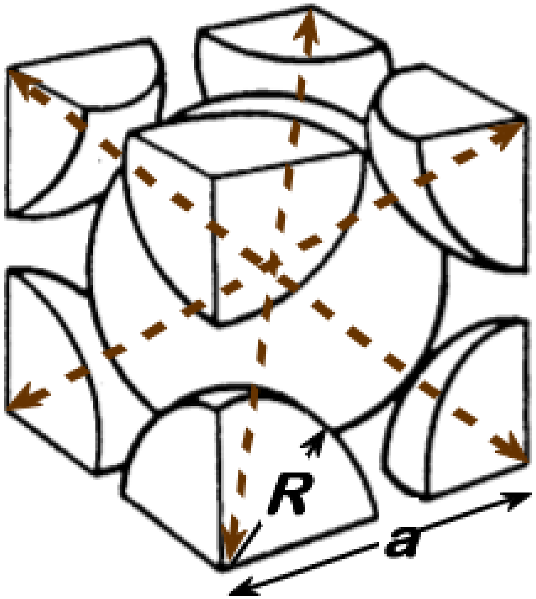
n: number of atoms associated with each unit cell

A: atomic weight

V_C: volume of the unit cell

N_A: Avogadro's number (6.023×10^{23} atoms/mol)

Theoretical Density, ρ



- Ex: Cr (BCC)

  $A = 52.00$ g/mol

  $R = 0.125$ nm

  $n = 2$

  $a = 4R/\sqrt{3} = 0.2887$ nm

$$\rho = \frac{2 \cdot 52.00}{a^3 \cdot 6.023 \times 10^{23}}$$

- 2: $\frac{\text{atoms}}{\text{unit cell}}$
- 52.00: $\frac{\text{g}}{\text{mol}}$
- a^3: $\frac{\text{volume}}{\text{unit cell}}$
- 6.023×10^{23}: $\frac{\text{atoms}}{\text{mol}}$

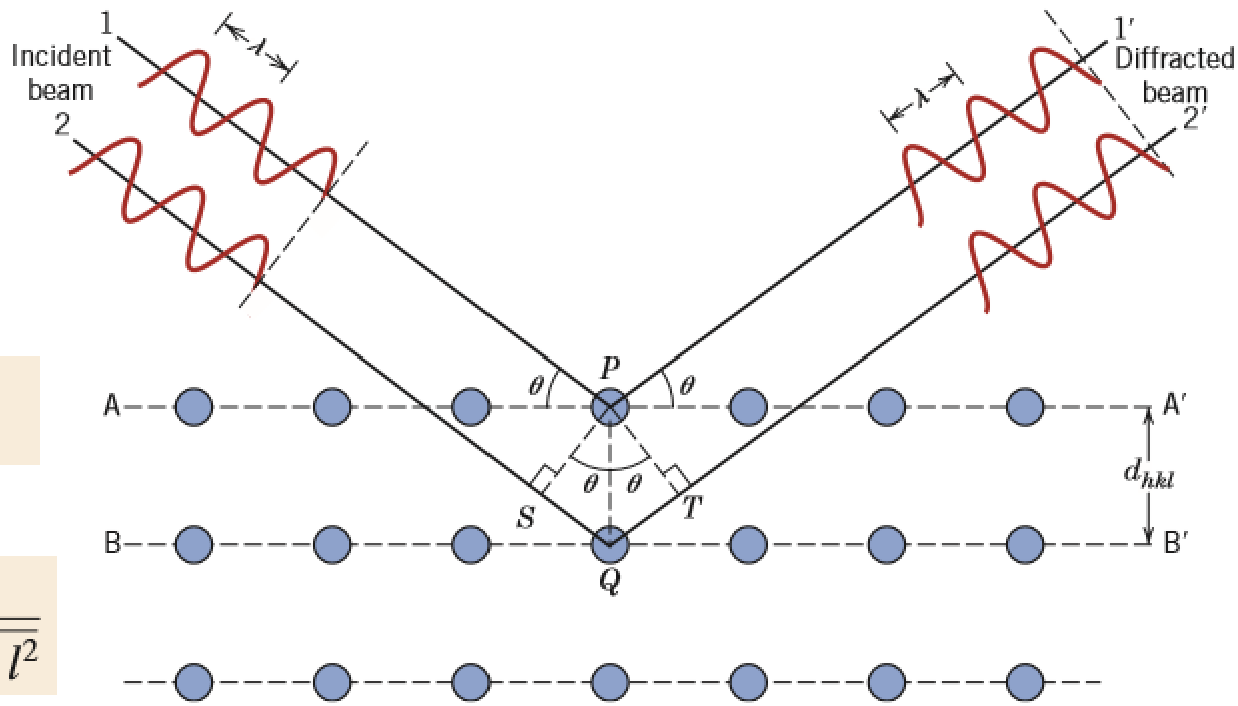
$\rho_{theoretical}$ = 7.18 g/cm^3

ρ_{actual} = 7.19 g/cm^3

Determination of crystal structure

- X-ray is electromagnetic radiation with high energy and short wave length.
- X-ray diffraction is used to determine the crystal structure.
- When a beam of x-rays impinges on a solid material, a portion of this beam will be scattered in all directions by the electrons associated with each atom

Figure 3.19
Diffraction of x-rays by planes of atoms (A–A′ and B–B′).



Braggs law

$$n\lambda = 2d_{hkl}\sin\theta$$

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

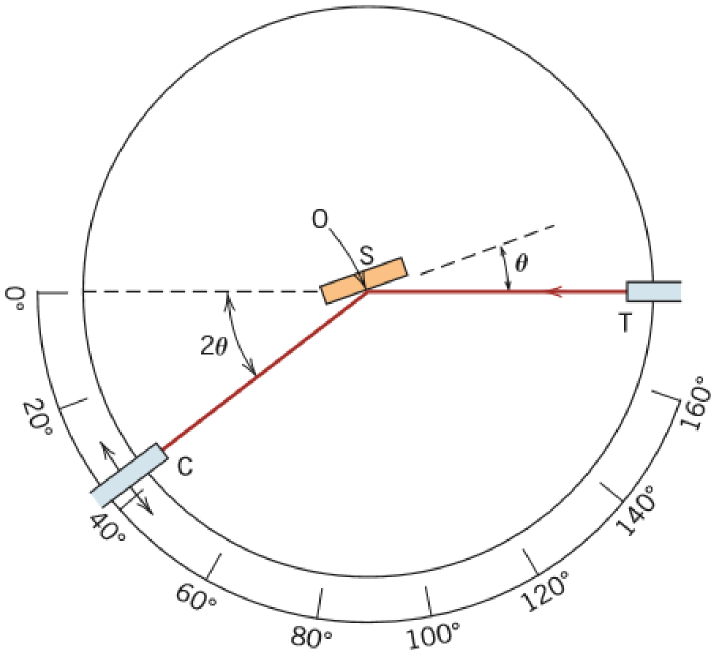


Figure 3.20 Schematic diagram of an x-ray diffractometer; T = x-ray source, S = specimen, C = detector, and O = the axis around which the specimen and detector rotate.

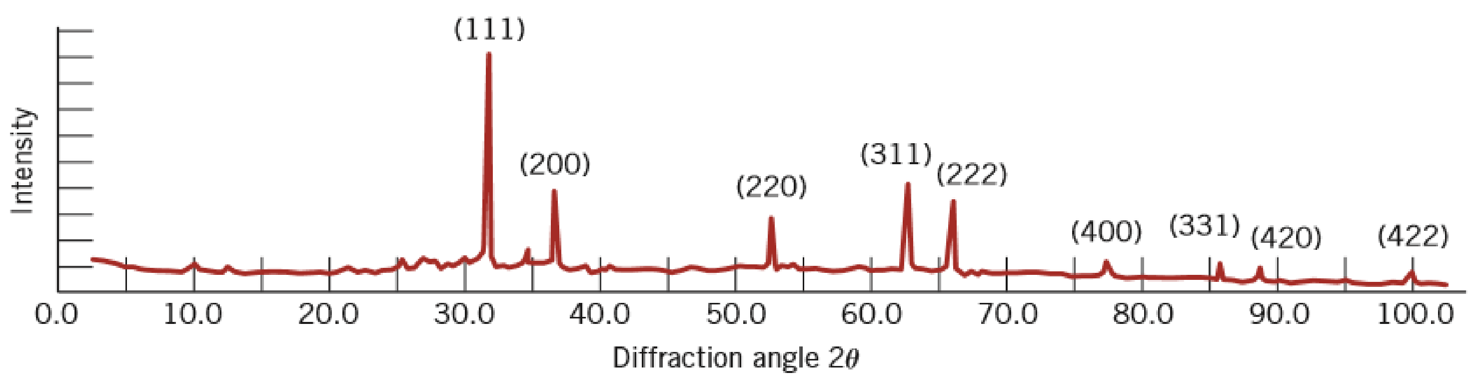
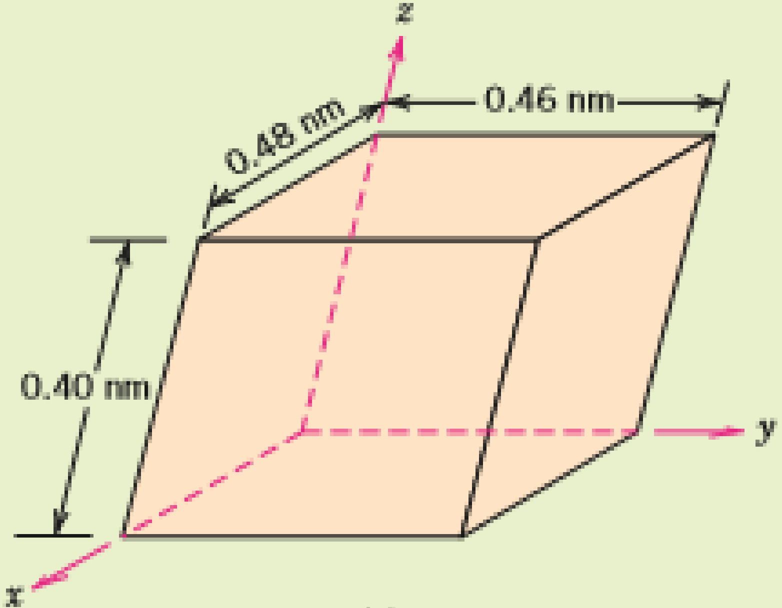


Figure 3.21 Diffraction pattern for powdered lead. (Courtesy of Wesley L. Holman.)

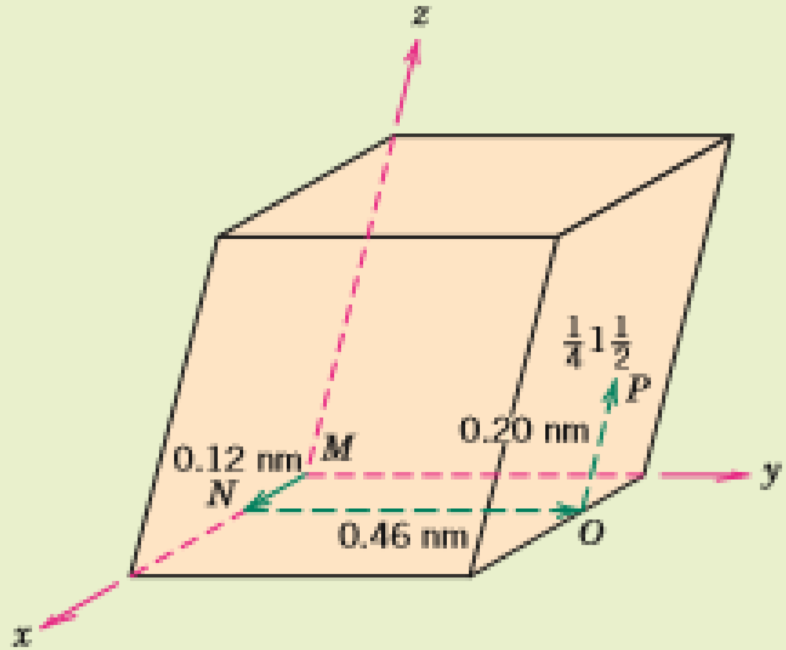
Some Revision exercises

Location of Point Having Specified Coordinates

For the unit cell shown in the accompanying sketch (*a*), locate the point having coordinates $\frac{1}{4}\ 1\ \frac{1}{2}$.



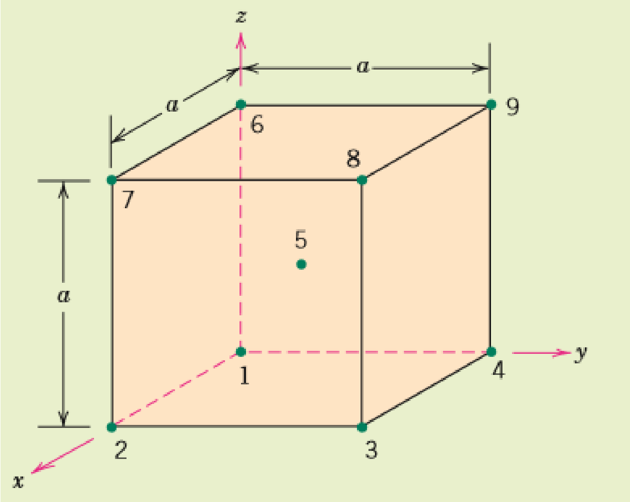
(*a*)



(*b*)

Specification of Point Coordinates

Specify point coordinates for all atom positions for a BCC unit cell.



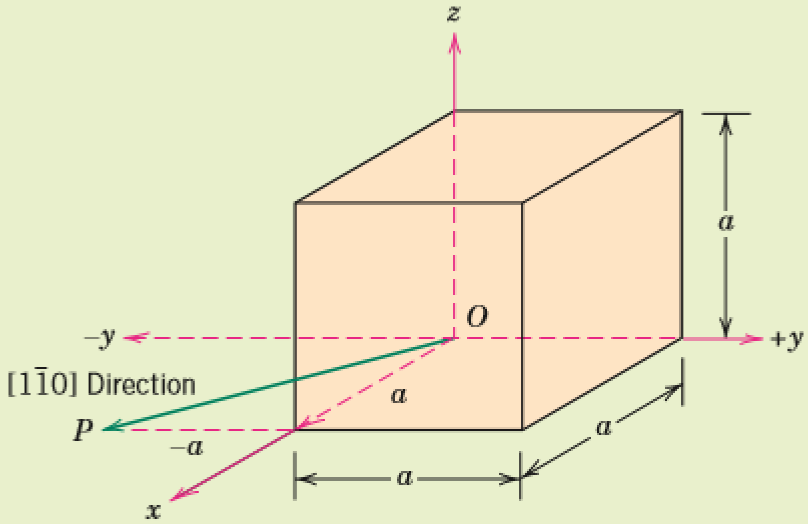
Point Number	Fractional Lengths x axis	y axis	z axis	Point Coordinates
1	0	0	0	0 0 0
2	1	0	0	1 0 0
3	1	1	0	1 1 0
4	0	1	0	0 1 0
5	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}\frac{1}{2}\frac{1}{2}$
6	0	0	1	0 0 1
7	1	0	1	1 0 1
8	1	1	1	1 1 1
9	0	1	1	0 1 1

Construction of Specified Crystallographic Direction

Draw a $[1\bar{1}0]$ direction within a cubic unit cell.

Solution

First construct an appropriate unit cell and coordinate axes system. In the accompanying figure the unit cell is cubic, and the origin of the coordinate system, point O, is located at one of the cube corners.



Crystallographic directions

Vector 1:

Start: 0, 0, 0

End: ½, 1, ½

End – Start = ½, 1, ½

[121]

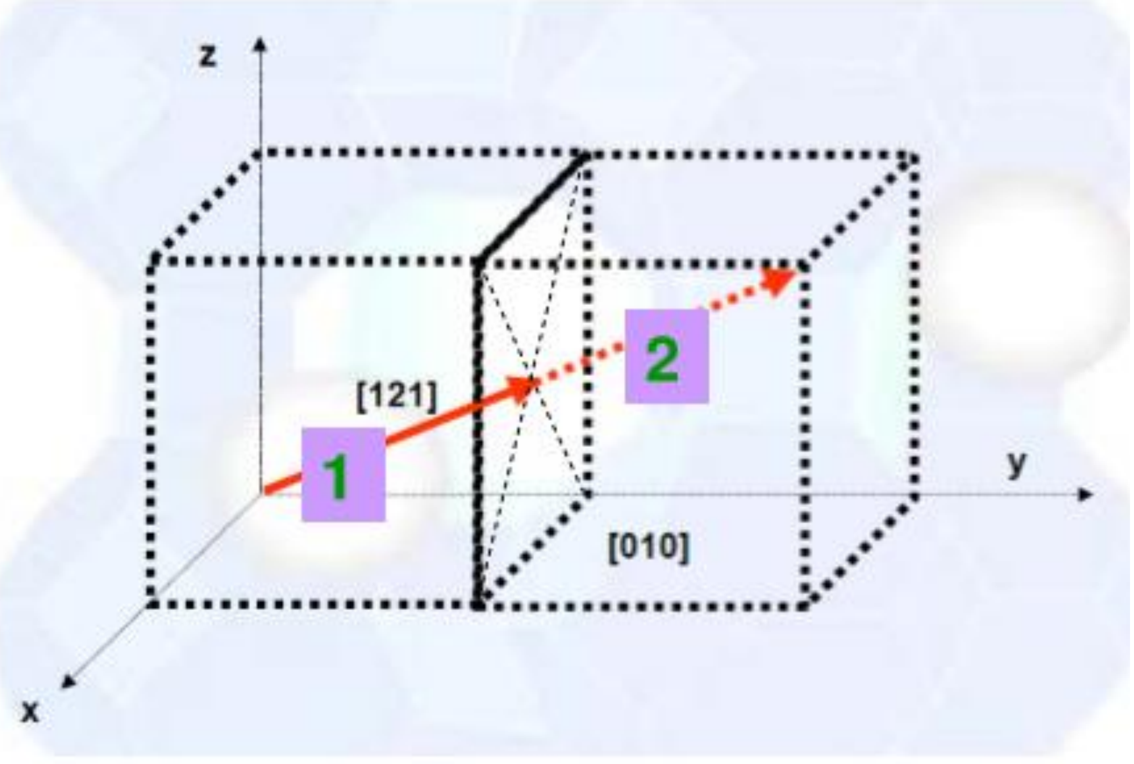
Vector 2:

Start: ½, 1, ½

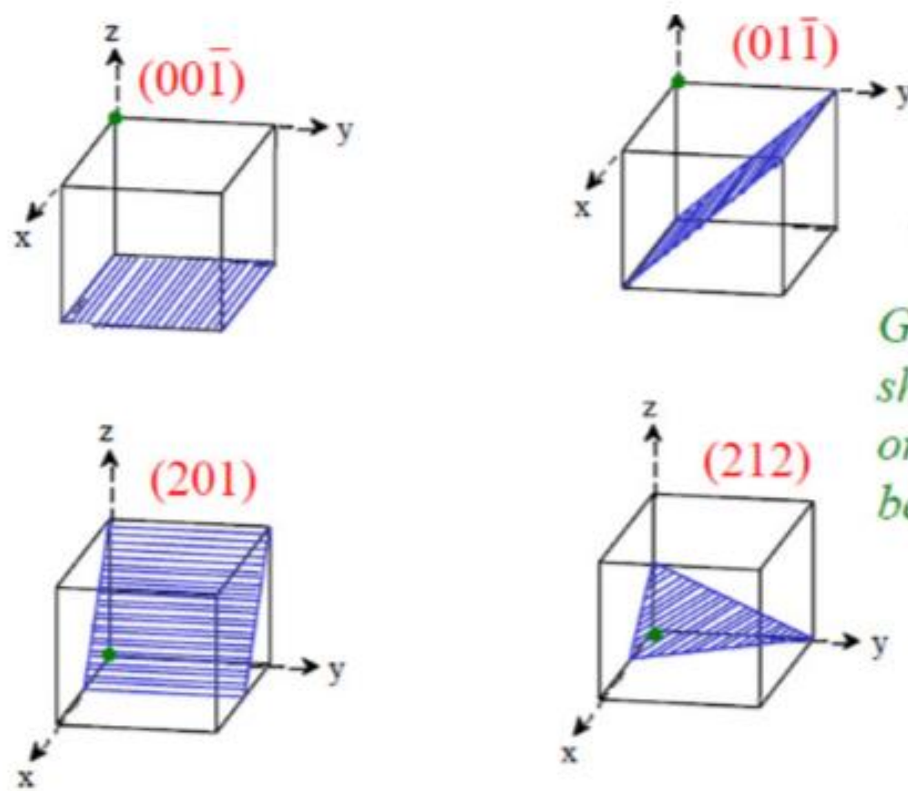
End: 1, 2, 1

End – Start =½, 1, ½

[121]



Crystallographic planes



Green circles show where the origins have been placed.

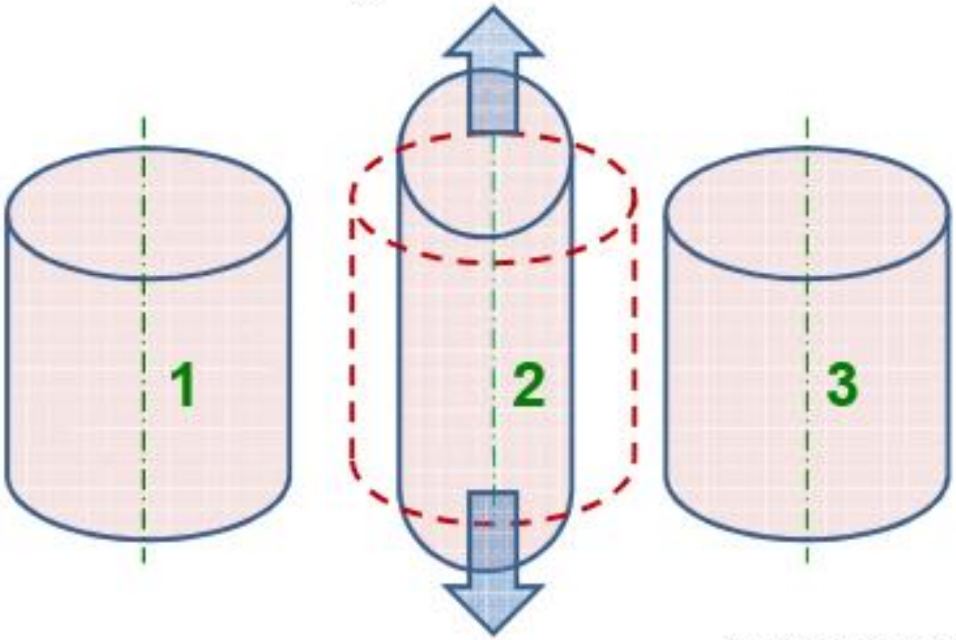
Chapter 3: Elastic Behavior

Learning objectives

- Understand the concept of stress and strain.
- Know the difference between direct and shear stresses, and strains.
- Be able to calculate the stress within a material of given dimensions for a specified external forces.
- Understand the development of thermally induced stresses within materials.

What is elasticity?

- When a solid material is subject to a (load) stress the material will change its shape in response to that stress.
- This response (deformation) may be ***elastic*** or ***plastic***.
- Elastic deformation: when the stress is removed, the material returns to its original dimensions.



(1) The instant just after the application of the load (the original shape of the bar)

(2) After the application of the load (the bar is elongated)

(3) After removing the load (the bar returns to its original dimension)

Elasticity among materials

- Many materials, including ceramics, glasses and many thermosetting polymers[1], exhibit elasticity at all levels of stress up to their fracture stress.
- Metals and alloys are elastic up to a certain level, after which they deform plastically. When the stress is removed the elastic portion of the deformation is recovered but any plastic deformation remains (permanent change in shape and dimensions).

(1) Thermosetting plastics can melt and take shape once; after they have solidified, they stay solid. They can't be recycled.

Thermoplastic material behavior

- Thermoplastic materials: plastic that can be remodeled when heated and hardened in that position when cooled .
- It have little true elasticity but show the property of viscoleasiticy in which much of the deformation is not completely recovered after the removal of deforming stress.

Elasticity among materials

Table 1: Various materials behave differently upon the application of load.

Material category	Response to applied load
Ceramics	Same behavior up to fracture stress (no plastic deformation)
Glasses	Same behavior up to fracture stress (no plastic deformation)
Thermoset plastic	Same behavior up to fracture stress
Metals and alloys	Elastic and then plastic Elastic can be recovered Plastic portion remains
Thermoplastic material	Viscoelastic behavior Deformation is not completely recovered

Stress

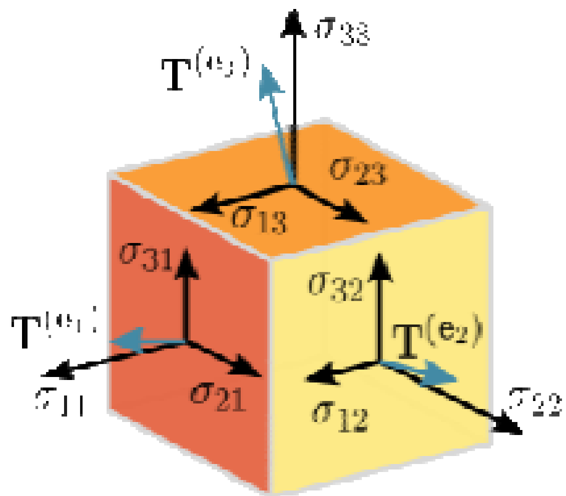
- **Stress:** the internally acting force that is developed within the material as a response to an applied load.
- The stress acting upon a material is defined as the force exerted per unit area.
- There are different type of stress:
  - Tensile stress
  - Compressive stress
  - Shear stress

Strain

- **Strain**: is the dimensional change caused by stress.
- In direct tension or compression the strain is the ratio of the change in length to the original length.
- Strain has no units (dimensionless) and is simply a numerical value.

Elastic material characteristics

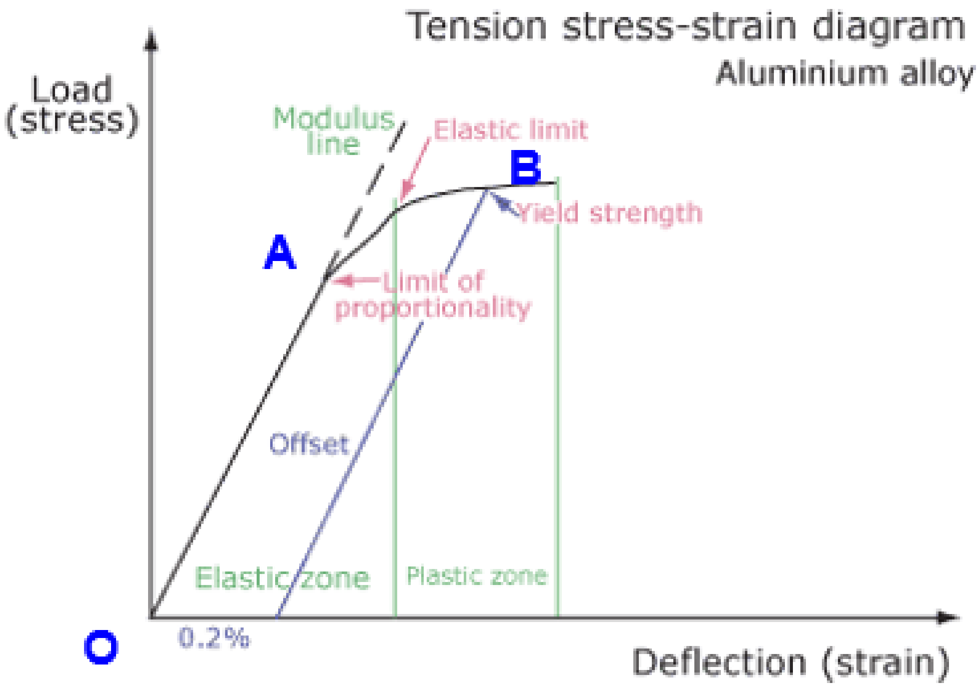
- Strain (amount of deformation) is directly proportional to the stress producing it.
- Ratio of stress to strain will be a constant for the material.
- Each material have several elastic constants, depending on the type of stress system applied.



Elasticity in metals

- **Metals** and **alloys** exhibit both elasticity and plasticity.
- **Yield stress, or elastic limit (σ_y):** the stress level above which the material will change its response to applied stress from elastic to plastic.
- For $\sigma < \sigma_y$: material is elastic, it will return to its original dimension after the load is removed (strain is recovered).
- For $\sigma > \sigma_y$: material is plastic, it will not return to its original dimension after the load is removed (strain is non-recoverable - plastic portion of the strain).

Hooke's law[1]



Force extension diagram

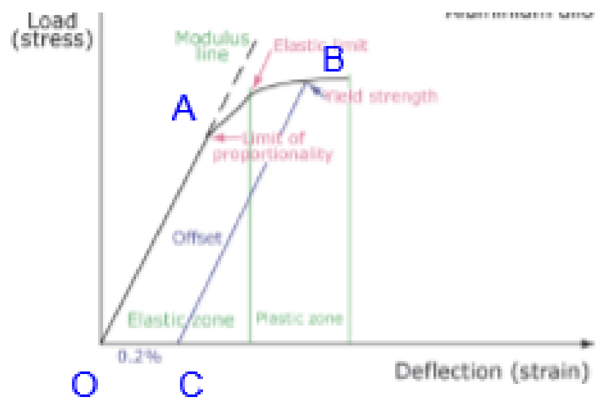
$$\sigma = E\varepsilon$$

- Strain developed in a material is directly proportional to the stress producing it.

(1) Robert Hooke, in 1678, developed his law

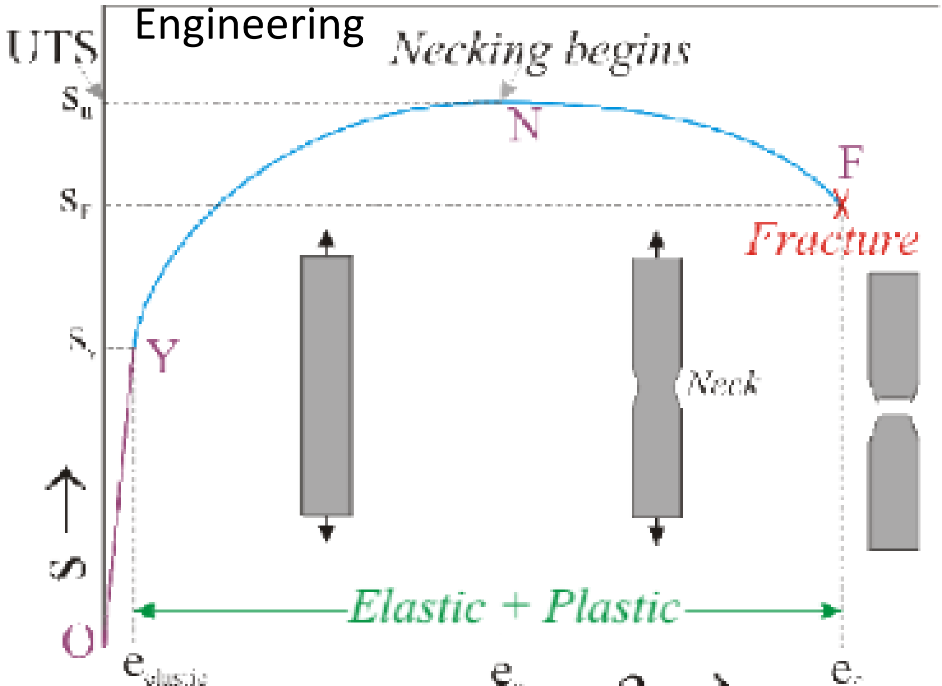
Hooke's law

- OA:
  - The length of the specimen increases in direct proportion to the applied load.
  - Strain will be proportional to stress.
  - Hooke's law is valid (linear).
  - Material is elastic.
  - Uniform deformation.
- Point A: elastic limit or limit of proportionality
- A-B:
  - Hooke's law is not valid (non linear)
  - Not Elastic
  - Not Uniform,



This discontinuity in the load-extension curve as indicated by the yield point dose not appear in most metals. In such circumstances the proof stress or offset yield stress is used.

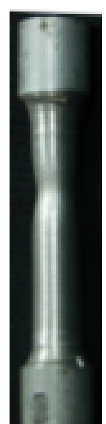
Schematic s-e and σ-ε curves (s-e: Engineering; σ-ε: True)

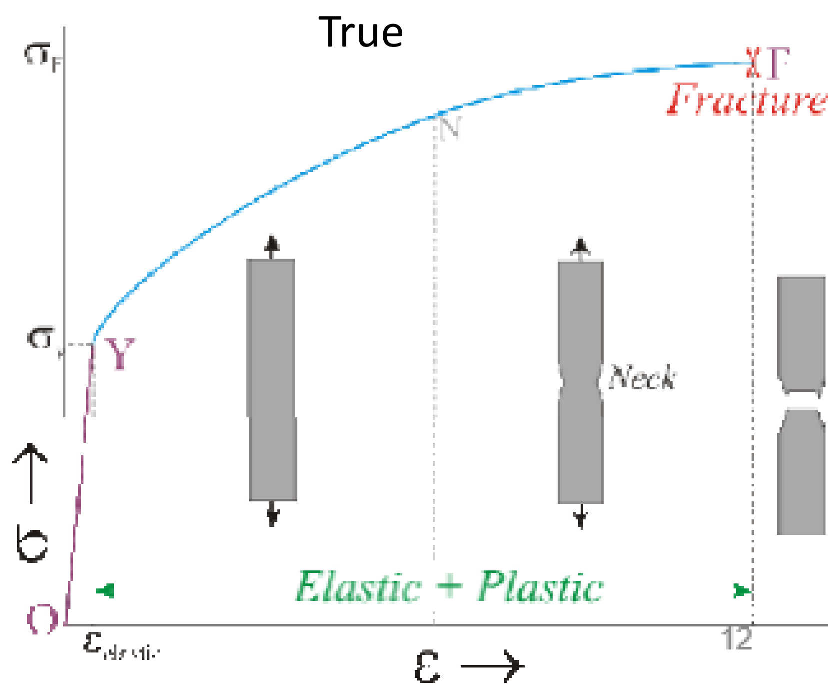


- These are simplified schematics which are close to the curves obtained for some metallic materials like Al, Cu etc. (polycrystalline materials at room temperature).
- Many materials (e.g. steel) may have curves which are qualitatively very different from these schematics.

Information gained from the test:
(i) Young's modulus
(ii) Yield stress (or proof stress)
(iii) Ultimate Tensile Stress (UTS)
(iv) Fracture stress

UTS- Ultimate Tensile Strength
Subscripts: y- yield, F,- fracture,
u- uniform (for strain)/ultimate (for stress)





What happens after necking?

Following factors come in to picture due to necking:

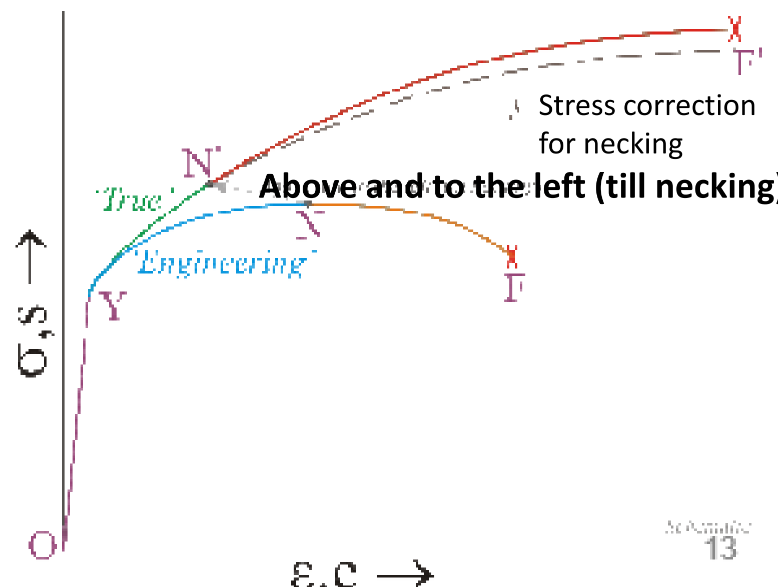
- Till necking the deformation is ~uniform along the whole gauge length.
- Till necking points on the σ-ε plot lie to the left and higher than the s-e plot (as below).
- After the onset of necking deformation is localized around the neck region.
- Formulae used for conversion of 'e' to 'ε' and 's' to 'σ' cannot be used after the onset of necking. $\sigma = s(1+e)$ $\varepsilon = \ln(1+e)$
- Necking can be considered as an instability in tension.

$$\text{Eng. stress}(s) = \frac{\text{Applied load (P)}}{\text{Original cross section }(A_0)}\ \text{N/m}^2$$

$$\text{Eng. strain}(e) = \frac{\text{Extension }(\Delta L)}{\text{Original length }(L_0)}$$

$$\text{True stress}(\sigma_i) = \frac{\text{Applied load (P)}}{\text{Instantanous cross section }(A_i)}\ \text{N/m}^2$$

$$\text{True strain}(\varepsilon_i) = \frac{\text{Instantaneous change in length}(L_i)}{\text{Original gauge length}(L_0)}$$



Stress

- For a force of 10 newton acting on a surface of 10 mm square, the stress is

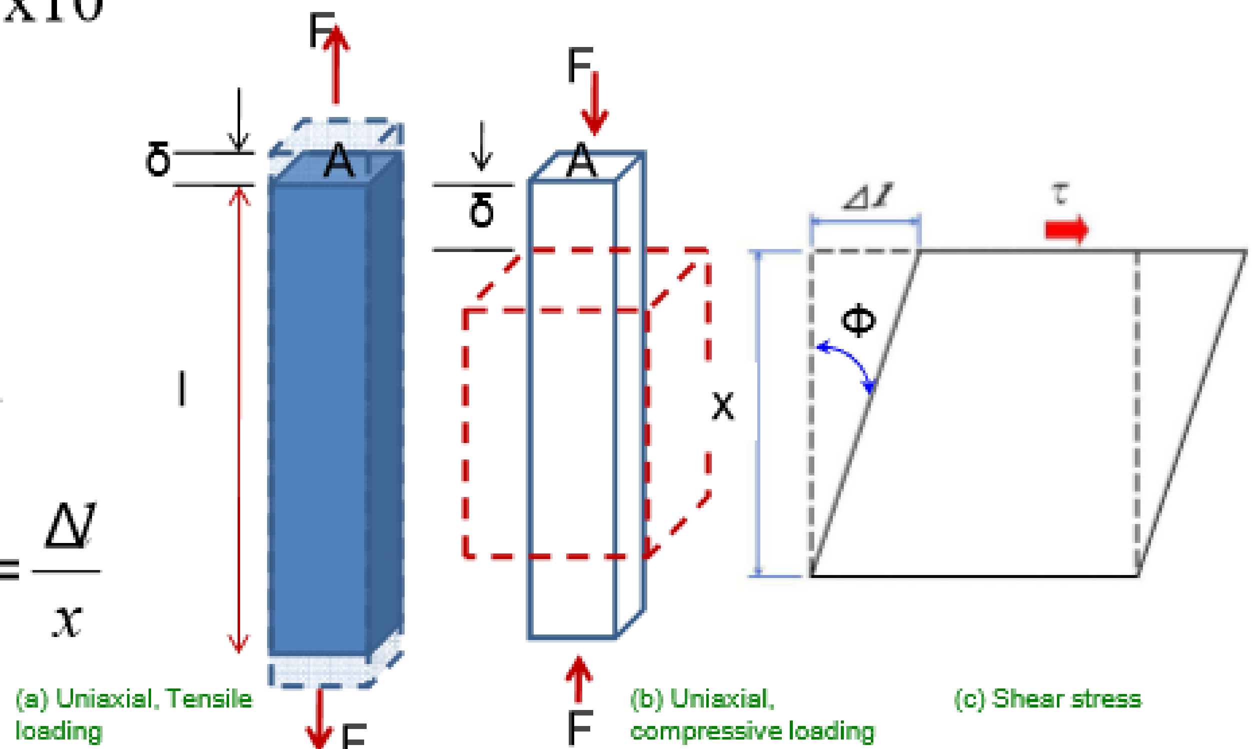
$$\frac{force}{area} = \frac{10}{10x10x10^{-6}} = 10^5 \,\text{newton/meter}^2 = 10^5 \,\text{pascal (Pa)}$$

(a) $\sigma = \frac{F}{A}, \varepsilon = \frac{\delta}{l}$

(b) $\sigma = -\frac{F}{A}, \varepsilon = -\frac{\delta}{l}$

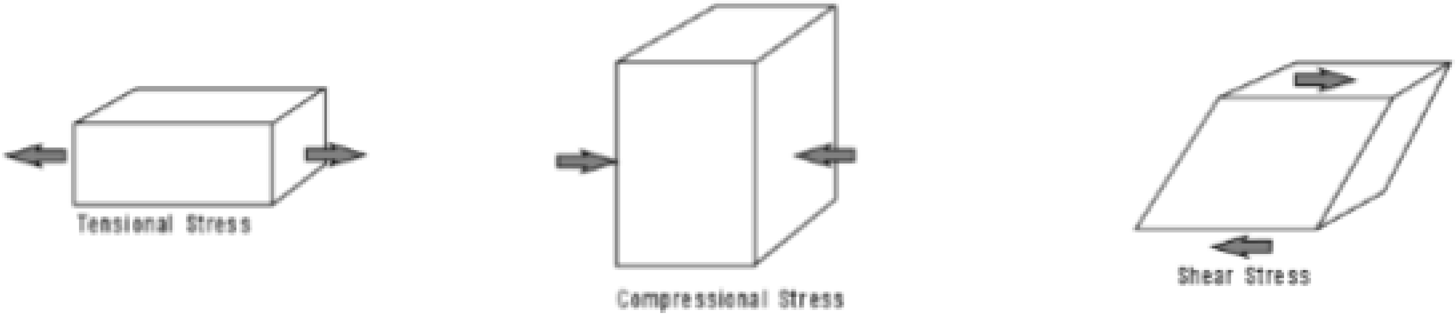
(c) $\tau = \frac{F}{A}, \gamma = \tan\varphi = \frac{\Delta l}{x}$

Angle of twist



Stress, type of stresses

- **Direct stresses:** tensile and compressive stress.
  - Tensile stress: cause an extension of the length of the material.
  - Compressive stress: shorten the length.
- **Shear stress**: imparts a twist to the material.



Stress and strain, symbols

- **L**: Length of the bar
- **A**: Cross sectional area of the bar
- F: Applied force (tensile, compressive, shear)
- **δL**: Elongation (increase in length) or shortening (reduction in length)
- **σ**: Direct stress developed in the material due to the applied load.
- ε: Developed strain in the material
- φ: Twist angle results from the action of a shear force
- τ: Shear stress developed due to the applied shear force
- γ: Shear strain developed in the material

Stress and strain, calculations

Tensile :

$$\sigma = \frac{F}{A}, \varepsilon = \frac{\delta}{l}$$

Compression :

$$\sigma = -\frac{F}{A}, \varepsilon = -\frac{\delta}{l}$$

Shear :

$$\tau = \frac{F}{A}$$

$$\gamma = \tan \varphi$$

Stress and strain signs:

(+ve) for tensile

(-ve) for compression

Elastic constants

I. Modulus of elasticity (young's modulus), (***E***)

II. Modulus of rigidity, (***G***)

III. Bulk modulus of elasticity, (***K***)

IV. Poisson ratio , (ν)

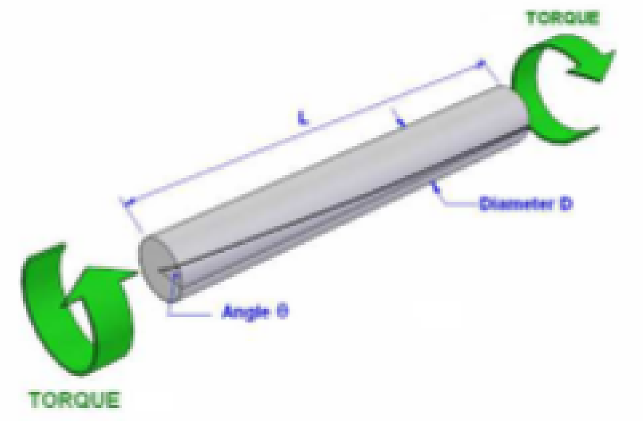
Modulus of elasticity, E

- Modulus of elasticity, or young's modulus, E
- Measure of the stiffness of a material
- Has the dimension of stress (Pa or N/m^2)
- Can be determined in a tensile or compressive stress test
- For an elastic materials, one that obeys Hooke's law

$$\frac{\text{Direct stress } (\sigma)}{\text{Direct strain } (\varepsilon)} = E \text{ (a constant for the material)}$$

Modulus of rigidity (G)

- Ratio of the shear stress and shear strain within elastic limit
- May be determined from the result of the torsion test.



$$\frac{\text{Shear stress } (\tau)}{\text{Shear strain } (\gamma)} = G \text{ (a constant for the material)}$$

Bulk modulus of elasticity (K)

- The elastic response of the material to equilateral tension or compression.
- It is a measure of the substances resistance for uniform compression.
- It is defined as the pressure increase needed to cause a given relative decrease in volume.

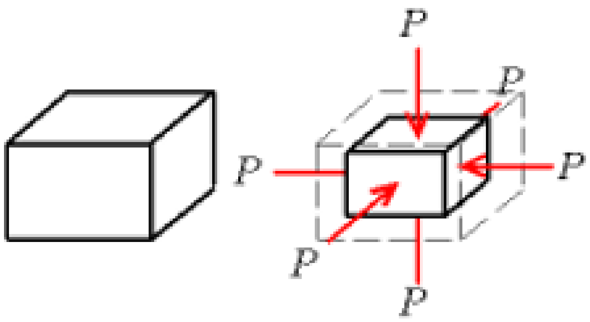
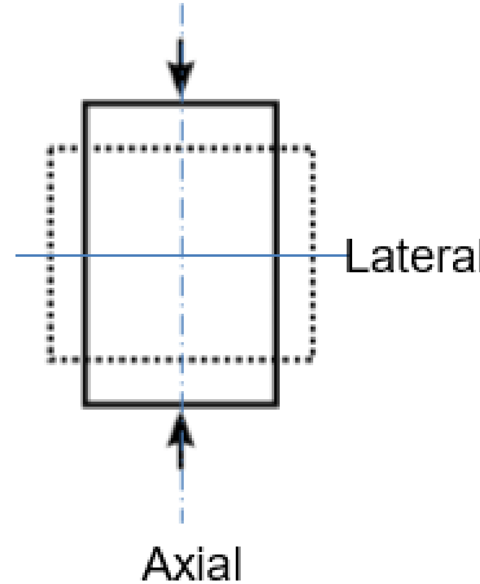


Illustration of uniform compression

$$\frac{\text{Stress}}{\text{Volume strain}} = K$$

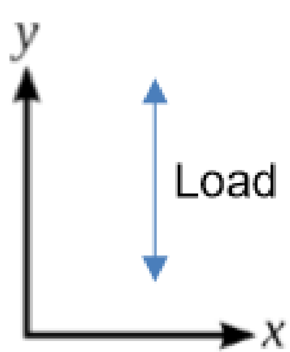
Poisson's ratio (ν)

If a material is subjected to a direct longitudinal stress, a longitudinal strain will be developed extending the length of the specimen. This will be accompanied by certain lateral contraction, compensating for the increase in length.



Rectangular specimen subject to compression, with Poisson's ratio 0.5

For many materials, ν = 0.28 -0.35



$$\frac{\text{Lateral strain}}{\text{Axial strain}} = \nu$$

$$-\frac{\varepsilon_x}{\varepsilon_y} = -\frac{\varepsilon_{transverse}}{\varepsilon_{axial}} = \nu$$

Elastic constants relationship

$$G = \frac{E}{2(1+\nu)} \quad \text{or} \quad \mathrm{E} = 2\mathrm{G}(1+\nu)$$

$$K = \frac{E}{3(1-2\nu)} \quad \text{or} \quad \mathrm{E} = 3\mathrm{K}(1-2\nu)$$

Example 7.2

Given that E for aluminum is 70.5 GPa, and Poisson's ratio (ν) is 0.34, estimate the value of G for aluminum.

SOLUTION

The relationship between E, G, and ν is

E=2G(1+ν)

Solve for G:

$$G = \frac{70.5\text{x}10^9}{2(1+0.34)}$$

$$G = 26.3\text{x}10^9\,Pa = 26.3\text{GPa}$$

Ductility

- The degree of plastic deformation that has been sustained at fracture.

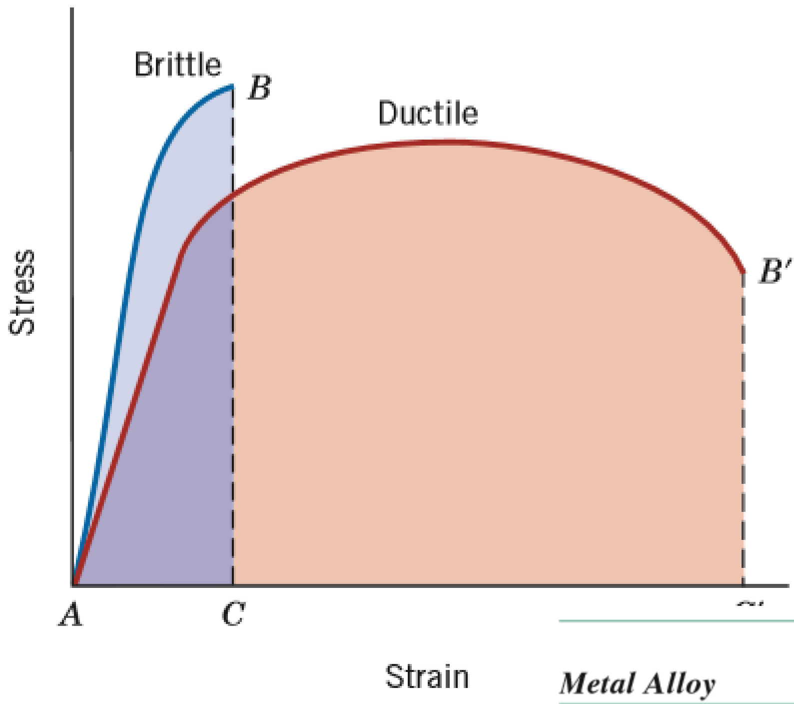


Figure 6.13 Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.

$$\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

Reduction in Area

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

Percent elongation

Metal Alloy	*Yield Strength MPa (ksi)*	*Tensile Strength MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

Example

Ductility and True-Stress-At-Fracture Computations

A cylindrical specimen of steel having an original diameter of 12.8 mm (0.505 in.) is tensile tested to fracture and found to have an engineering fracture strength σ_f of 460 MPa (67,000 psi). If its cross-sectional diameter at fracture is 10.7 mm (0.422 in.), determine:

(a) The ductility in terms of percent reduction in area

(b) The true stress at fracture

Solution

(a) Ductility is computed using Equation 6.12, as

$$\%RA = \frac{\left(\frac{12.8\text{ mm}}{2}\right)^2\pi - \left(\frac{10.7\text{ mm}}{2}\right)^2\pi}{\left(\frac{12.8\text{ mm}}{2}\right)^2\pi} \times 100$$

$$= \frac{128.7\text{ mm}^2 - 89.9\text{ mm}^2}{128.7\text{ mm}^2} \times 100 = 30\%$$

(b) True stress is defined by Equation 6.15, where in this case the area is taken as the fracture area A_f. However, the load at fracture must first be computed from the fracture strength as

$$F = \sigma_f A_0 = (460 \times 10^6\text{ N/m}^2)(128.7\text{ mm}^2)\left(\frac{1\text{ m}^2}{10^6\text{ mm}^2}\right) = 59{,}200\text{ N}$$

Thus, the true stress is calculated as

$$\sigma_T = \frac{F}{A_f} = \frac{59{,}200\text{ N}}{(89.9\text{ mm}^2)\left(\frac{1\text{ m}^2}{10^6\text{ mm}^2}\right)}$$

$$= 6.6 \times 10^8\text{ N/m}^2 = 660\text{ MPa } (95{,}700\text{ psi})$$

Hardness

- A measure of material resistance to localized plastic deformation (scratch and indentation)

-The Mohs scale of hardness is used to compare the hardness or scratch resistance of minerals through the ability of a harder material to scratch a softer material . The scale is based on ten minerals

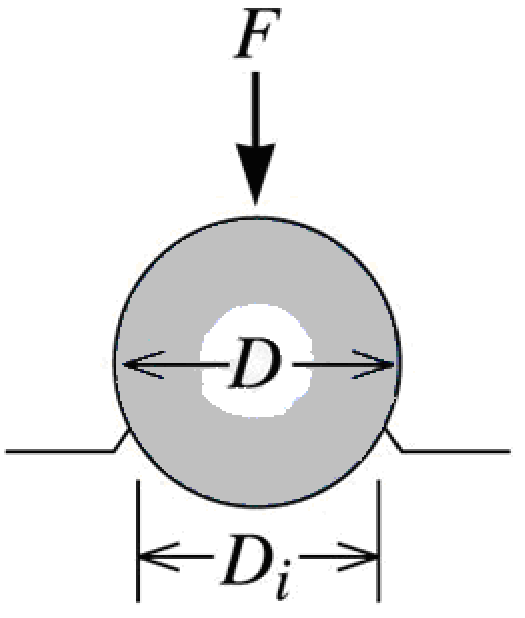
Mohs hardness scale

Hardness	Mineral
1	Talc ($Mg_3Si_4O_{10}(OH)_2$)
2	Gypsum ($CaSO_4 \cdot 2H_2O$)
3	Calcite ($CaCO_3$)
4	Fluorite (CaF_2)
5	Apatite ($Ca_5(PO_4)_3$(OH-,Cl-,F-))
6	Orthoclase Feldspar ($KAlSi_3O_8$)
7	Quartz (SiO_2)
8	Topaz (Al_2SiO_4(OH-,F-)$_2$)
9	Corundum (Al_2O_3)
10	Diamond (C)

Brinell hardness test

- Indenting the surface of the material being tested using a hardened steel or a tungsten carbide ball
- The diameter of the indentation is in the range 2.5 to 6.0 mm.

$$BHN = \frac{2F}{(\Pi D)\left[D - \sqrt{(D^2 - d^2)}\right]}$$



Hardness Testing Techniques

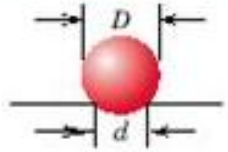
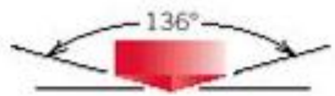
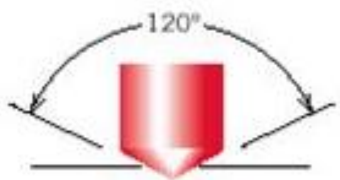
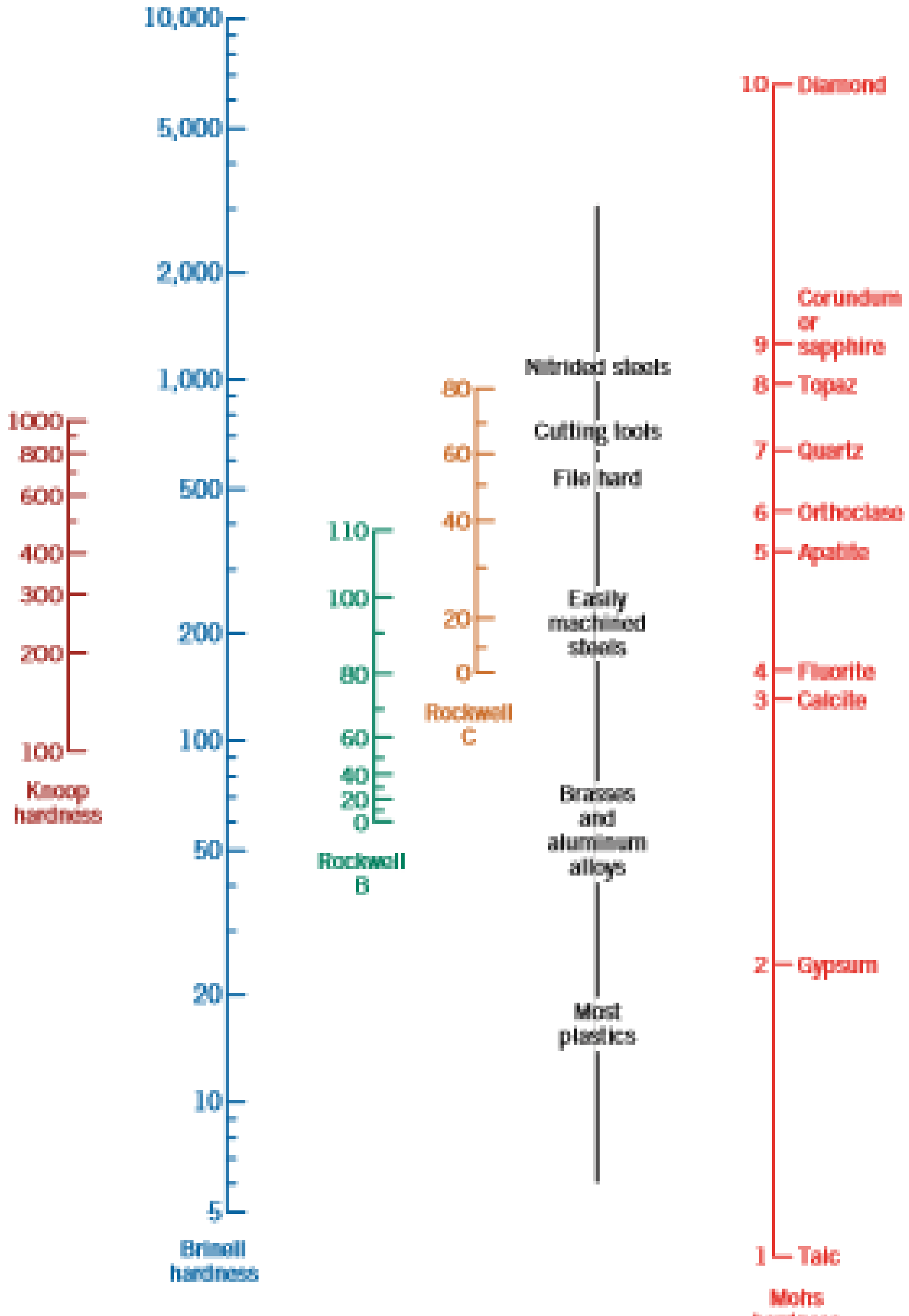
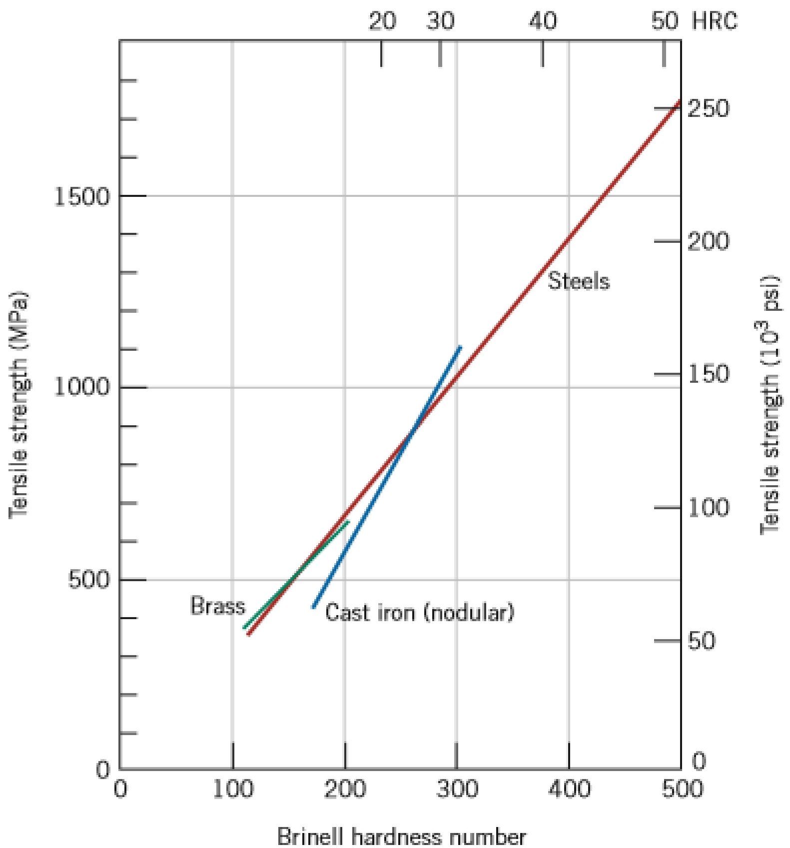
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg: Rockwell; 15 kg, 30 kg, 45 kg: Superficial Rockwell	

Figure 6.18 Comparison of several hardness scales. (Adapted from G. F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202. Copyright © 1957 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



Correlation between hardness and tensile strength

- Both tensile strength and hardness are indicators of a metal's resistance to plastic deformation



$$TS(\text{MPa}) = 3.45 \times \text{HB}$$

- Just for most of steels

Isotropic and anisotropic materials

- Isotropic materials: those materials have the same properties in all directions. The values of the elastic constants for a material will be independent of the direction of stressing for some materials.
- Anisotropic materials: the values of the elastic constants differ according to the directions in which they are measured.

Isotropic and anisotropic material

- Single crystal shows different values of E, G and Poisson's ratio, depending on the direction of stressing relative to the crystal axes.
- Most ceramics and metals are polycrystalline (the structure consists of many crystals with a random orientation). Therefore, their approximate in behavior to **isotropic**.

General solved example

Mechanical Property Determinations from Stress–Strain Plot

From the tensile stress–strain behavior for the brass specimen shown in Figure 6.12, determine the following:

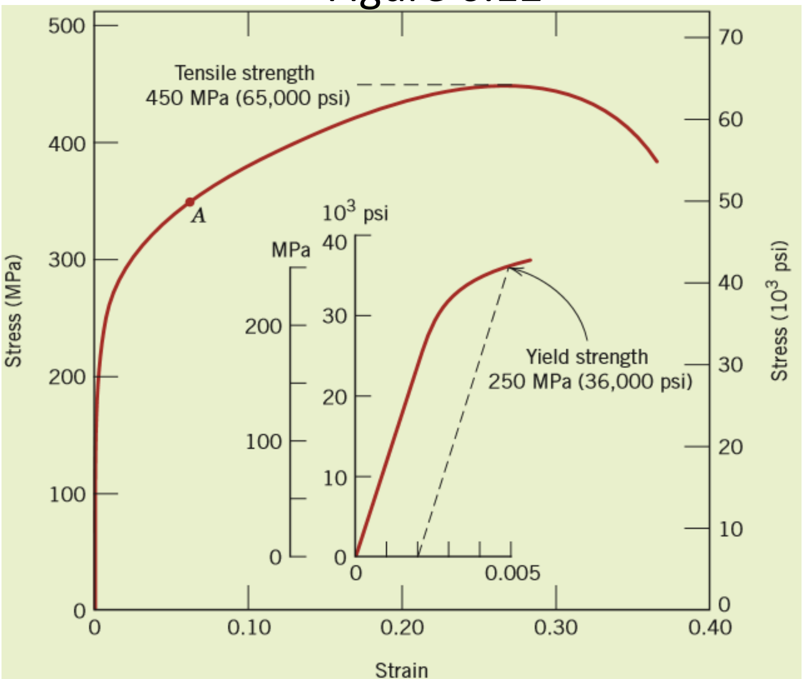
(a) The modulus of elasticity

(b) The yield strength at a strain offset of 0.002

(c) The maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm (0.505 in.)

(d) The change in length of a specimen originally 250 mm (10 in.) long that is subjected to a tensile stress of 345 MPa (50,000 psi)

Figure 6.12



Solutions:

(a) $$E = \frac{(150 - 0)\ \text{MPa}}{0.0016 - 0} = 93.8\ \text{GPa}\ (13.6 \times 10^6\ \text{psi})$$

(b) The 0.002 strain offset line is constructed as shown in the inset; its intersection with the stress–strain curve is at approximately 250 MPa (36,000 psi), which is the yield strength of the brass.

(c) The maximum load that can be sustained by the specimen is calculated by using Equation 6.1, in which σ is taken to be the tensile strength, from Figure 6.12, 450 MPa (65,000 psi). Solving for F, the maximum load, yields

$$F = \sigma A_0 = \sigma\left(\frac{d_0}{2}\right)^2 \pi$$

$$= (450 \times 10^6 \text{ N/m}^2)\left(\frac{12.8 \times 10^{-3} \text{ m}}{2}\right)^2 \pi = 57{,}900 \text{ N } (13{,}000 \text{ lb}_\text{f})$$

(d) To compute the change in length, Δl, in Equation 6.2, it is first necessary to determine the strain that is produced by a stress of 345 MPa. This is accomplished by locating the stress point on the stress–strain curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06. Inasmuch as $l_0 = 250$ mm, we have

$$\Delta l = \epsilon l_0 = (0.06)(250 \text{ mm}) = 15 \text{ mm } (0.6 \text{ in.})$$

Chapter 4: Dislocations and plasticity in Metals

Why learn about dislocations?

- Metals are crystalline but, unlike crystalline ceramics, show both elasticity and plasticity.
- Crystalline structure contain imperfections, i.e. dislocations and point defects.
- These imperfections have a major influence on the properties of the materials.
- The plastic deformation of metal crystals is the result of the movement of dislocations under the action of shear stresses.
- The point defects in crystal lattices make the movement of dislocations more difficult, and thus have a strengthening effect.

Plastic flow in metals

- Many materials have an elastic limit. When those materials stresses they strain in an elastic manner up to a certain point.
- Beyond this point:
  - The strain developed is no longer directly proportional to the applied stress.
  - The strain developed is no longer fully recoverable. (if the stress is removed, elastic strain will be recovered but the material will be left in a state of permanent, or plastic, strain.
- The mechanism of plastic deformation is not the same for all classes of materials.

Plastic flow in metals

- Metals:
  - Have high elastic modulus values
  - The ability to be strained in a plastic manner.
- Some metals will begin to deform plastically at very low values of stress and will yield to a very considerable extent before fracture occurs.
- Other metals and alloys show a little plastic before fracture.

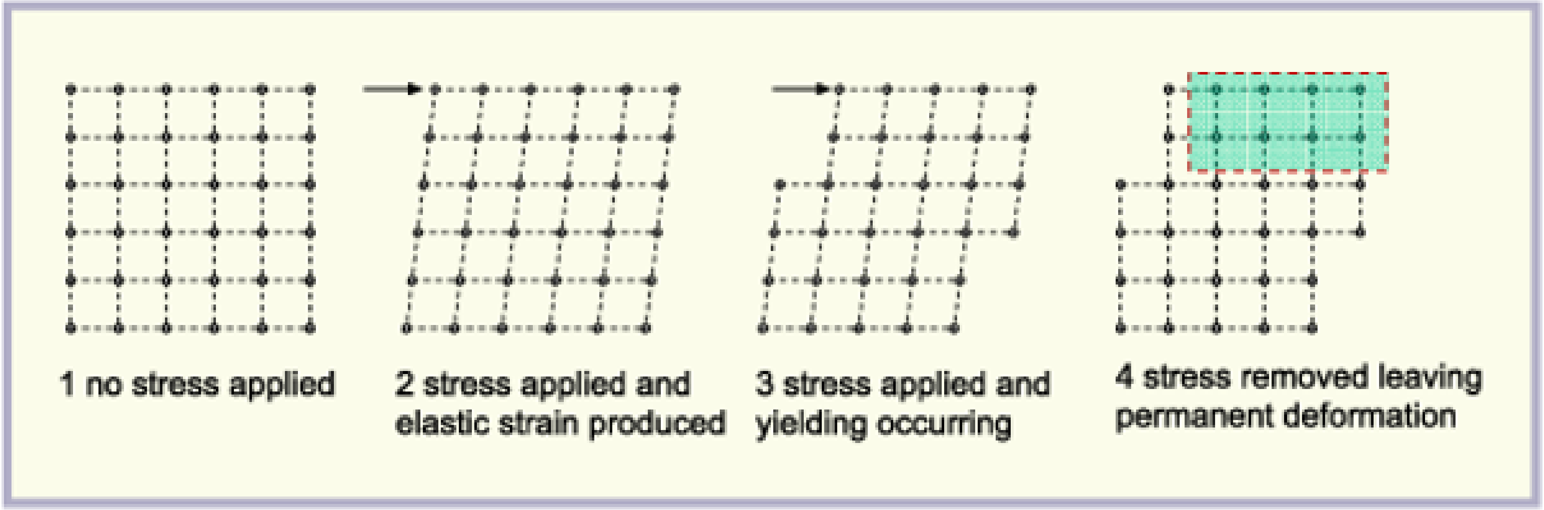
Plastic flow in metals

- Materials can be classified into:
  - Ductile material: those can have a considerable amount of plastic deformation before fracture occurs.
  - Brittle material: those show just a little plastic before fracture.
- What is the mechanism of plastic deformation in metals?

  Plastic deformation take place by the process of slip, or by twinning.

Block slip theory [1]

"When the yield stress of the metal was exceeded, plastic deformation took place by the movement of large blocks of atoms sliding relative to one another across certain planes (slip planes) within the crystal".



(1) The first theory used to describe the mechanism of plastic deformation in metals.

Block slip theory

- The theoretical shear yield strength of a metal (τ_c), calculated on the basis of this theory is given by

$$\tau_c = G/2\pi$$

where G is the modulus of rigidity.

- Drawback of the block slip theory: the calculated value of (τ_c) is many times greater than the experimentally observed yield strength of pure metals.

Plastic flow in metals

- The new theories are based on the existence of small imperfections, or defects, within crystals.
- These structural defects, termed dislocations, and plastic deformation is due to the movement of dislocations across the slip planes of a crystal under the action of an applied stress.
- The calculated stress required to move the dislocations is of the same order of magnitude as observed yield stresses in metals.

Dislocation: What will we cover?

- Dislocation types
- Dislocation characteristics
  - Dislocation line (ξ)
  - Burger's vector (b)
  - Strain field (⊥)
- Interaction of dislocations
- Density of dislocations
- Movement of dislocations (Where, When, How)

Dislocation Types

Linear Defects (Dislocations)

- Are one-dimensional defects around which atoms are misaligned.

- Edge dislocation:
  - Extra half-plane of atoms inserted in a crystal structure
  - (B) ⊥ to dislocation line (ξ)
- Screw dislocation:
  - Spiral planar ramp resulting from shear deformation
  - (b) || to dislocation line (ξ)
- Mixed dislocation:
  - Line of dislocation contains both an edge and a screw component.

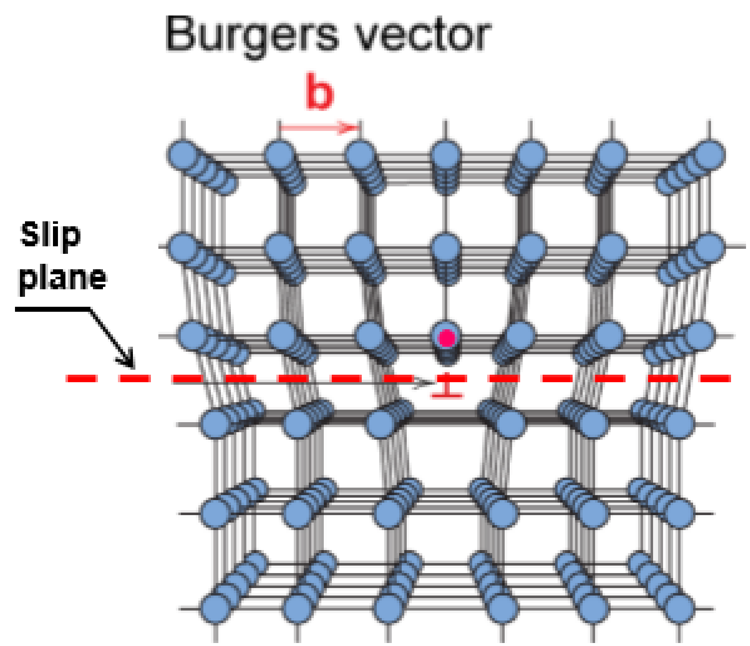
In practice, dislocation lines are rarely of the pure-edge or pure-screw type but are mixed dislocations.

Edge dislocation

- An edge dislocation can be viewed as an extra half plane of atoms inserted in a crystal structure.
- Dislocation line (ξ) : the line that extends along the end of the extra half-plane of atoms.
- The symbol (⊥) is used to denote the edge dislocation, where the horizontal line indicate the slip plane, and the vertical line indicates the extra half plane of atom.

B is the direction where the slipping will occur

Edge dislocation



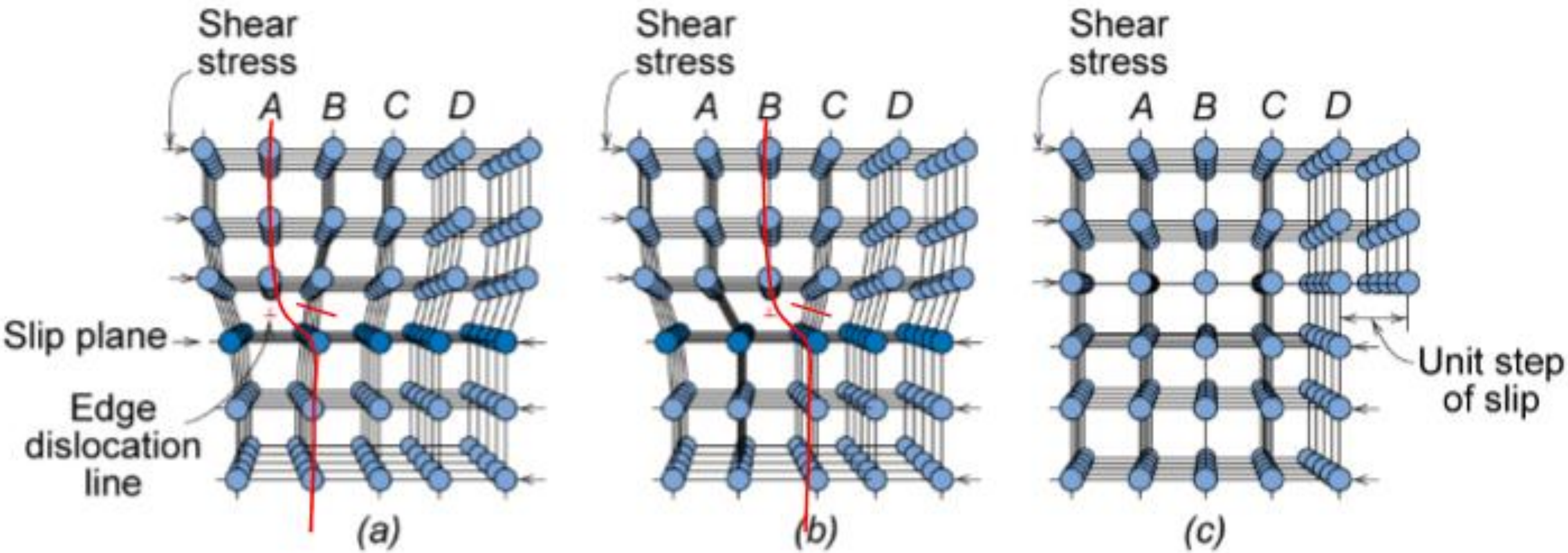
Dislocation line (ξ) is out of the paper and passes at ●

For edge dislocation (b ⊥ ξ)

Dislocation Motion /Edge dislocation

Dislocations & plastic deformation

- Cubic & hexagonal metals - plastic deformation by plastic shear or slip where one plane of atoms slides over adjacent plane by defect motion (dislocations).



- If dislocations don't move, deformation doesn't occur!

Adapted from Fig. 7.1, *Callister 7e.*

Dislocation motion analogy

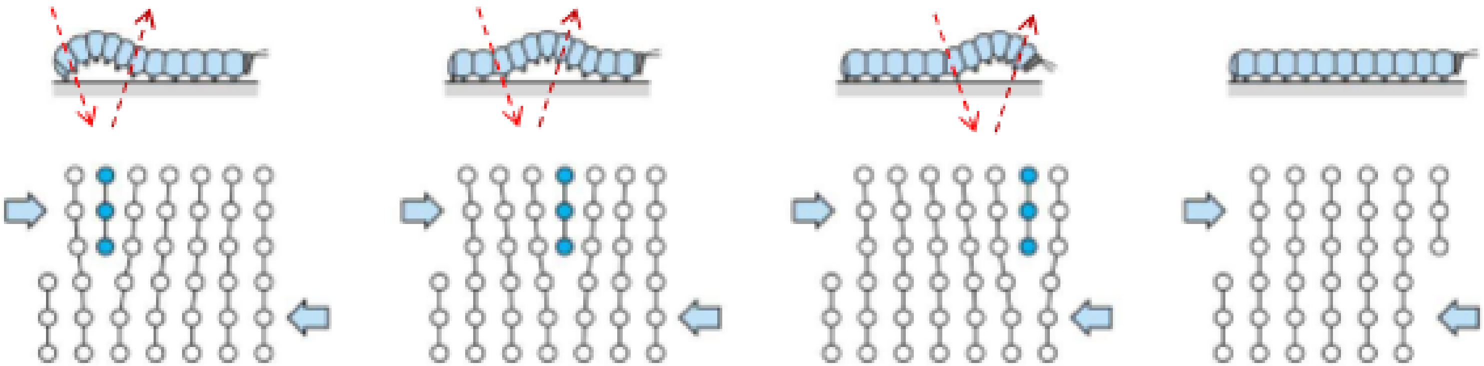
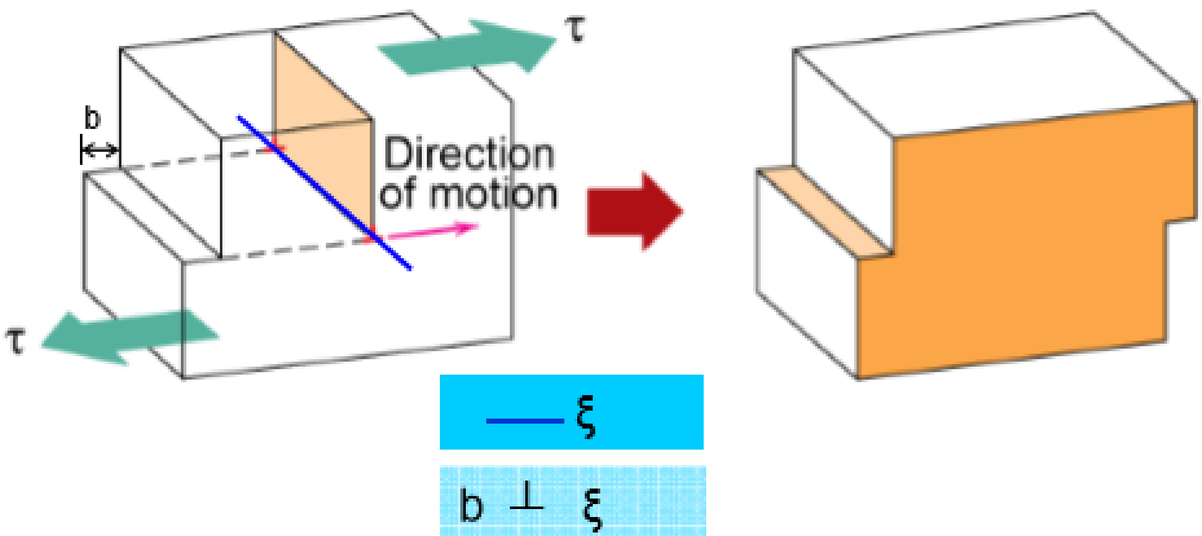


Figure 7.3 Representation of the analogy between caterpillar and dislocation motion.

- Dislocation motion is analogous to the mode of locomotion employed by a caterpillar.
- The caterpillar forms a hump near its posterior end by pulling in its last pair of legs a unit leg distance.
- The hump is propelled forward by repeated lifting and shifting of leg pairs.
- When the hump reaches the anterior end, the entire caterpillar has moved forward by the leg separation distance. The caterpillar hump and its motion correspond to the extra half-plane of atoms in the dislocation model of plastic deformation.

Dislocation Motion / edge dislocation

- Edge dislocation moves along slip plane in slip direction perpendicular to dislocation line
- Slip direction same direction as Burgers vector
- Slip direction is parallel to the applied shear stress



Edge dislocation

Adapted from Fig. 7.2, *Callister 7e.*

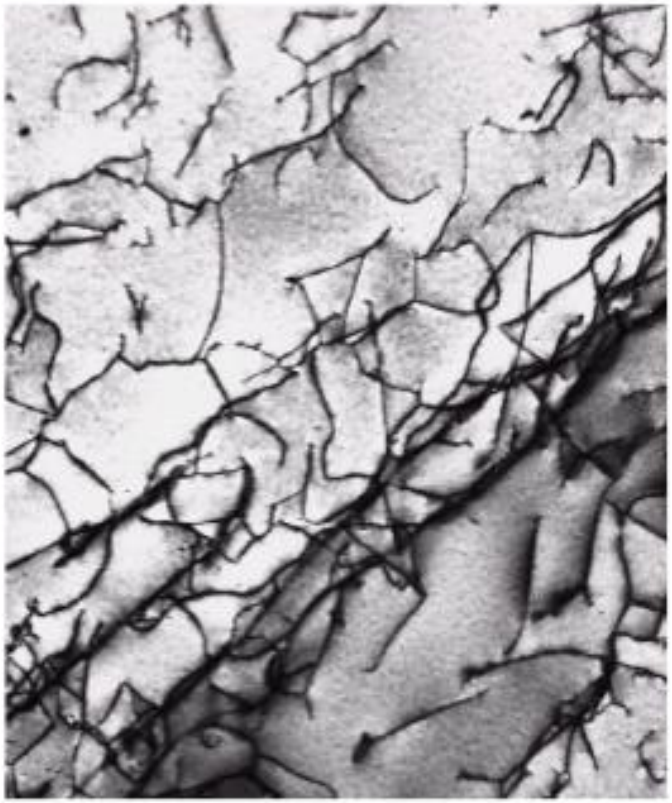
What is the difference between block slip theory and dislocation movement theory?

I. The magnitude of the stress necessary to initiate the movement of a dislocation a cross slip plane is considerably less than that which would be required to bring about block slip.

II. Dislocation theory give closer results to the experimental results for the theoretical value of the shear stress required to initiate plastic deformation compared to the slip block theory.

Imperfections in Solids

Dislocations are visible in electron micrographs



A transmission electron micrograph of a titanium alloy in which dark lines are dislocations. 51450X (Courtesy of M.R. Plichta, Michigan Technological University)

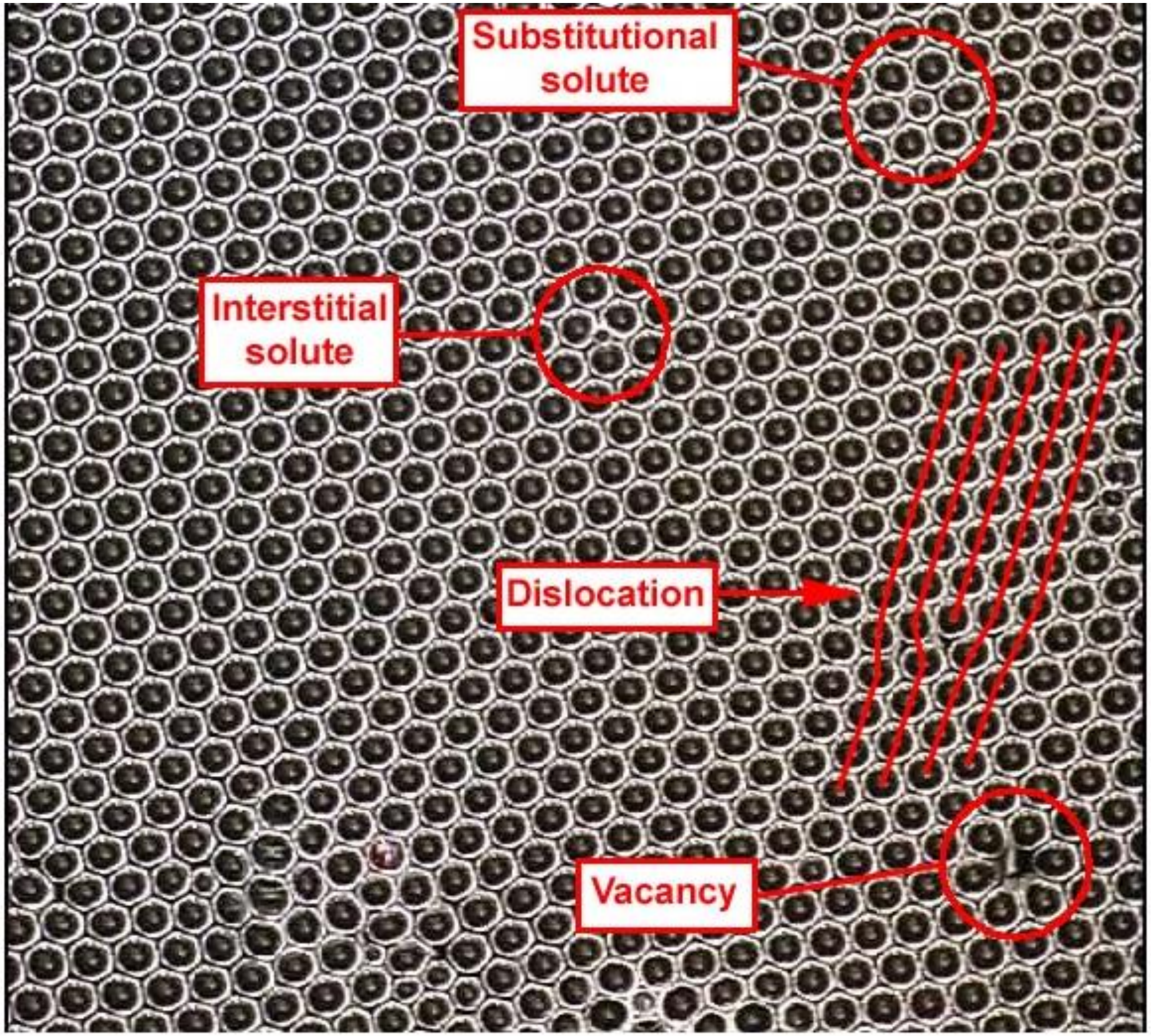
Adapted from Fig. 4.6, *Callister 7e.*

Dislocations may introduced to the crystalline materials during solidification; plastic deformation; and as consequence of thermal stresses that result from rapid cooling.

Dislocations are more widely observed in metals and ceramics, and they have been observed in polymeric materials.

dislocation1

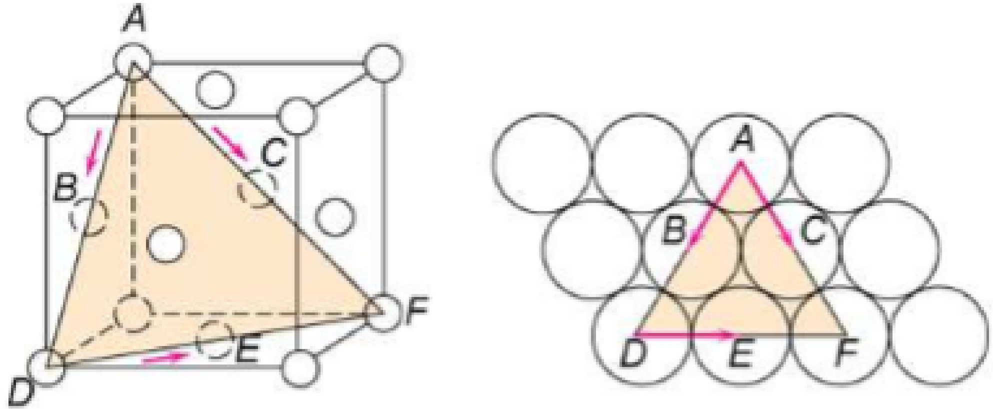
dislocation2


Substitutional solute
Interstitial solute
Dislocation
Vacancy

Deformation Mechanisms

Slip System

- Slip plane - plane allowing easiest slippage
  - Wide inter-planar spacing - highest planar densities
- Slip direction - direction of movement
  - Highest linear densities (within the slip plane)



- FCC Slip occurs on {111} planes (close-packed) in <110> directions
- In BCC & HCP other slip systems occur

Where does the slipping occur?

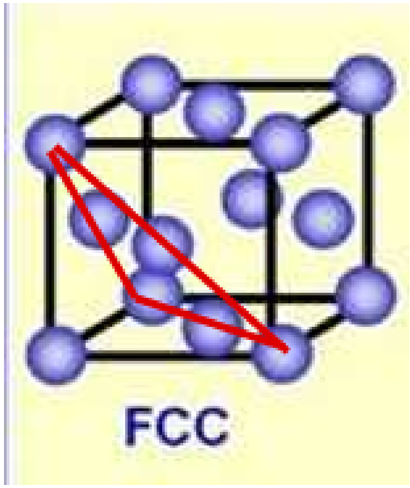
- Where does the slipping take place?

  Slipping occurs in crystal planes that have high atomic density (closed packed plane) and in the direction of greatest atomic line density within the slip plane.

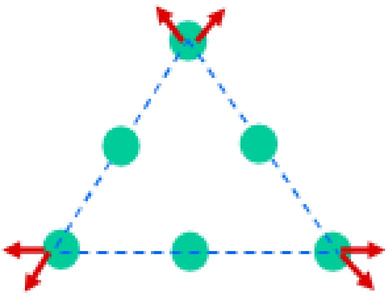
- What do we mean by closed packed plane? plane with higher atomic density, or in other words closed packed planes are those planes that posses the highest degree of atomic packing.
- Metals crystallites as HCP, FCC, and BCC

Slip planes, Face Centered Cubic

- The most dense close packed plane are those of {111} family
- Within each (111) plane, there are three possible directions of slip, slip direction is <110>
- There are four sets of planes of this type (111) in the unit cell, each set occurring at different inclinations.
- No matter from what direction relative to the crystal a direct stress is applied, there will be a resolved shearing stresses acting on several slip planes and at least one slip system will be inclined in such a way that plastic deformation can occur.
- Face centered cubic crystals are comparatively soft and ductile



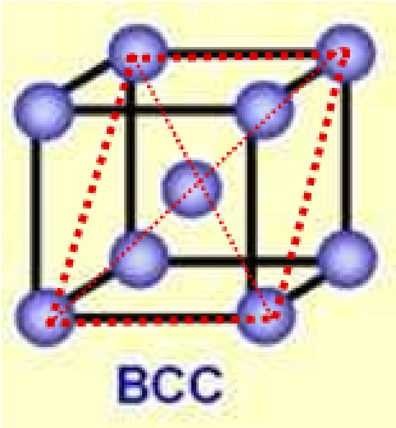
Red plane (111) is the closed packed plane FCC



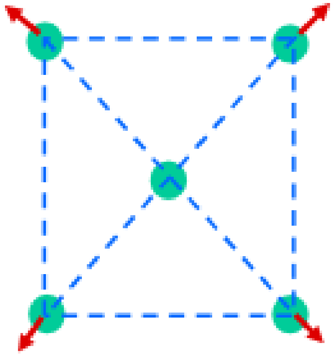
Slip directions in the f.c.c. system

Slip planes, Body Centered Cubic

- The most dense packed planes are those of the {110}.
- Within this type of plane there are two possible slip directions.
- In addition to slip taking place on (110) planes, slip may also occur on planes of the (112) and (123) types.
- Also, there are numerous possible slip directions within body centered cubic crystal.
- In general, metals crystallites in BCC form are harder and less ductile than FCC metals. WHY?
- BCC is less dense packed than FCC



Unit cell showing a (110) slip plane, BCC

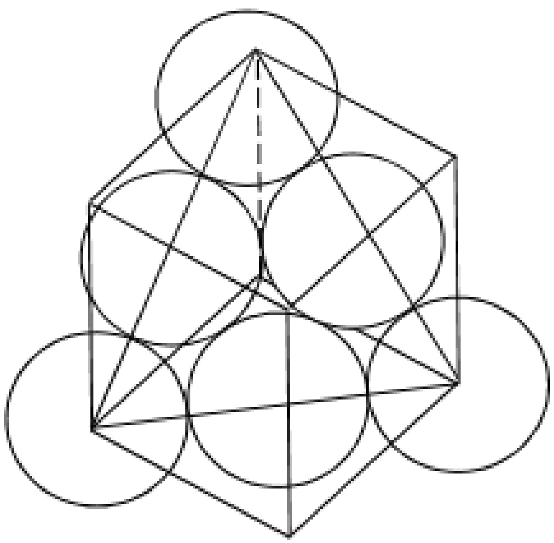


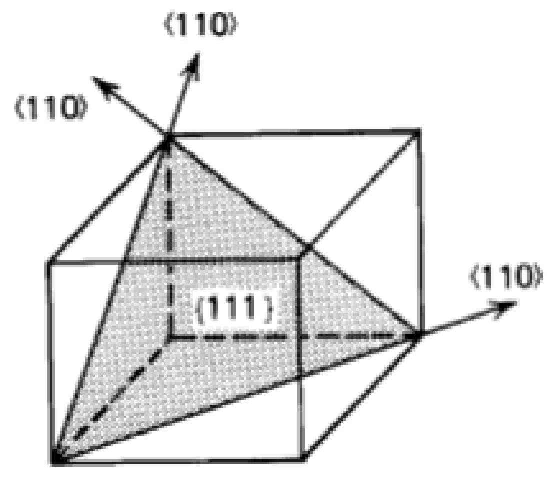
Plane view of (110) plane showing the slip directions

Slip Plane & Slip Direction

FCC crystals

- Slip planes (111) - close packed planes
- Slip direction [101] - close packed direction





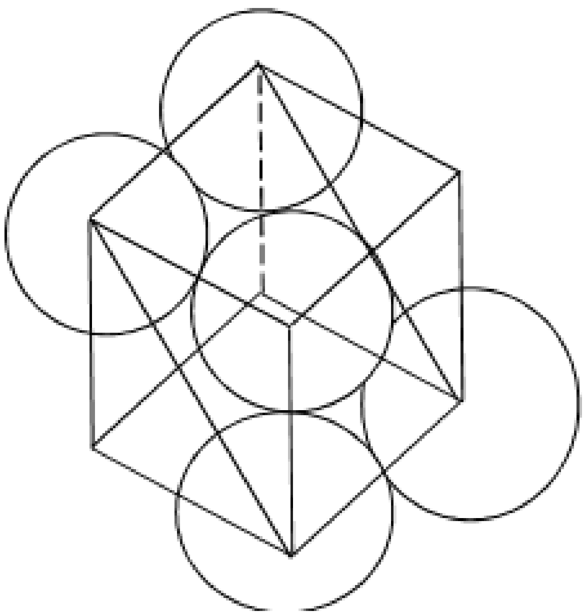
Slip Plane & Slip Direction

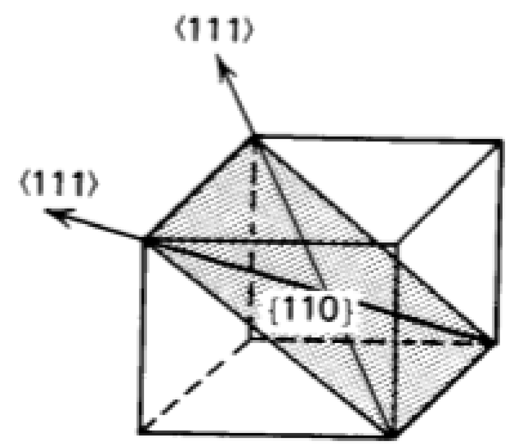
BCC Crystals

< 111 > slip direction (close-packed direction)

Any plane containing < 111 > is a potential slip plane

Experimentally observed in (110), (112) & (123) planes



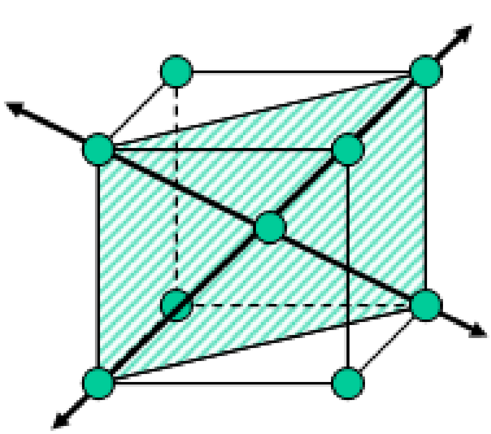


Slip system

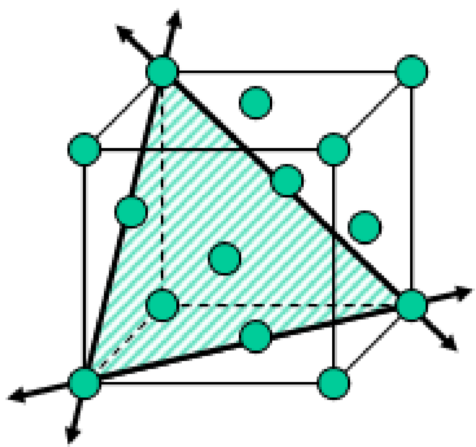
- The combination of a slip plane and a slip direction is termed a slip system.
- Slip plane: the most dense plane (closed packed plane).
- Within each slip plane, there will be a set of slip directions along which dislocation movement occur.

Slip Systems

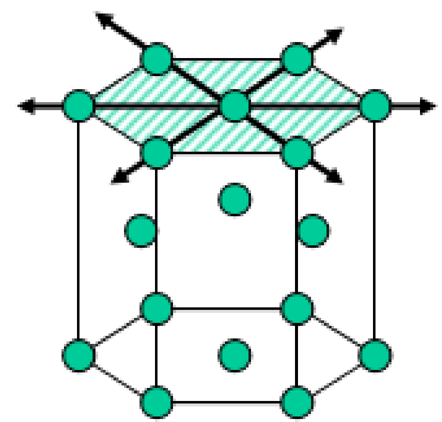
- Deformation (dislocation) occurs on preferential crystallographic planes and directions, called slip systems.
- The slip plane/direction is the plane/direction with the most closely packed atoms.



6x2=12



4x3=12

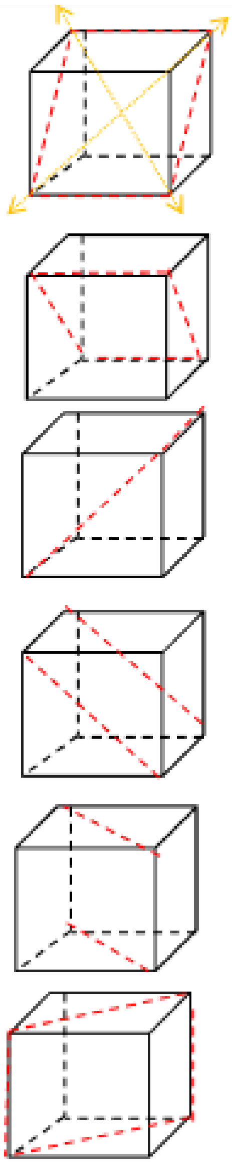


1x3=3

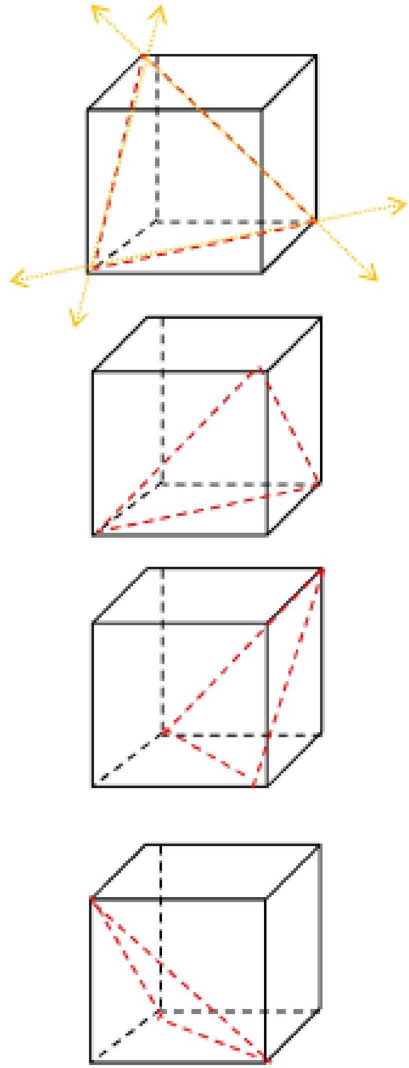
Slip planes and directions in metal crystals

Crystal type	Slip planes	No. of slip planes	Slip directions	No. of slip directions per plane	Total no. of slip systems
h.c.p.	(0001)	1	$[2\underline{1}\underline{1}0][\underline{1}2\underline{1}0][\underline{1}\underline{1}20]$	3	3
f.c.c.	{111}	4	<110>	3	12
b.c.c.	{110}	6	<111>	2	12

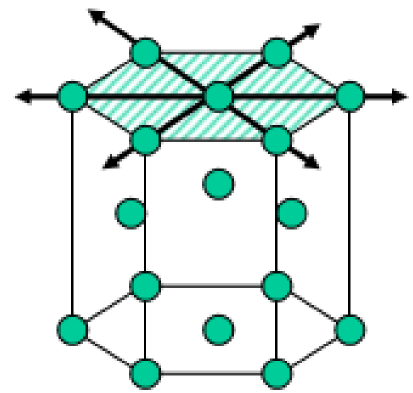
Slip Systems



6x2=12



4x3=12



1x3=3

Slip Systems

- **BCC** has 6 slip planes and 2 slip directions per plane (12 slip systems), but distance between slip planes is small, therefore the required stress is high. Good Strength and moderate ductility, e.g. Steel, Titanium, Molybdenum, Tungsten.
- **FCC** has 4 slip planes and 3 slip directions per plane (12 Slip Systems), but distance between slip planes is larger than BCC. Therefore, probability of slip is moderate, shear stress to cause slip is low. Moderate Strength and Good Ductility, e.g., Aluminum, Copper, Gold, Silver
- **HCP** has 1 slip plane and 3 slip directions on that plane (3 systems). Low probability of slip. Generally brittle materials, e.g., Beryllium, Magnesium, and Zinc

Chapter 5: Introduction to manufacturing processes

Main Types of manufacturing processes

1. Metal Casting Processes.

2. Forming and shaping processes

- Rapid prototyping process
- Metal rolling process
- Metal forging processes
- Metal extrusion and drawing processes
- Sheet metal forming process
- Powder metal process
- Ceramic and glass processing
- Plastic and composite forming and shaping

3. Machining processes

- Turning
- Milling, broaching, sawing, filling and gear manufacturing
- Abrasive machining and finishing operations.
- Advanced machining processes, chemical machining, electrochemical, laser beam, electron beam, water jet, abrasive jet, hybrid machining

4. Joining processes

- Fusion Welding
- Brazing,
- Soldiering etc..

Rapid prototyping techniques

Definition: Group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data.

or a Class of technologies that can automatically construct physical models from CAD data.

-Why to do:

- Excellent visual aids for communicating ideas.
- Design testing
- Faster and less expensive

Synonyms: Solid Freeform Fabrication, or layered manufacturing.

The reasons of Rapid Prototyping are:

- To increase effective communication.
- To decrease development time.
- To decrease costly mistakes.
- To minimize engineering changes.
- To extend product lifetime by adding necessary features and eliminating redundant features early in the design.

Traditional Machining vs rapid prototyping

	Rapid Prototyping	**Machining Processes**
Process characteristics	Additive processes	Subtractive processes
Internal Feature characteristics	Complicated	Geometrical
Product Size	Part Volume $\leq 0.125\ m^3$	Large
Product Strength	Low	High
Production Time	Shorter	Longer

Prototyping methodology

The basic methodology for all current rapid prototyping techniques can be summarized as follows:

1. Construct a solid CAD model.

2. Convert the model into the rapid prototyping format, like STL for example

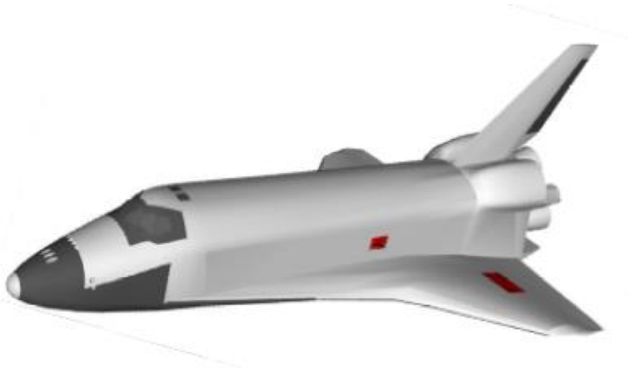
3. The prototyping machine processes the file and create sliced layers of the model

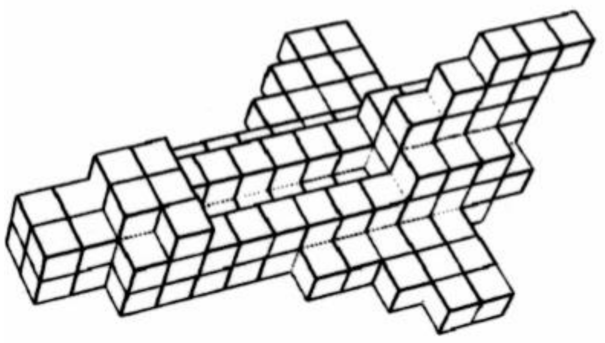
4. After creating the first layer, the model is lowered by the thickness of the next layer

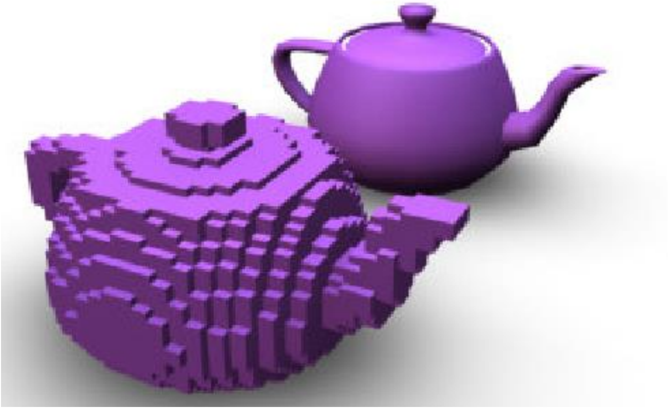
5. The process is repeated until finish the model.

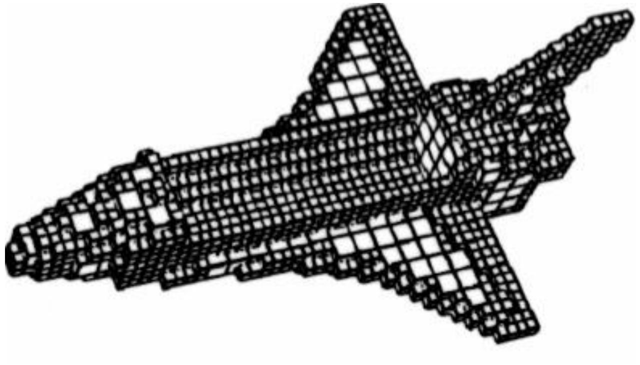
6. The surface of the model is then finished and cleaned.

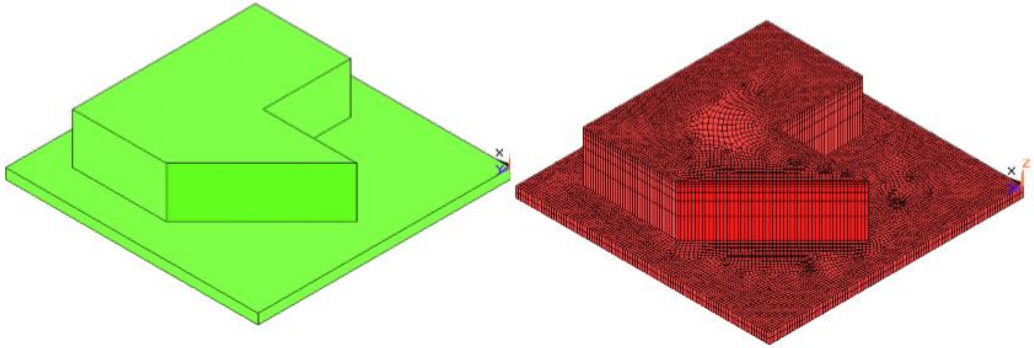
Some Examples







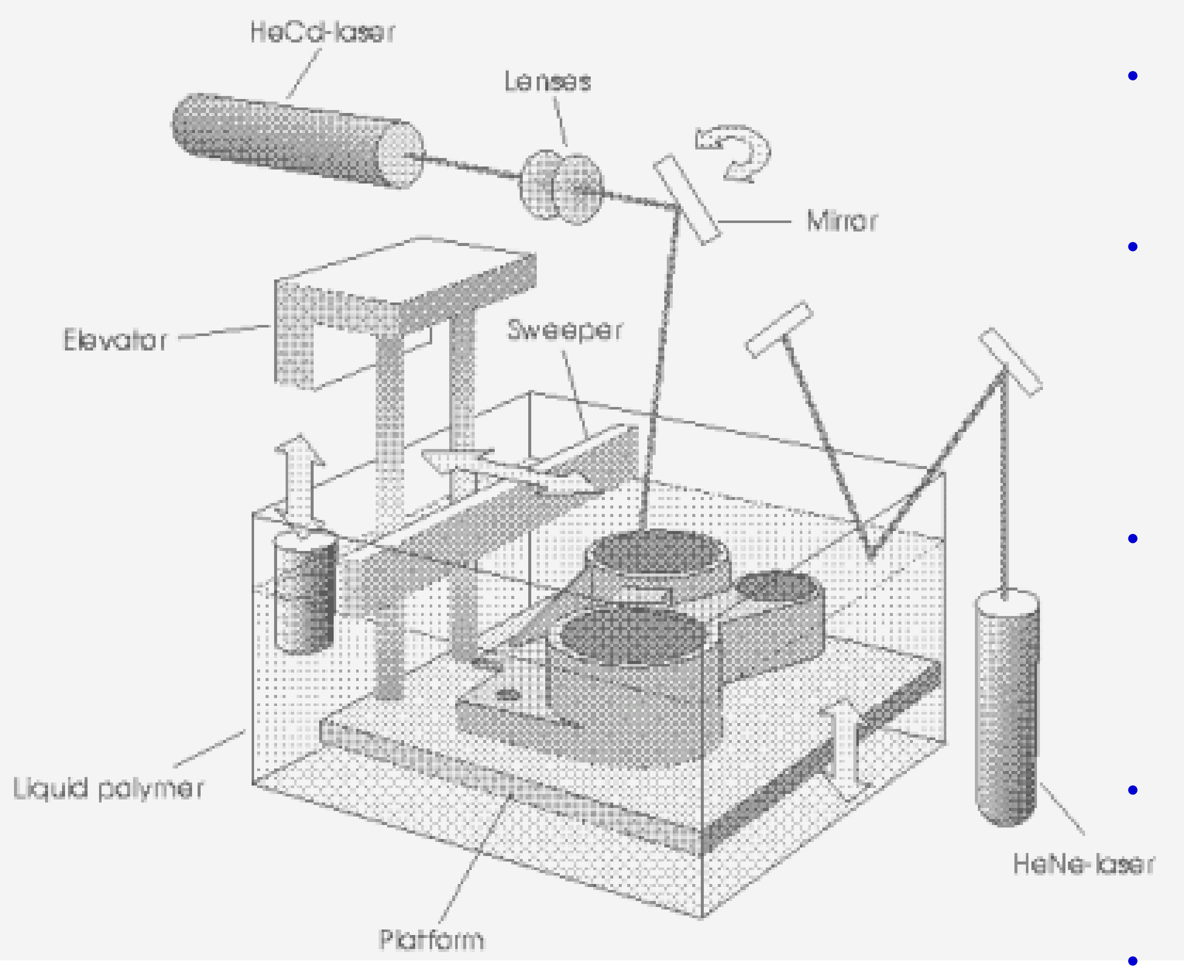




Rapid prototyping technologies

1. Stereolithography (SLA)
2. Laminated Object Modelling (LOM)
3. Selective Laser Sintering (SLS)
4. Fusion Deposition Modelling (FDM)
5. Solid Ground Curing (SGC)

1. Stereolithography (SLA)

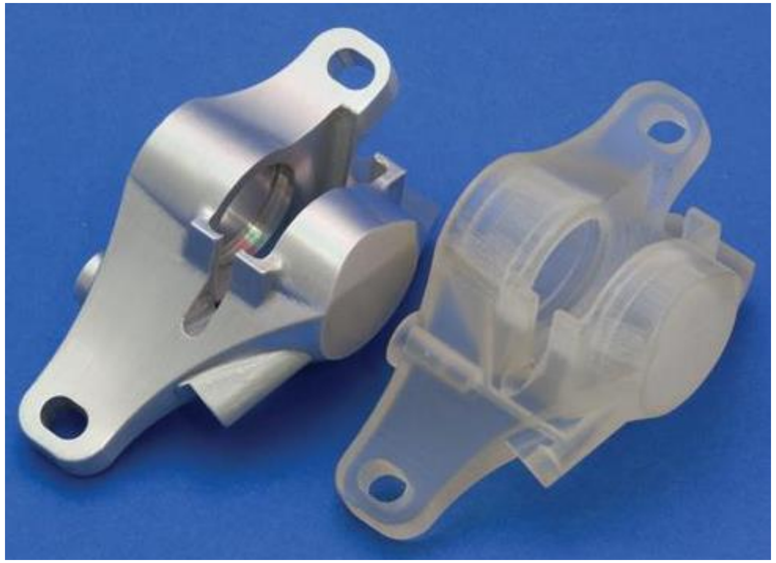


- **Pour the liquid resin into a vessel, which is kept very still.**
- **Expose the surface of the liquid to UV radiation in those solid area. This creates a layer of solid resin with the same shape as the layer geometry of the part.**
- **Lower the solidified resin into the vessel by a distance equal to its thickness. The solid is now covered by a fresh layer of liquid resin.**
- **Now apply the UV radiation to the area corresponding to the next layer.**
- **Repeat this process till all layers of the solid are built.**

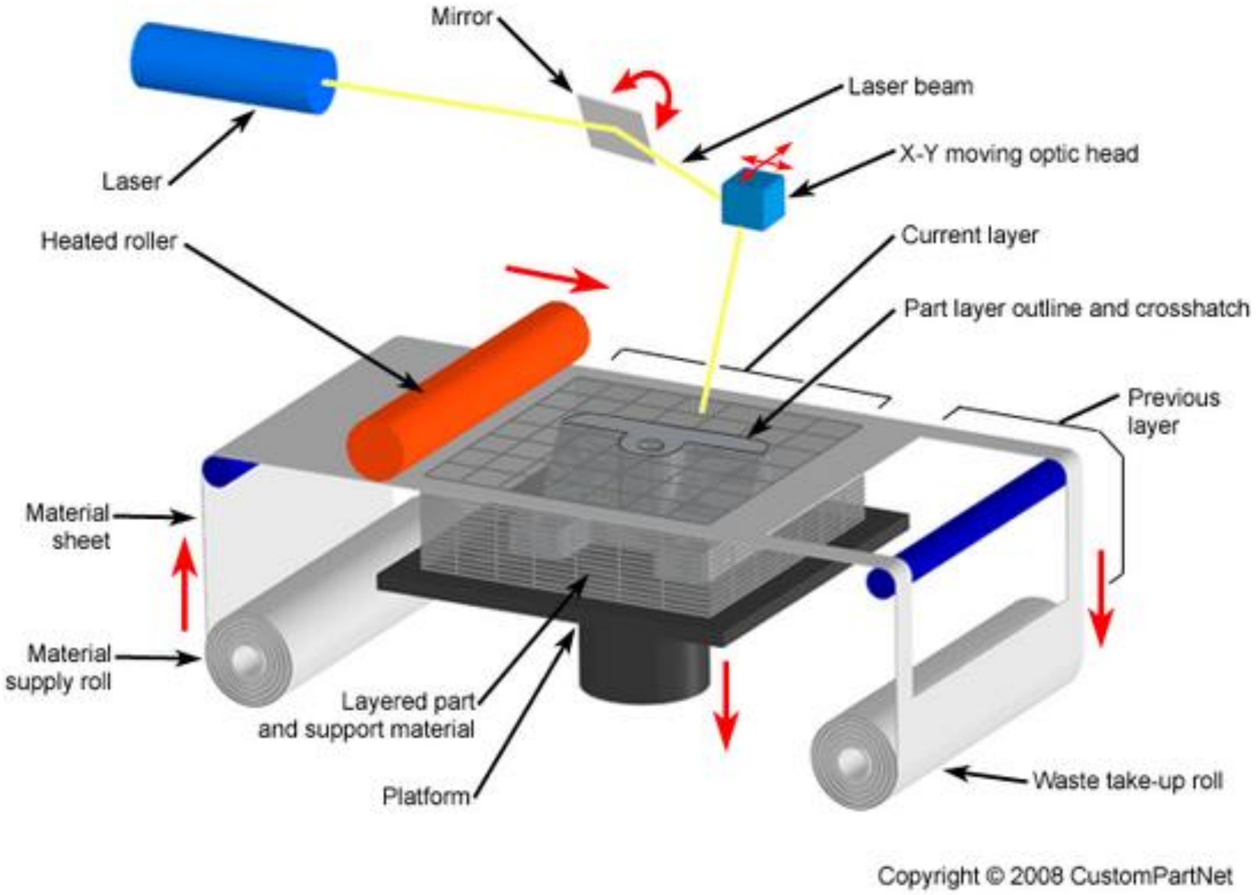
A **photopolymer** is a polymer that changes its properties when exposed to light.

Video

1. Stereolithography (SLA) products



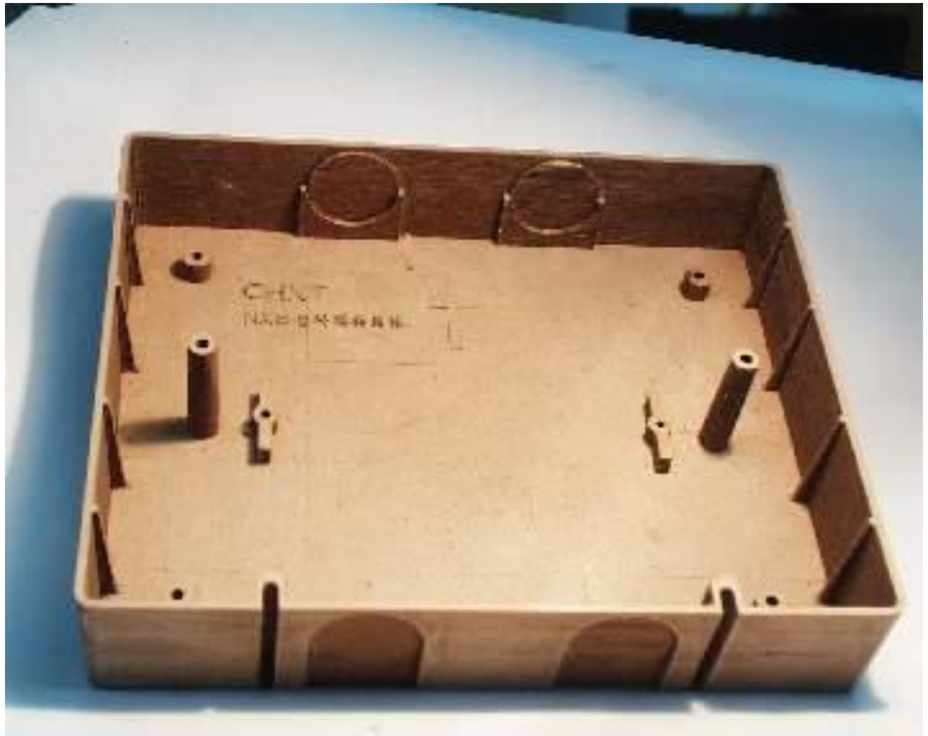
2. Laminated Object Manufacturing (LOM)



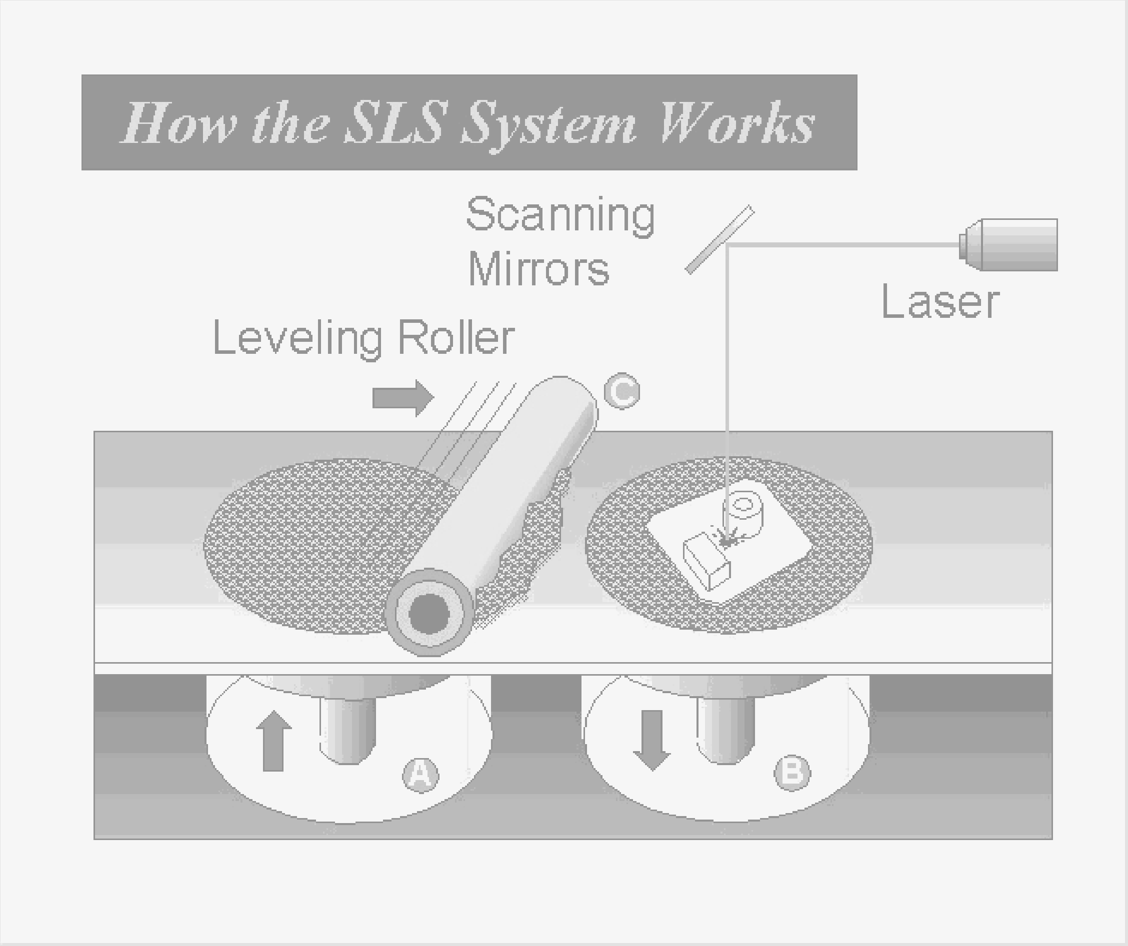
- Layers of adhesive-coated sheet material are bonded together.
- The original material consists of paper laminated with heat-activated glue and rolled up on spools.
- A feeder/collector mechanism advances the sheet over the build platform.
- A heated roller applies pressure to bond the paper to the base.
- A focused laser cuts the outline of the first layer into the paper and then cross-hatches the excess area.
- Cross-hatching breaks up the extra material, making it easier to remove during post-processing.

Video

2. Laminated Object Manufacturing (LOM) part



3. Selective Laser Sintering (SLS)

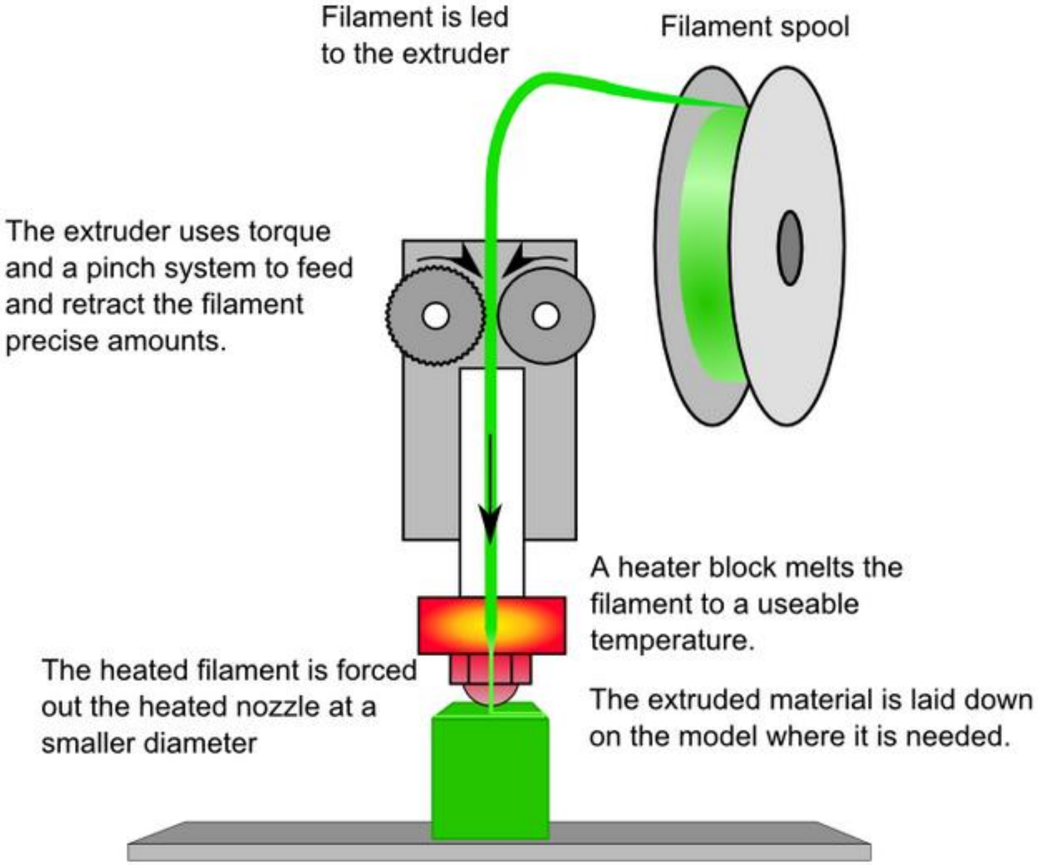


- The sintering powder is specially coated with a very thin layer of thermo-plastic (melts at higher temperatures) resin.
- The CO2 laser passes over the areas of the layer to be solidified.
- When the laser beam heats the powder, the resin melts, causing the powder to glue together.
- The platform is lowered, and a new layer of powder is spread on top of the old layer.
- The process is repeated.
- At the end, we have a solidified model, and the remaining powder can be shaken off and re-used.
- The model is heated in an oven to a temperature just below the melting point of the metal powder. At this temperature, the resin burns away, and the metal powder gets united due to diffusion, into a solid form.

Video

3. Selective laser sintering (SLS) parts

4. Fused Deposition Modeling (FDM)



- **The filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane.**

  Like a baker decorating a cake, the controlled extrusion head deposits very thin beads of material onto the build platform to form the layer.

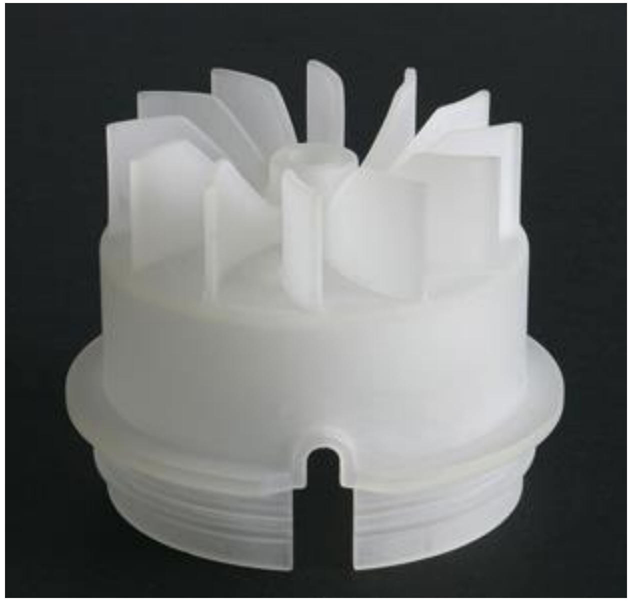
  The platform is maintained at a lower temperature, so that the thermoplastic quickly hardens.

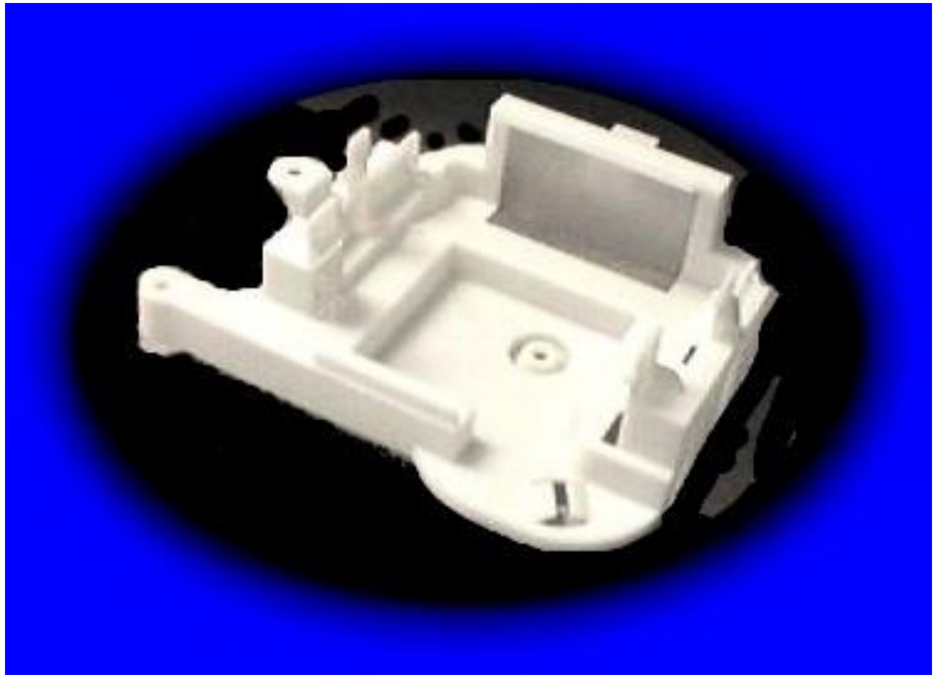
  After the platform lowers, the extrusion head deposits a second layer upon the first.

  Supports are built along the way, fastened to the part either with a second, weaker material or with a perforated junction.

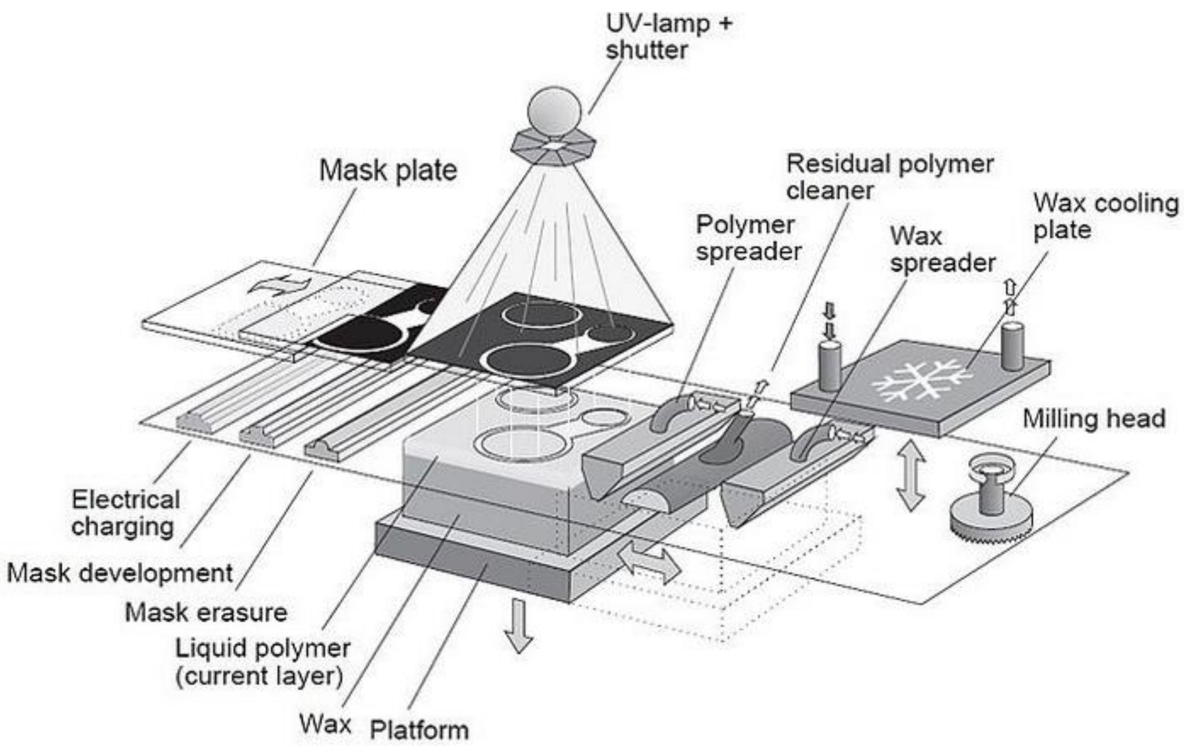
Video

4. Fused deposition modeling (FDM) products





5. Solid Ground Curing (SGC)



- Similar to SLA that both use ultraviolet light to selectively harden photosensitive polymers.

  Cures an entire layer at a time.

1. Photosensitive resin is sprayed on the build platform.

2. The machine develops a photomask of the layer.

3. This photomask is printed on a glass plate above the build platform using an electrostatic process similar to that found in photocopiers.

4. The mask is then exposed to UV light, which only passes through the transparent portions of the mask to selectively harden the shape of the current layer.

5. After the layer is cured, the machine vacuums up the excess liquid resin and spray wax in its place to support the model during the build.

6. The top surface is milled flat, and then the process repeats.

7. When the part is completed, it must be de-waxed by immersing it in a solvent bath.

Video

5. Solid Ground Curing (SGC) parts

Main Types of manufacturing processes

1. Metal Casting Processes.

2. Forming and shaping processes

- Rapid prototyping process
- Metal rolling process
- Metal forging processes
- Metal extrusion and drawing processes
- Sheet metal forming process
- Powder metal process
- Ceramic and glass processing
- Plastic and composite forming and shaping
- 3. Machining processes
- 4. Joining processes

Metal Casting process

- Types of molds

- **1. Expendable mold:** typically made from sand ceramic, plaster and similar materials mixed with binders to improve properties. For example in sand type there are 90% sand, 7% clay and 3% water. The pattern is reused in different molds.

- **2. Permanent molds:** Metals that maintain their strength at high temperature. The mold can be used next time. The microstructure can be changed due to the conductivity of the mold material (metal).

- **3. Composite molds:** different materials are used here, such as sand with graphite and metals combining the advantage for each material. They have permanent and expandable portions. Used to improve the mold strength, control cooling rate and optimize the overall economics of the casting process.

Casting Examples

Figure 11.2 Typical gray-iron castings used in automobiles, including transmission valve body (left) and hub rotor with disk-brake cylinder (front). *Source*: Courtesy of Central Foundry Division of General Motors Corporation.

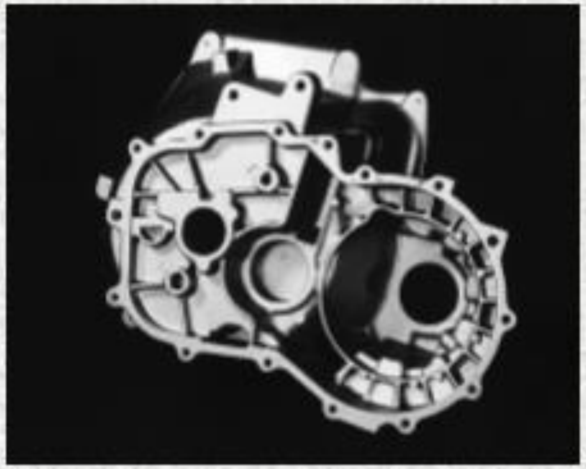


Figure 11.3 A cast transmission housing.

Sand Casting process

- More than 15 million ton of metal are casted by this method every year in the US.
- Use silica (SiO_2) as a mold material because of low cost and high melting point.

- <u>Sand casting consists of :</u>

A. Placing a pattern (having the shape of the desired casting) in sand to make an imprint.
B. Incorporating a gating system
C. Removing the pattern and filling the mold cavity with molten metal.
D. Allowing the metal to cool until it solidifies.
E. Breaking away the sand mold, and
F. Removing the casting

Steps in Sand Casting

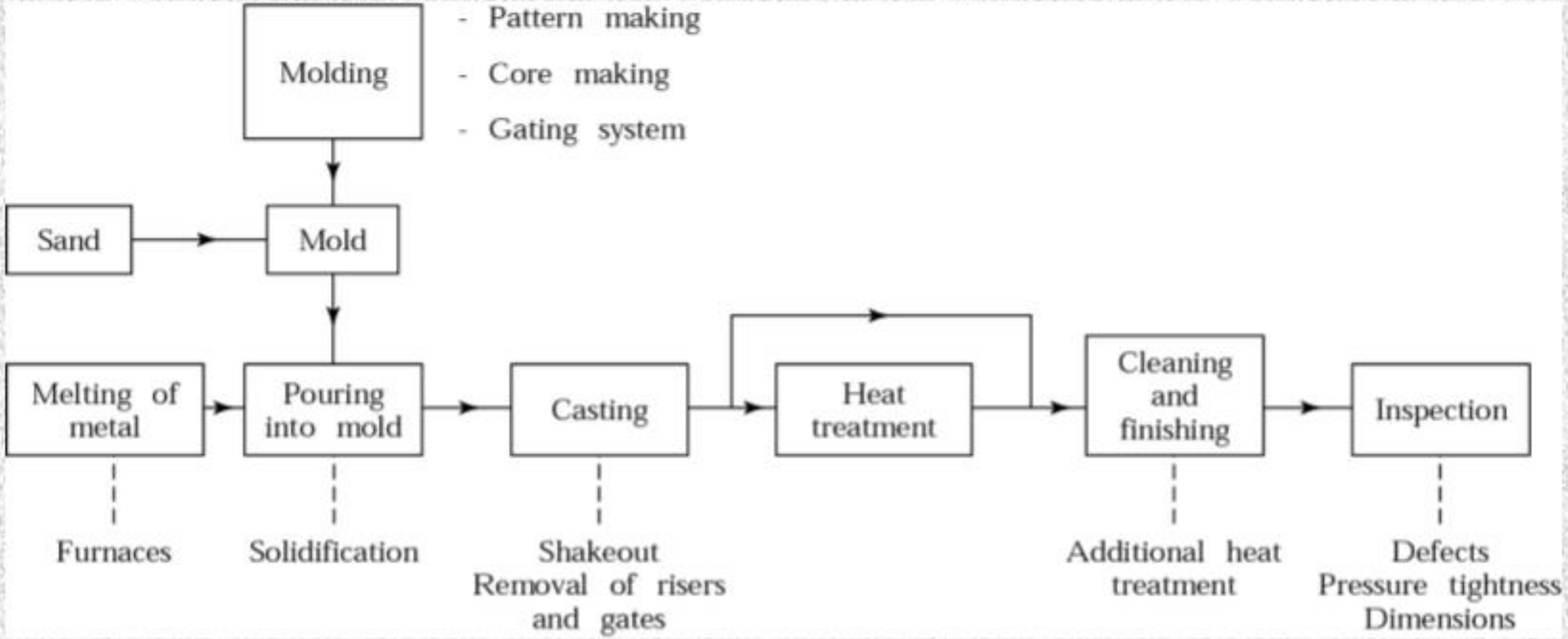


Figure 11.5 Outline of production steps in a typical sand-casting operation.

Sand casting

- The major features of molds in sand casting are as follows:

- I. The ***flask***, which supports the mold itself. Two-piece molds consist of a cope on top and a drag on the bottom; the seam between them is the parting line.
- 2. A ***pouring basin*** or pouring cup, into which the molten metal is poured.
- 3. A ***sprue***, through which the molten metal flows downward.
- 4. ***The runner system***, which has channels that carry the molten metal from the sprue to the mold cavity. **Gates** are the inlets into the mold cavity.
- 5. ***Risers,*** which supply additional molten metal to the casting as it shrinks during solidification. Two types of risers-a blind riser and an open riser.
- 6. ***Cores***, which are inserts made from sand. They are placed in the mold to form hollow regions or otherwise define the interior surface of the casting. Cores also are used on the outside of the casting to form features such as lettering on the surface or deep external pockets.
- 7. ***Vents*** which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the mold and the core. Vents also exhaust air from the mold cavity as the molten metal flows into the mold.

Sand Mold Features

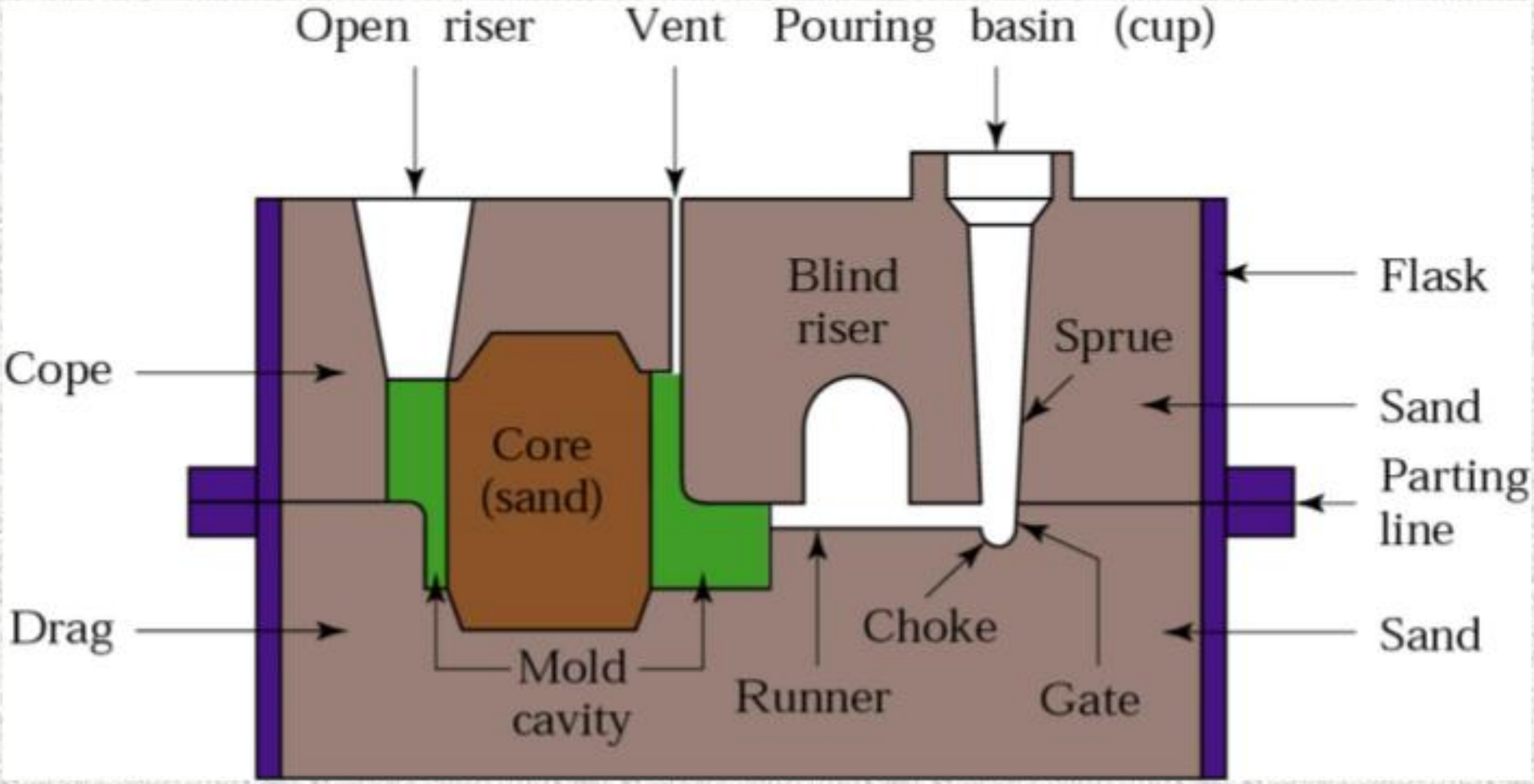


Figure 11.4 Schematic illustration of a sand mold, showing various features.

Video

Patterns for Sand Casting

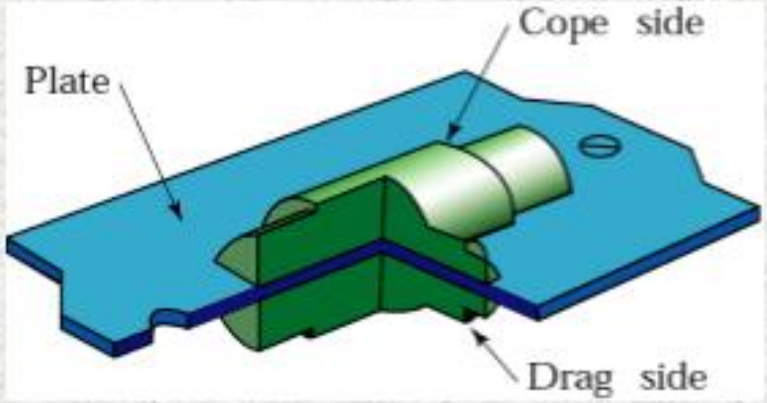


Figure 11.6 A typical metal match-plate pattern used in sand casting.

Types of patterns :

1. A piece pattern
2. Split pattern
3. Match plate pattern

-Pattern design should take In consideration the shrinkage

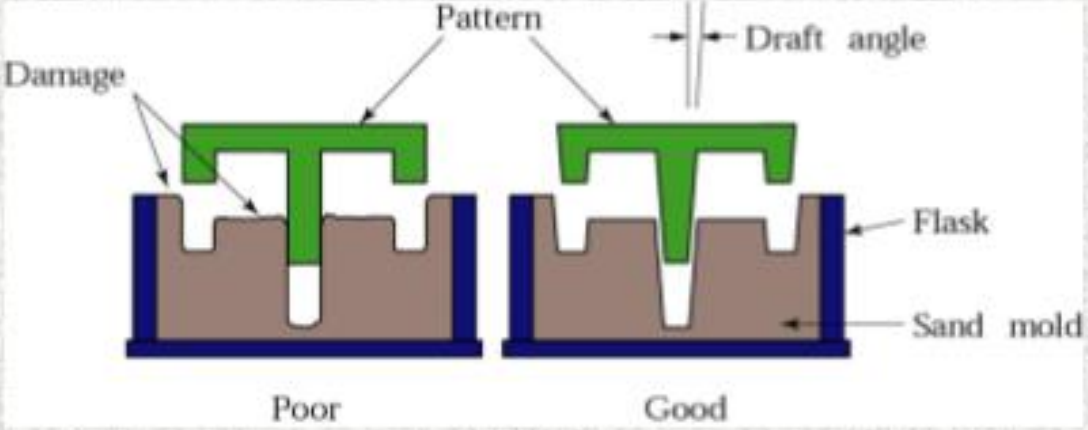


Figure 11.7 Taper on patterns for ease of removal from the sand mold.

Patterns : Patterns are used to mold the sand mixture into the shape of the casting and may be made of wood, plastic, or metal. The selection of a pattern material depends on the size and shape of the casting,

Pattern Material Characteristics

TABLE 11.3

			Rating[a]		
Characteristic	*Wood*	*Aluminum*	*Steel*	*Plastic*	*Cast iron*
Machinability	E	G	F	G	G
Wear resistance	P	G	E	F	E
Strength	F	G	E	G	G
Weightb	E	G	P	G	P
Repairability	E	P	G	F	G
Resistance to:					
Corrosionc	E	E	P	E	P
Swellingc	P	E	E	E	E

aE, Excellent; G, good; F, fair; P, poor.

bAs a factor in operator fatigue.

cBy water.

Sequence of Operations for Sand Casting

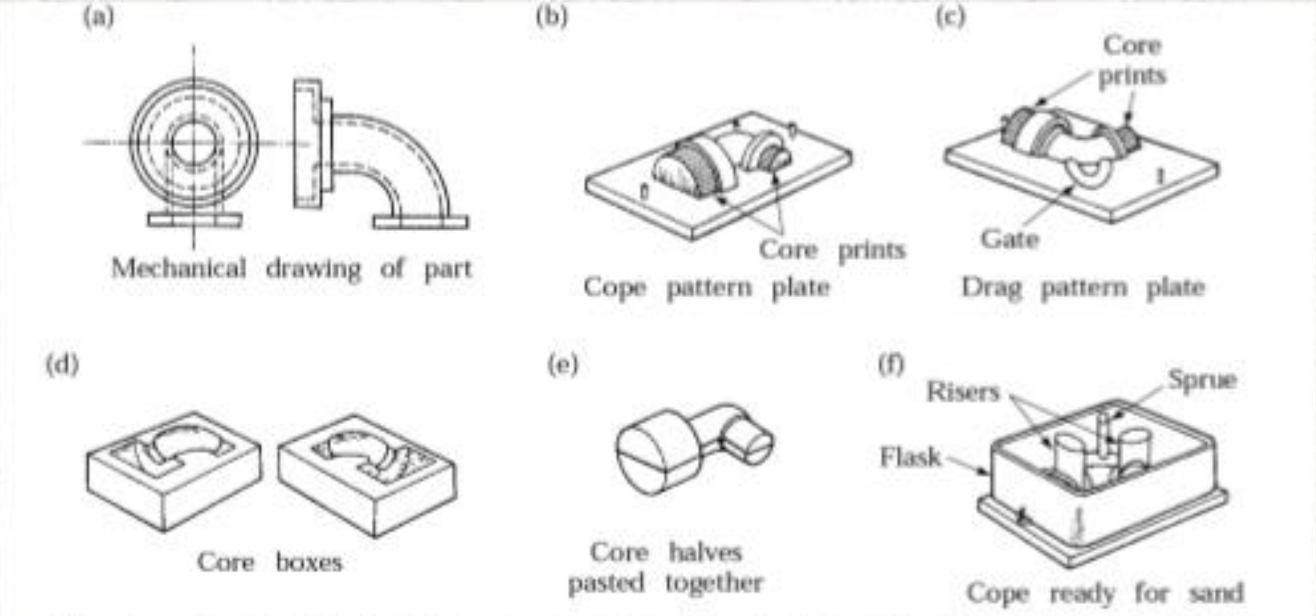


Figure 11.11 Schematic illustration of the sequence of operations for sand casting. *Source*: Steel Founders' Society of America. (a) A mechanical drawing of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be built into the drawing. (b-c) Patterns have been mounted on plates equipped with pins for alignment. Note the presence of core prints designed to hold the core in place. (d-e) Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a). (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins, and attaching inserts to form the sprue and risers. (continued)

Sequence of Operations for Sand Casting (cont.)

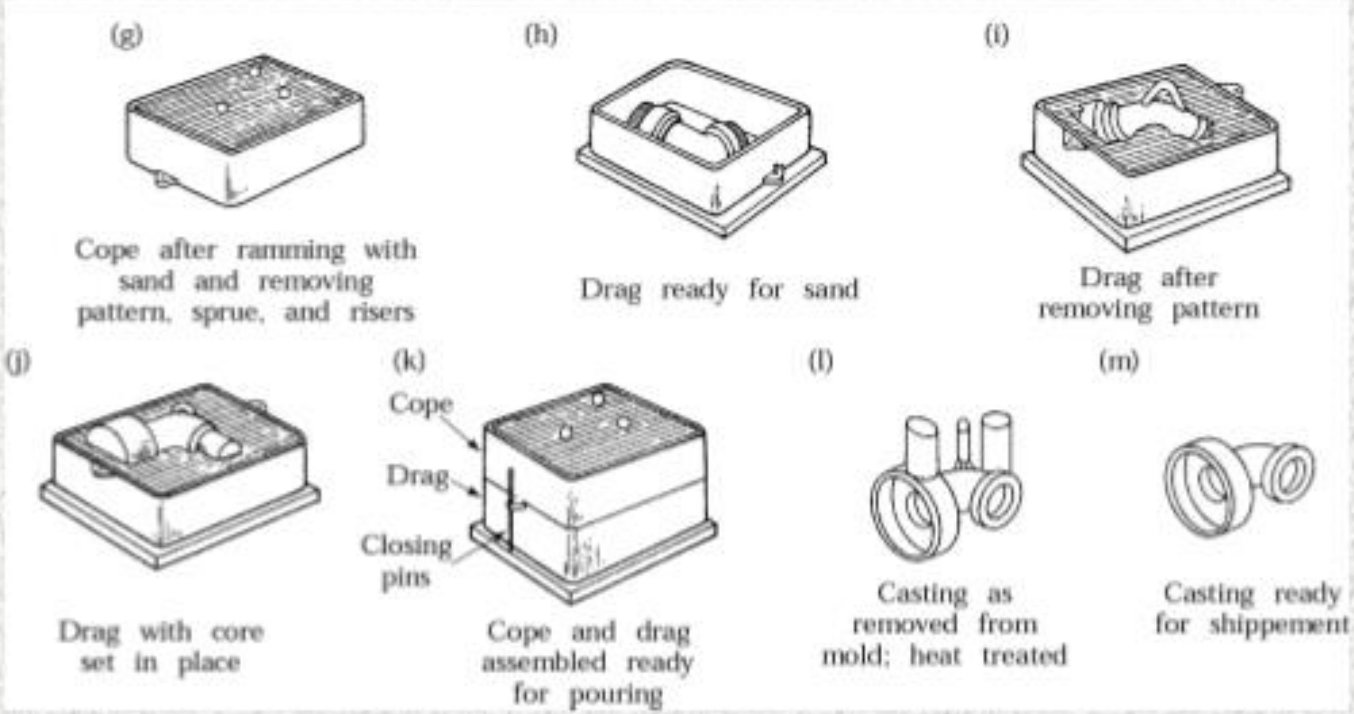


Figure 11.11 (g) The flask is rammed with sand and the plate and inserts are removed. (g) The drag half is produced in a similar manner, with the pattern inserted. A bottom board is placed below the drag and aligned with pins. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and buoyant forces in the liquid, which might lift the cope. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled and the casting is cleaned, inspected, and heat treated (when necessary).

Surface Roughness for Various Metalworking Processes

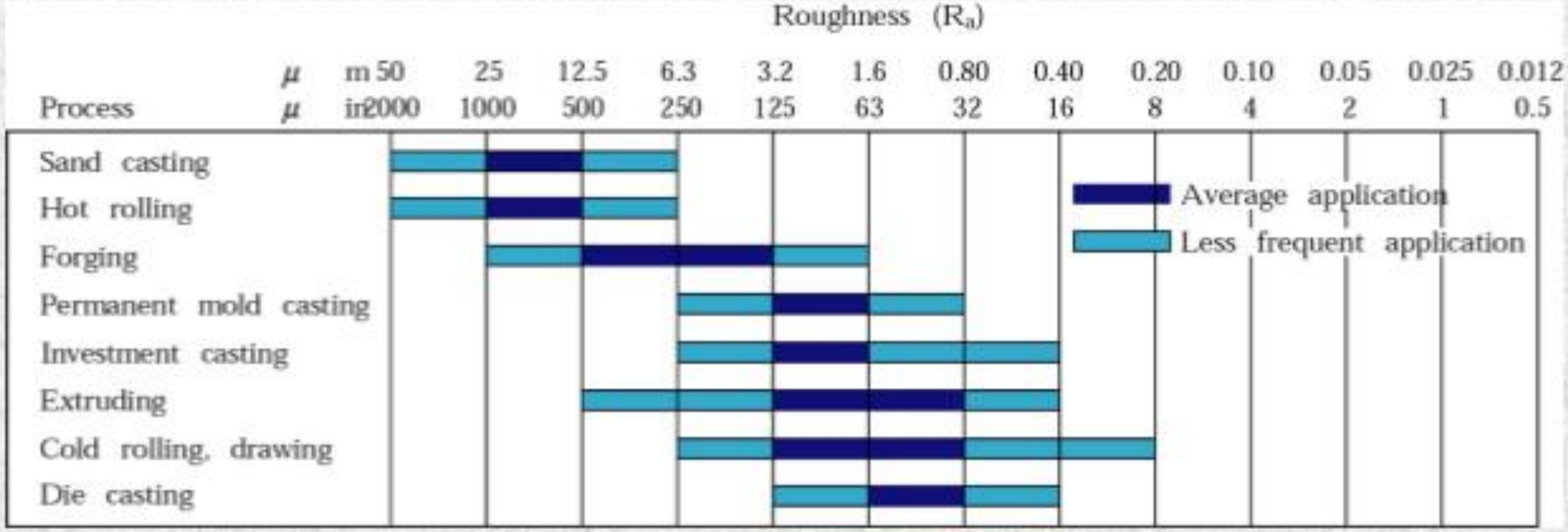


Figure 11.12 Surface roughness in casting and other metalworking processes. See also Figs. 22.14 and 26.4 for comparison with other manufacturing processes.

Shell Molding

- Used to get close dimensional tolerances and good surface finish at low cost.
- High precision parts include gear housing and connecting rods or high precision molding cores.
- In this process, a mounted pattern made of a ferrous metal or aluminum is:

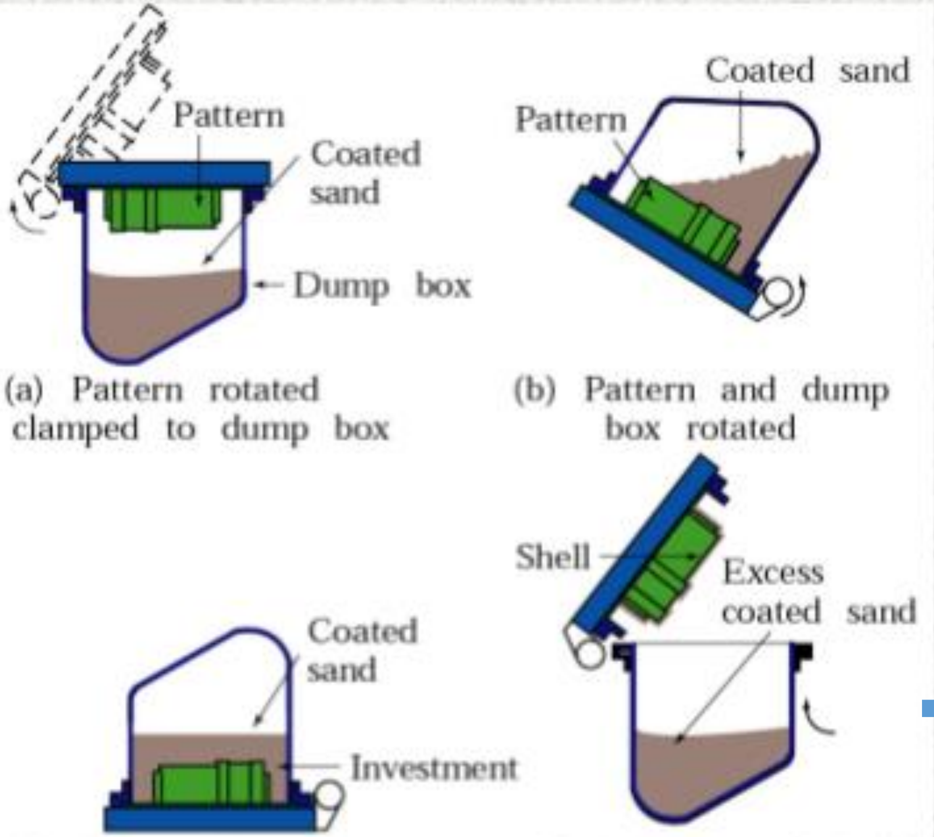
(a) Heated to a range of 175° to 37O°C,

(b) Coated with a parting agent (such as silicone), and

(c) Clamped to a box or chamber which contains fine sand mixed with 2.5-4 % of thermosetting resin binder that coats the sand powders.

(d) The sand mixture is blown over the pattern

Dump-Box Technique



(a) Pattern rotated and clamped to dump box

(b) Pattern and dump box rotated

(c) Pattern dump box in position for the investment

(d) Pattern and shell removed from dump box

Figure 11.13 A common method of making shell molds. Called *dump-box* technique, the limitations are the formation of voids in the shell and peelback (when sections of the shell fall off as the pattern is raised). *Source*: ASM International.

→ Then forming the Cavity

Video

Plaster Mold Casting

- Typical produced parts are: *gears, valves, fittings because of high precision dimensions needed.*
- The mold is made of plaster of paris (gypsum or calcium sulfate) with the addition of talc and silica flour to improve strength and to control the time required for the plaster to set.
- These components are mixed with water, and the resulting *slurry* is poured over the pattern. After the plaster sets (usually within 15 minutes), it is removed, and the mold is dried at a temperature range of 120° to 260°C. Higher drying temperatures may be used, depending on the type of plaster. The mold halves are assembled to form the mold cavity and are preheated to about 120°C. The molten metal is then poured into the mold.

Video

Ceramic Mold Casting

- The ceramic-mold casting process is *similar* to the plaster-mold process, except that it **uses refractory mold materials** suitable for high-temperature applications.
- Typical parts made are impellers, cutters for machining operations.
- The slurry is a mixture of fine-grained zircon ($ZrSiO_4$), aluminum oxide, and fused silica, which are mixed with bonding agents and poured over the pattern which has been placed in a flask.

Ceramic mold casting

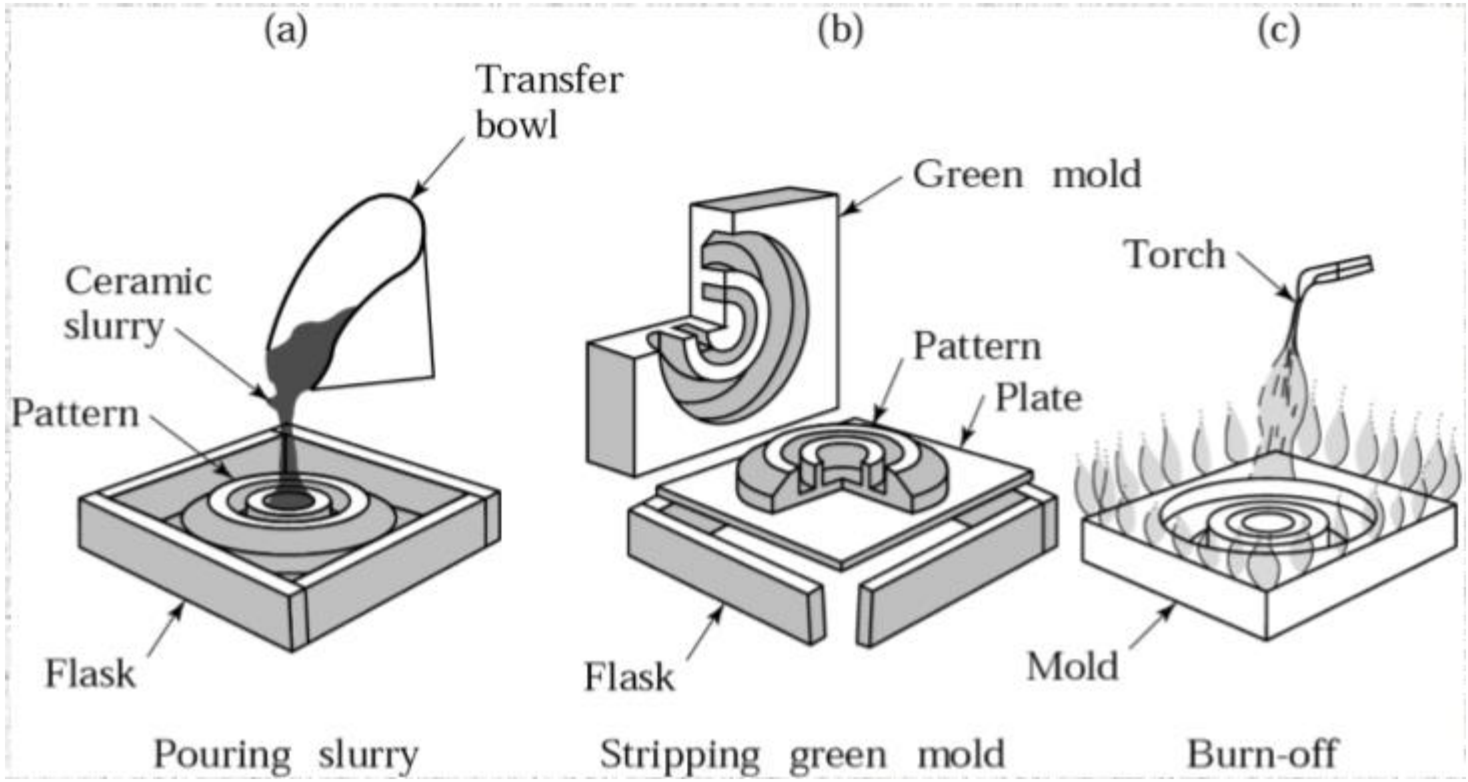
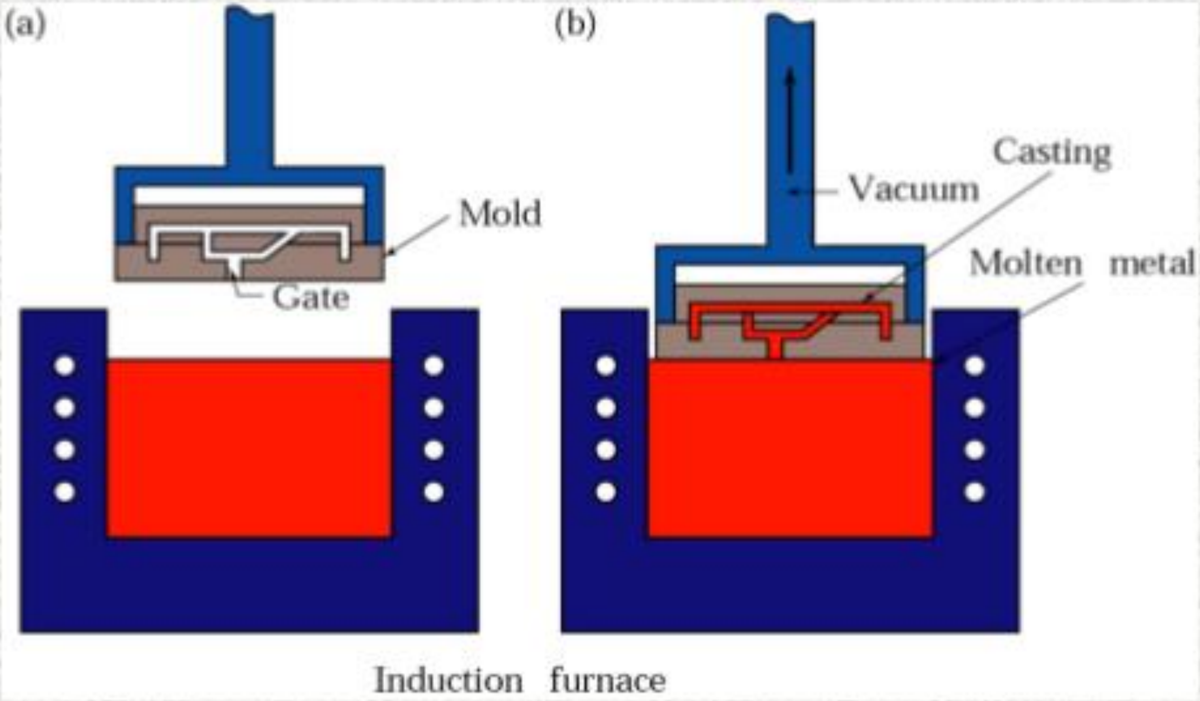


Figure 11.16 Sequence of operations in making a ceramic mold. *Source*: *Metals Handbook*, vol. 5, 8th ed.

Permanent Mold Casting Processes

- Two halves of a mold are made from materials with *high resistance to erosion and thermal fatigue*, such as cast iron, steel, bronze, graphite, or refractory metal alloys.
- Typical parts made are automobile pistons, cylinder heads, connecting rods.
- The mold cavity and gating system are machined into the mold and thus become an integral part of it.
- To produce castings with internal cavities, cores made of metal or sand aggregate are placed in the mold prior to casting

Vacuum-Casting Process



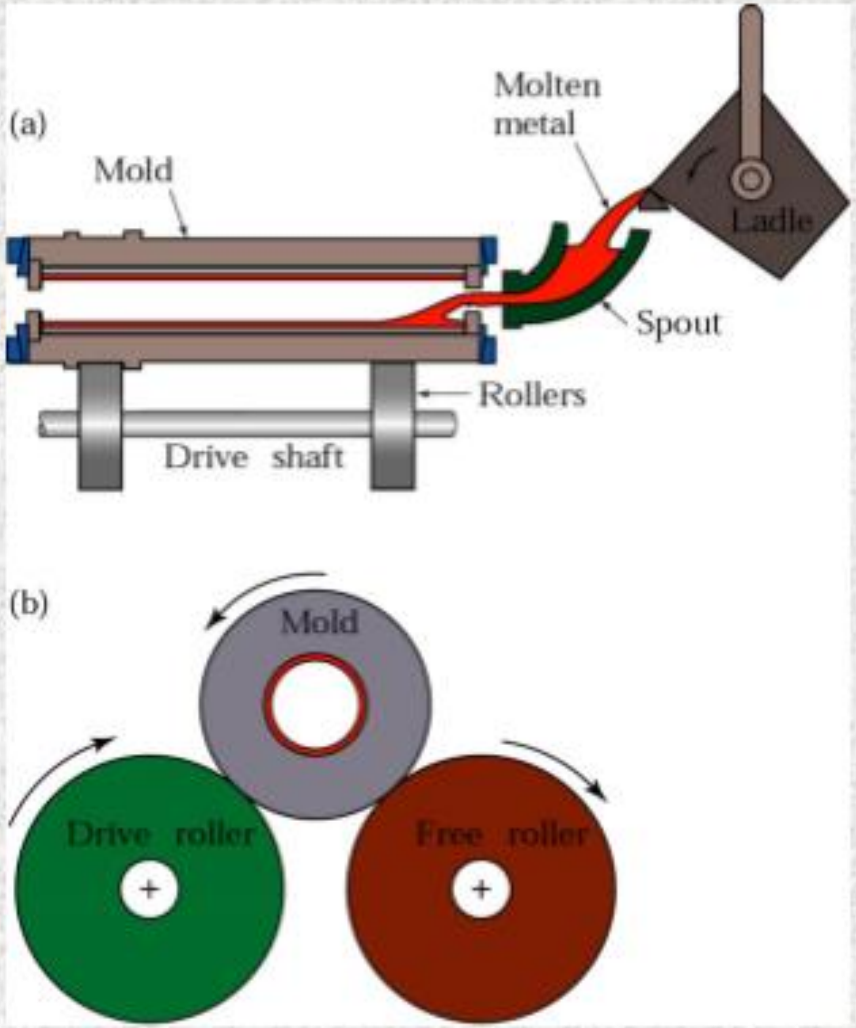
- The mold is held with a robot arm

-The vacuum reduces the air pressure inside the mold to about two-thirds of atmospheric pressure , thus drawing the molten metal into the mold Cavities.

Figure 11.21 Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal. *Source*: From R. Blackburn, "Vacuum Casting Goes Commercial," *Advanced Materials and Processes*, February 1990, p. 18. ASM International.

Video

Centrifugal Casting Process



- Products: hollow cylindrical parts (such as pipes, gun barrels)

- Molds are made of steel, iron, or graphite and may be coated with a refractory lining to increase mold life

Figure 11.27 Schematic illustration of the centrifugal casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process.

Video

Squeeze-Casting

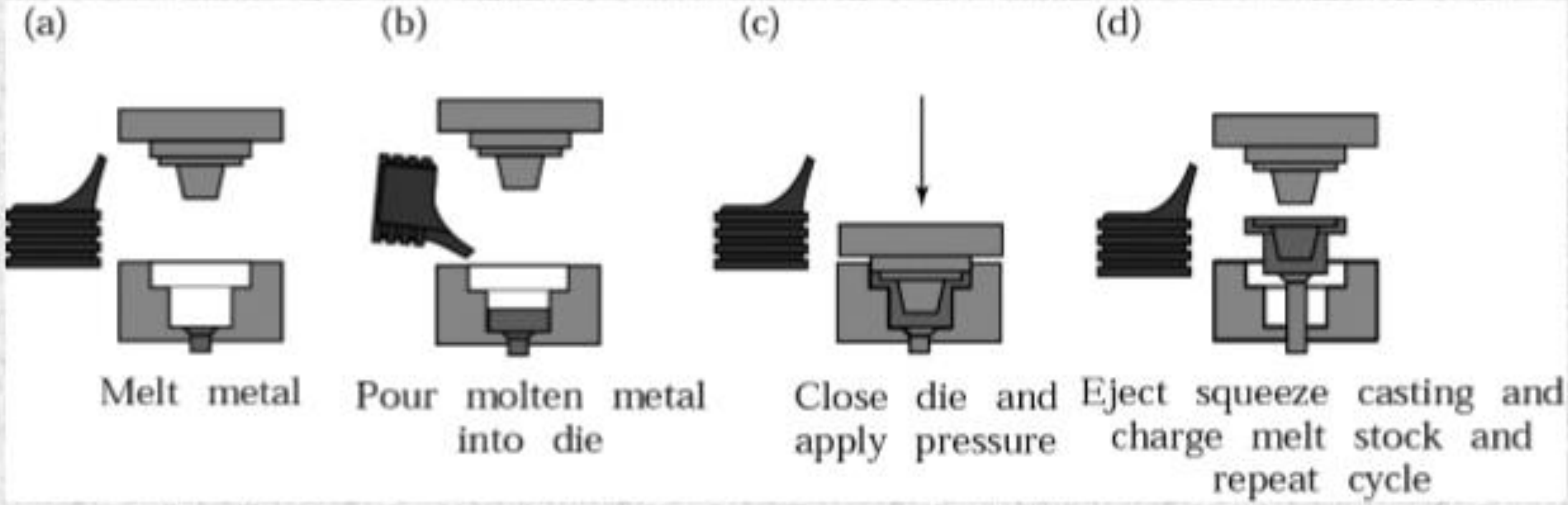


Figure 11.29 Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.

Video

Typical products made are automotive components and mortar bodies

Forming and Shaping Processes

Forming and Shaping Processes

- **Forming processes,** the starting material (usually called the workpiece, stock, or blank) may be in the shape of a plate, sheet, bar, rod, wire, or tubing of various cross sections.
- For example, an ordinary wire coat hanger is made by forming a straight piece of wire by bending and twisting it into the shape of a hanger.

- **Shaping processes** typically involve the molding and casting of soft or molten materials, and the finished product is usually at or near the final desired shape. It may require little or no further finishing.
- A plastic coat hanger, for example, is made by forcing molten plastic into a two-piece mold with a cavity in the shape of the hanger.
- The initial material used in forming and shaping metals is usually molten metal, which is cast into individual ingots or continuously cast into slabs, rods, or pipes. Cast structures are converted to wrought (Metal working) structures by plastic-deformation processes

TABLE III.1

General Characteristics of Forming and Shaping Processes

Process	Characteristics
Rolling	
Flat	Production of flat plate, sheet, and foil at high speeds; good surface finish, especially in cold rolling; very high capital investment; low-to-moderate labor cost
Shape	Production of various structural shapes (such as I-beams and rails) at high speeds; includes thread rolling; requires shaped rolls and expensive equipment; low-to-moderate labor cost; requires moderate operator skill
Forging	Production of discrete parts with a set of dies; some finishing operations usually required; usually performed at elevated temperatures, but also cold for smaller parts; die and equipment costs are high; moderate-to-high labor cost; requires moderate-to-high operator skill
Extrusion	Production of long lengths of solid or hollow shapes with constant cross section; product is then cut into desired lengths; usually performed at elevated temperatures; cold extrusion has similarities to forging and is used to make discrete products; moderate-to-high die and equipment cost; low-to-moderate labor cost; requires low-to-moderate operator skill
Drawing	Production of long rod and wire with various cross sections; good surface finish; low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill
Sheet-metal forming	Production of a wide variety of shapes with thin walls and simple or complex geometries; generally low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill
Powder metallurgy	Production of simple or complex shapes by compacting and sintering metal powders; moderate die and equipment cost; low labor cost and skill
Processing of plastics and composite materials	Production of a wide variety of continuous or discrete products by extrusion, molding, casting, and fabricating processes; moderate die and equipment costs; requires high operator skill in processing of composite materials
Forming and shaping of ceramics	Production of discrete products by various shaping, drying, and firing processes; low-to-moderate die and equipment cost; requires moderate-to-high operator skill

Metal Rolling Process

- **Rolling** is the process of reducing the thickness or changing the cross section of a long workpiece by compressive forces applied through a set of rolls.

- **Plates** generally have a thickness of more than 6 mm and are used for structural applications, such as ship hulls, boilers, bridges, machinery, and nuclear vessels. Plates can be as thick as 300 mm for large structural supports, 150 mm for reactor vessels, and 100 to 125 mm for machinery frames and warships.

- **Sheets** generally are less than 6 mm thick and typically are provided to manufacturing facilities as coils-weighing as much as 30,000 kg-or as flat sheets for further processing into various products

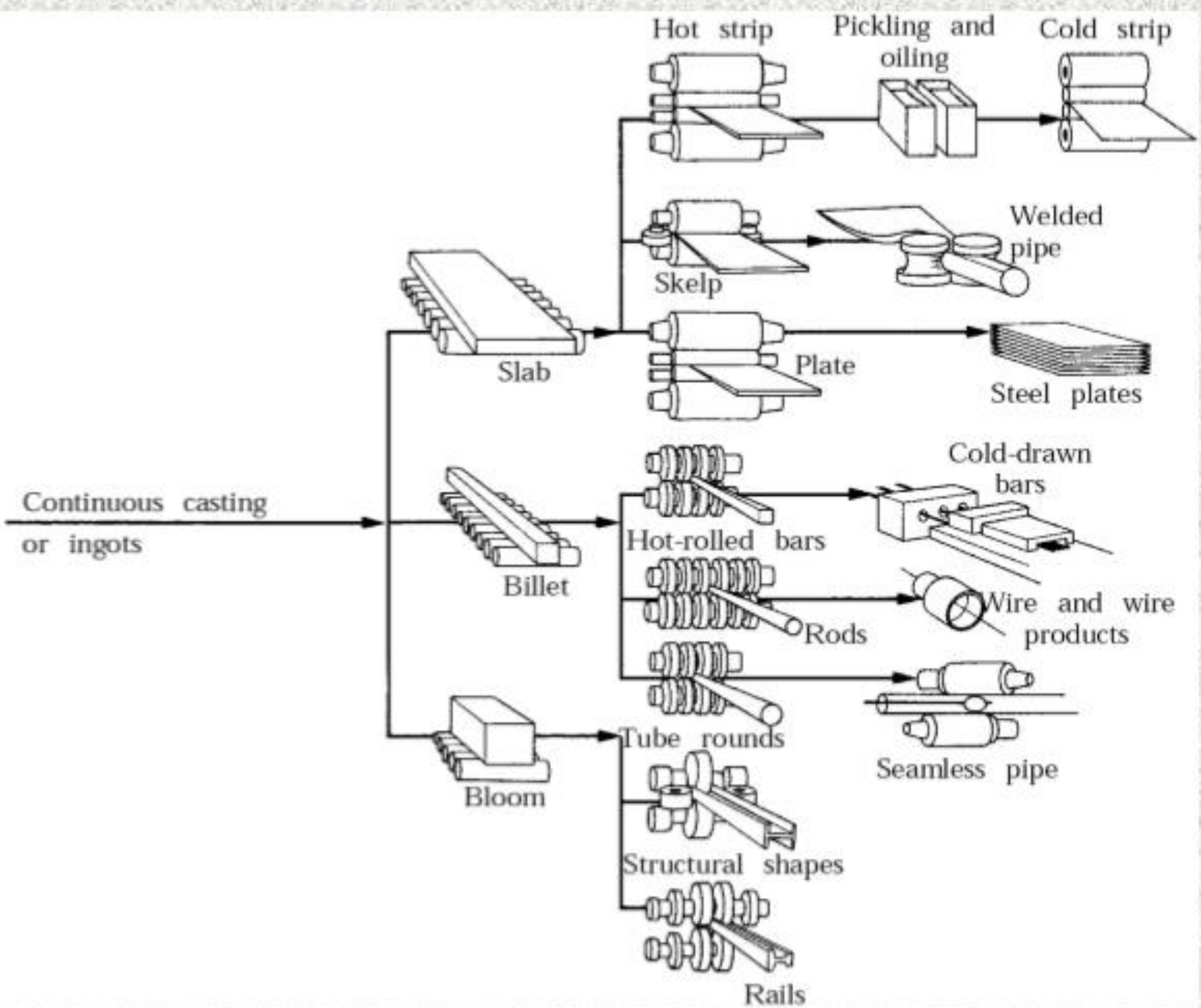


Figure 13.1 Schematic outline of various flat- and shape-rolling processes. *Source*: American Iron and Steel Institute.

Pickling is a metal surface treatment used to remove impurities

Video

Flat-Rolling

The rolls pull the material into the roll gap through a net frictional force on the material. friction is necessary for rolling materials

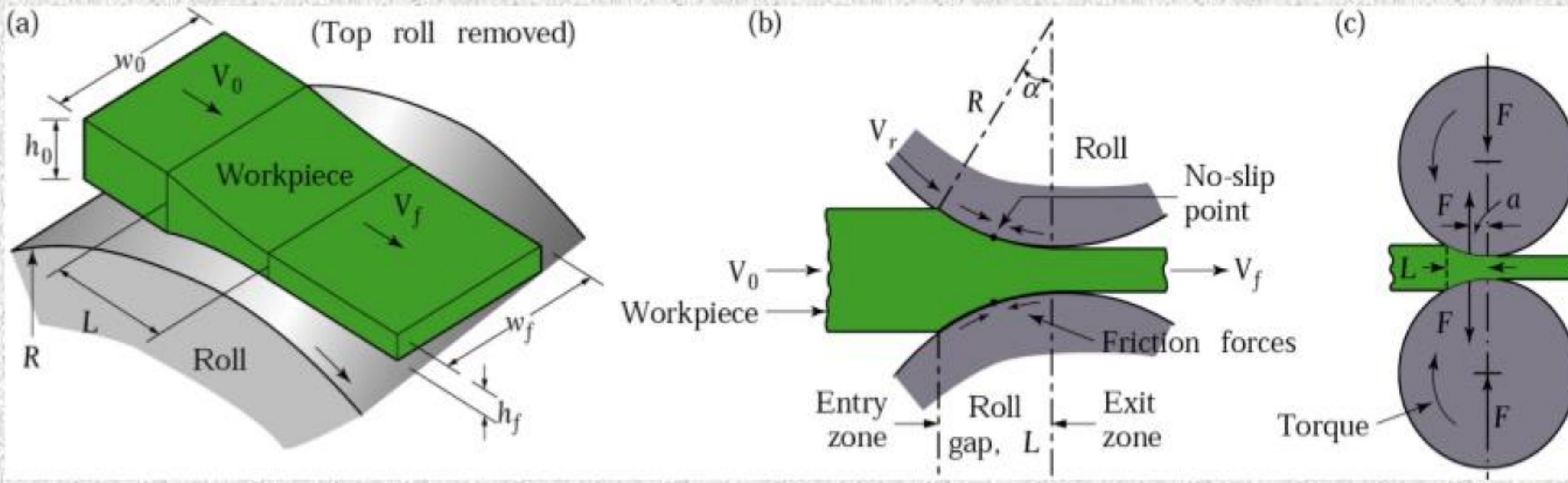


Figure 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) The roll force, *F*, and the torque acting on the rolls. The width *w* of the strip usually increases during rolling, as is shown in Fig. 13.5.

- Initial thickness h_o • Final thickness h_f • Roll gap L
- Surface speed of rolls V_r • Entry velocity of strip V_o
- Final velocity of the strip V_f
- Neutral point, no-slip point – point along contact length where velocity of the strip equals velocity of the roll

roll radius, *R*, and the coefficient of friction, μ,

Video

The maximum possible draft is defined as the difference between the initial and final strip thicknesses, or $(h_o - h_f)$

$$h_o - h_f = \mu^2 R.$$

roll radius, R, and the coefficient of friction, μ,

The roll force in flat rolling can be estimated from the formula:

$$F = LwY_{avg},$$

where L is the roll-strip contact length, W is the width of the strip, and Y_{avg} is the average true stress.

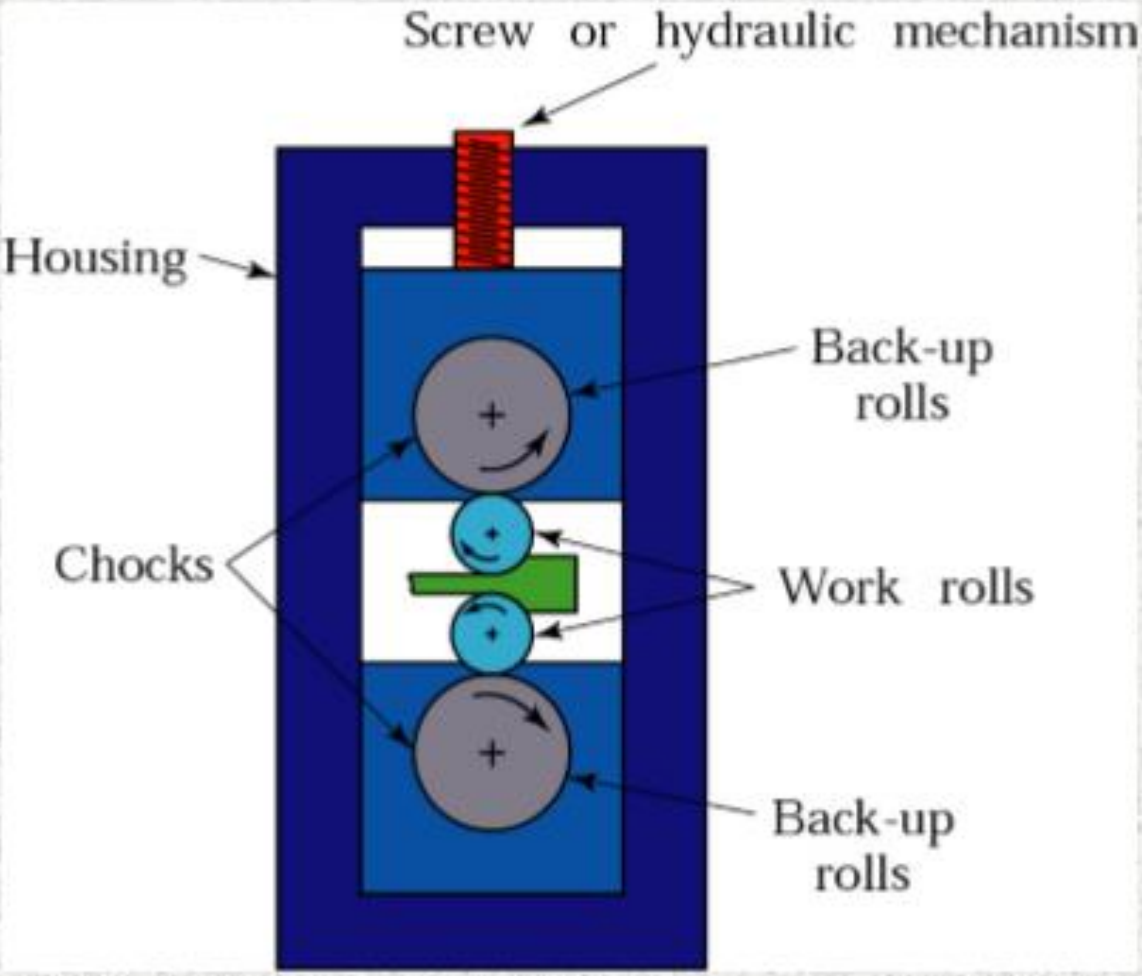
the total power (for two rolls), in S.I. units, is

$$\text{Power (in kW)} = \frac{2\pi FLN}{60{,}000}$$

N=rpm

Four-High Rolling Mill

Figure 13.3 Schematic illustration of a four-high rolling-mill stand, showing its various features. The stiffnesses of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip.

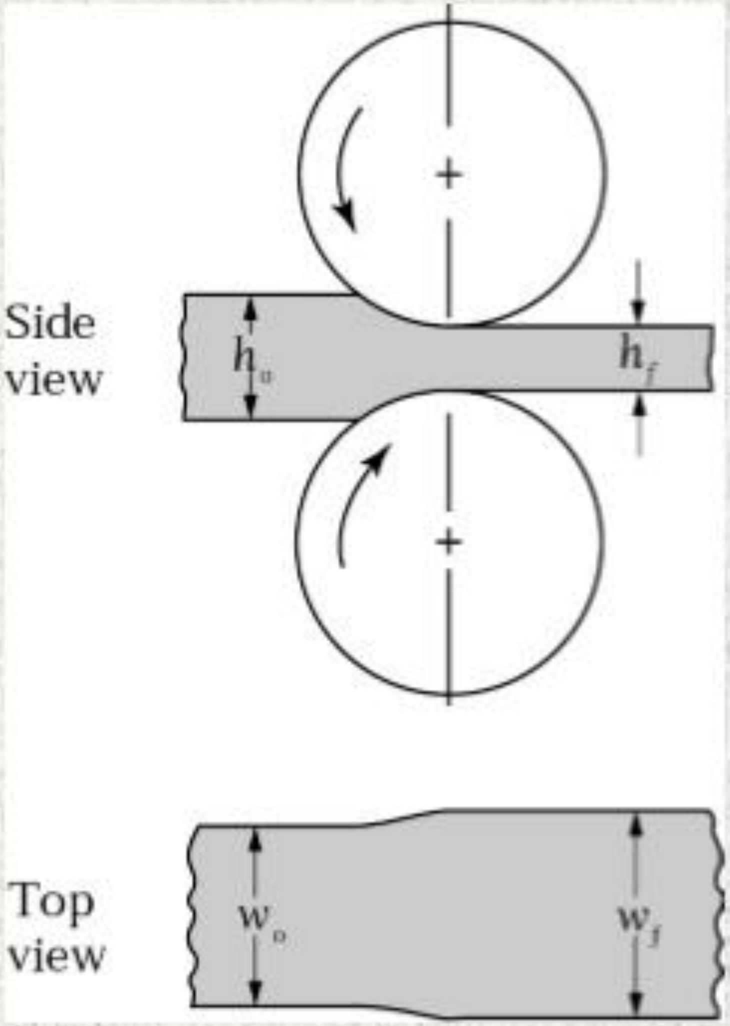


Roll forces can be reduced by the following means:

- Reducing friction at the roll-workpiece interface °
- Using smaller diameter rolls to - reduce the contact area
- Taking smaller reductions per pass to reduce the contact area
- Rolling at elevated temperatures to lower the strength of the material

Video

Spreading of a Strip



This increase in width is called spreading.

spreading increases with:

(a) decreasing width-to-thickness ratio of the entering strip

(b) increasing friction

(c) decreasing ratio of the roll radius to the strip thickness

Figure 13.5 Increase in the width (spreading) of a strip in flat rolling (see also Fig. 13.2a). Similarly, spreading can be observed when dough is rolled with a rolling pin.

Shape Rolling

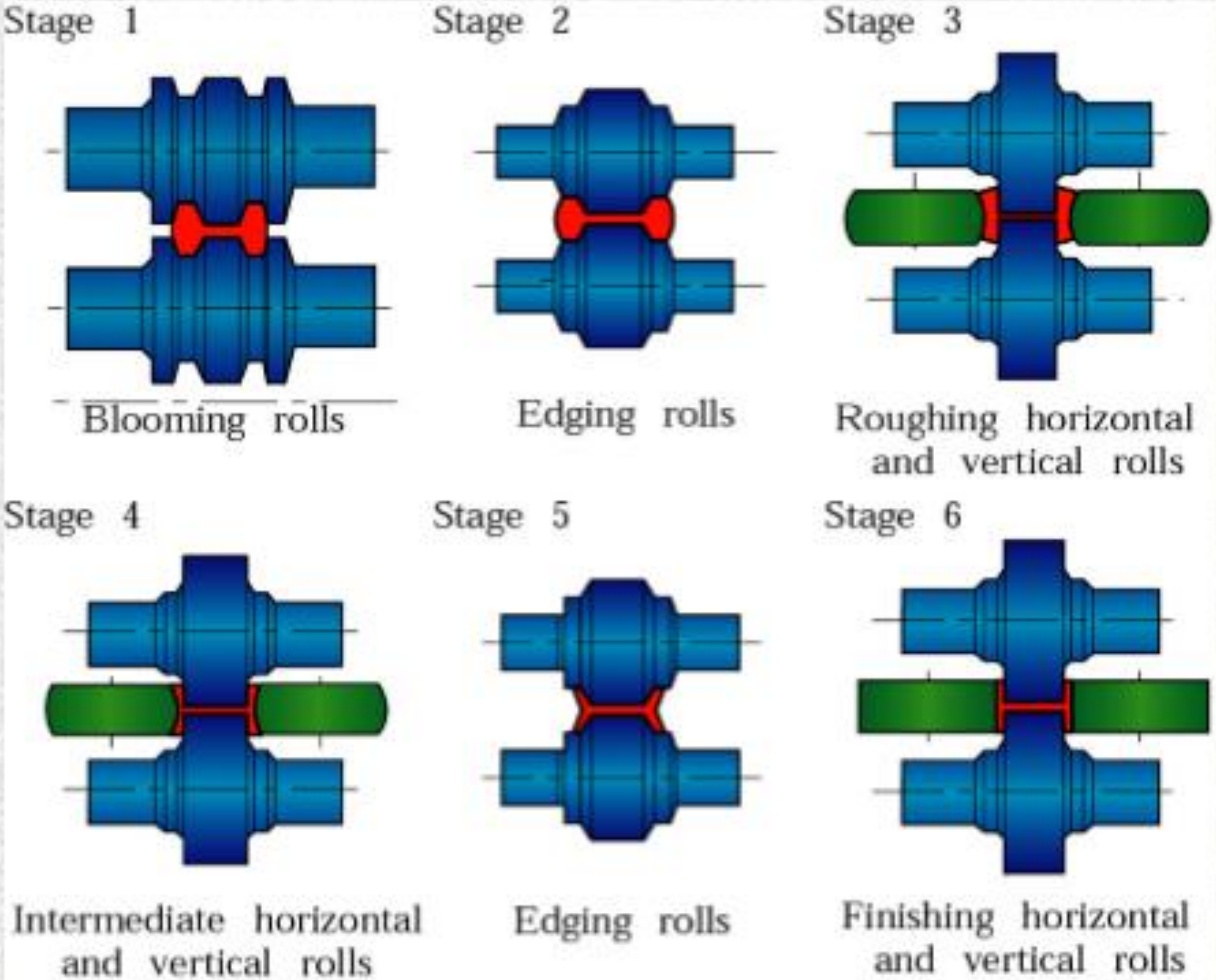


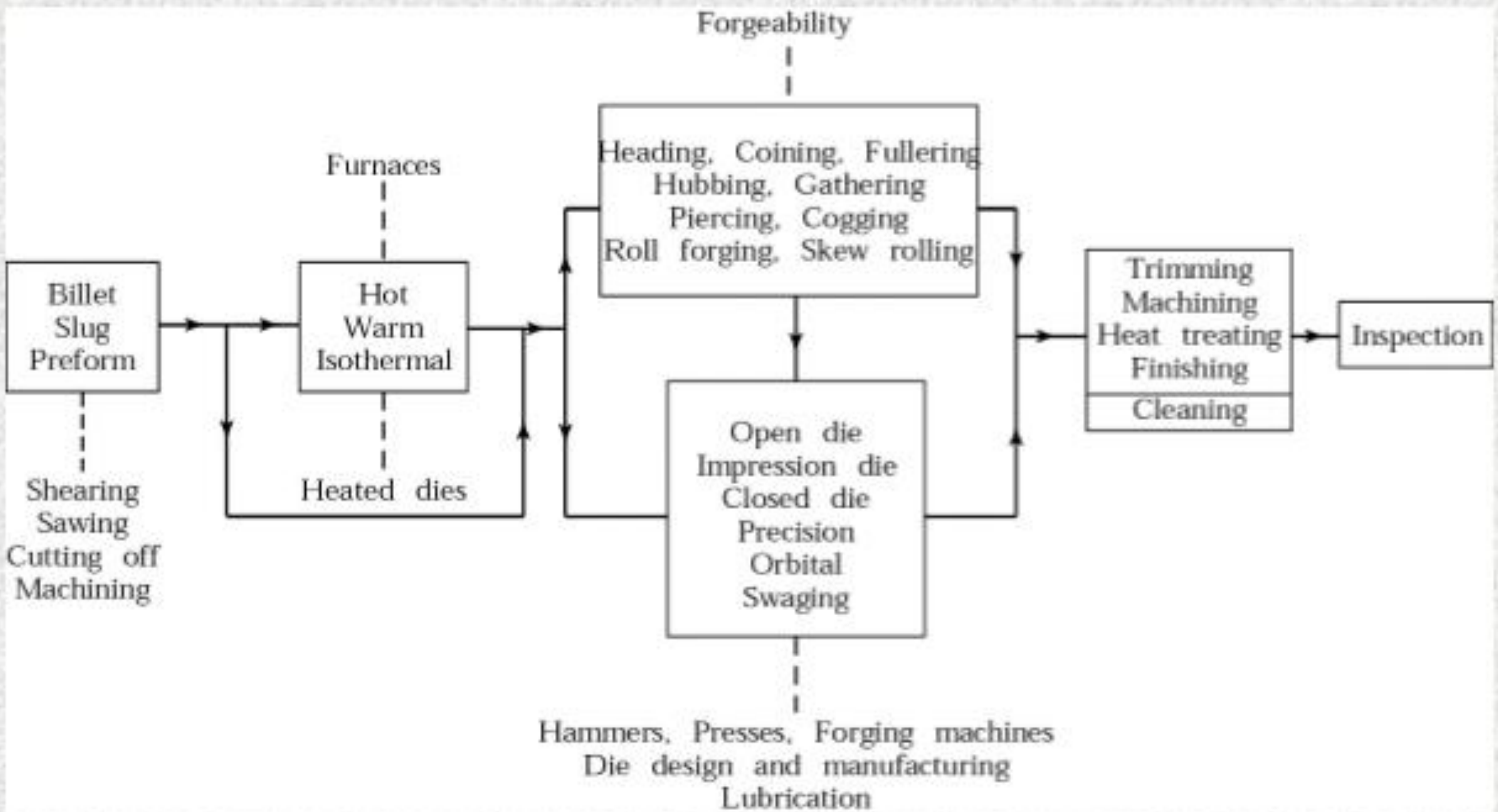
Figure 13.13 Stages in the shape rolling of an H-section part. Various other structural sections, such as channels and I-beams, are also rolled by this kind of process.

Straight and long structural shapes (such as channels, I-beams, railroad rails, and solid bars) are formed at elevated temperatures by shape rolling

Metal forging process

- **Forging** is a basic process in which the workpiece is shaped by *compressive forces* applied through various dies and tooling.
- Unlike rolling operations that generally produce continuous plates, sheets, strips, or various structural cross sections, forging operations produce ***discrete parts*** such as large rotors for turbines; gears; bolts and rivets; cutlery.
- Because the metal flow in a die and the material's grain structure can be controlled, *forged parts have good strength and toughness*, and are very reliable for highly stressed and critical applications.
- Forging may be carried out at room temperature (*cold forging*) or at elevated temperatures (warm or *hot forging*) depending on the temperature and material type.
- Forgings generally are subjected to *additional finishing operations*, such as heat treating to modify properties and machining to obtain accurate final dimensions and a good surface finish

Outline of Forging and Related Operations



Characteristics of Forging Processes

TABLE 14.1

Process	Advantages	Limitations
Open die	Simple, inexpensive dies; useful for small quantities; wide range of sizes available; good strength characteristics	Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; relatively poor utilization of material; high degree of skill required
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost for small quantities; machining often necessary
Blocker type	Low die costs; high production rates	Machining to final shape necessary; thick webs and large fillets necessary
Conventional type	Requires much less machining than blocker type; high production rates; good utilization of material	Somewhat higher die cost than blocker type
Precision type	Close tolerances; machining often unnecessary; very good material utilization; very thin webs and flanges possible	Requires high forces, intricate dies, and provision for removing forging from dies

Upsetting

Open die Forging

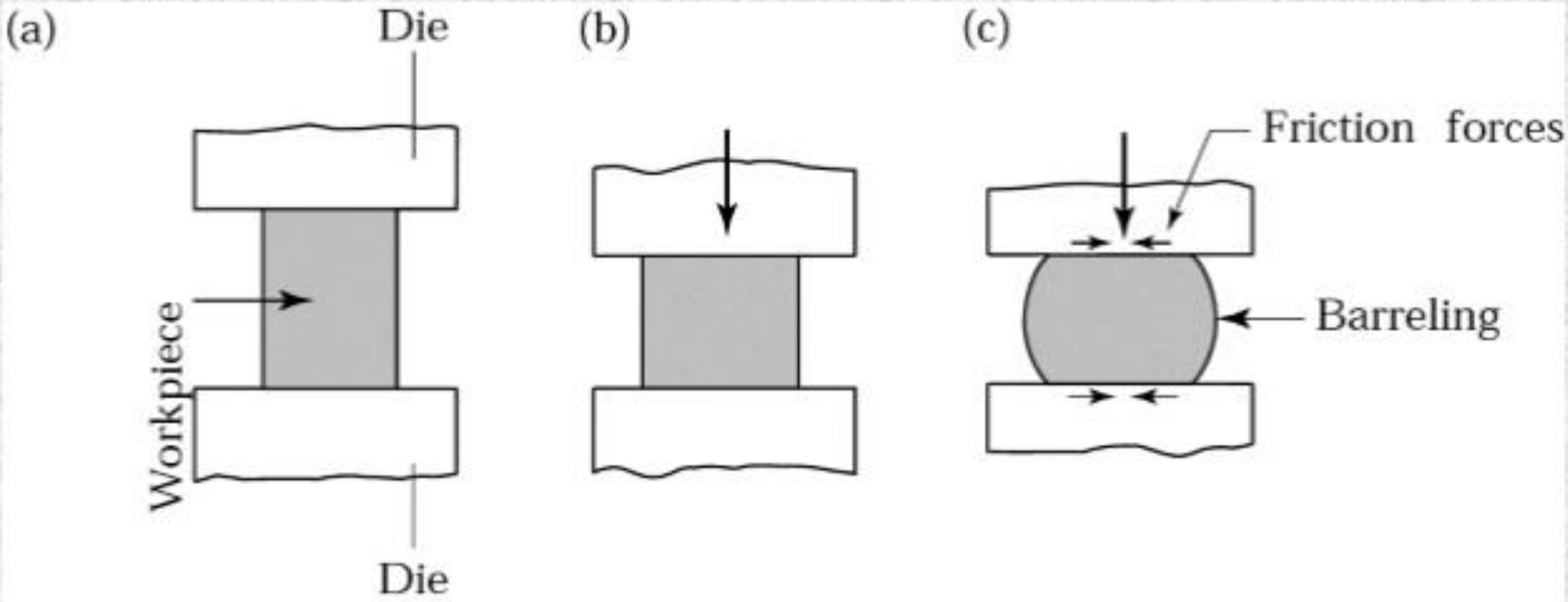


Figure 14.4 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction. Note barreling of the billet caused by friction forces at the billet-die interfaces.

- Part sizes may range from very small (the size of nails, pins, and bolts) to very large
- Open-die forging can be done by a solid workpiece placed between two flat dies and reduced in height by compressing it

Video

Impression-Die Forging

Closed die Forging

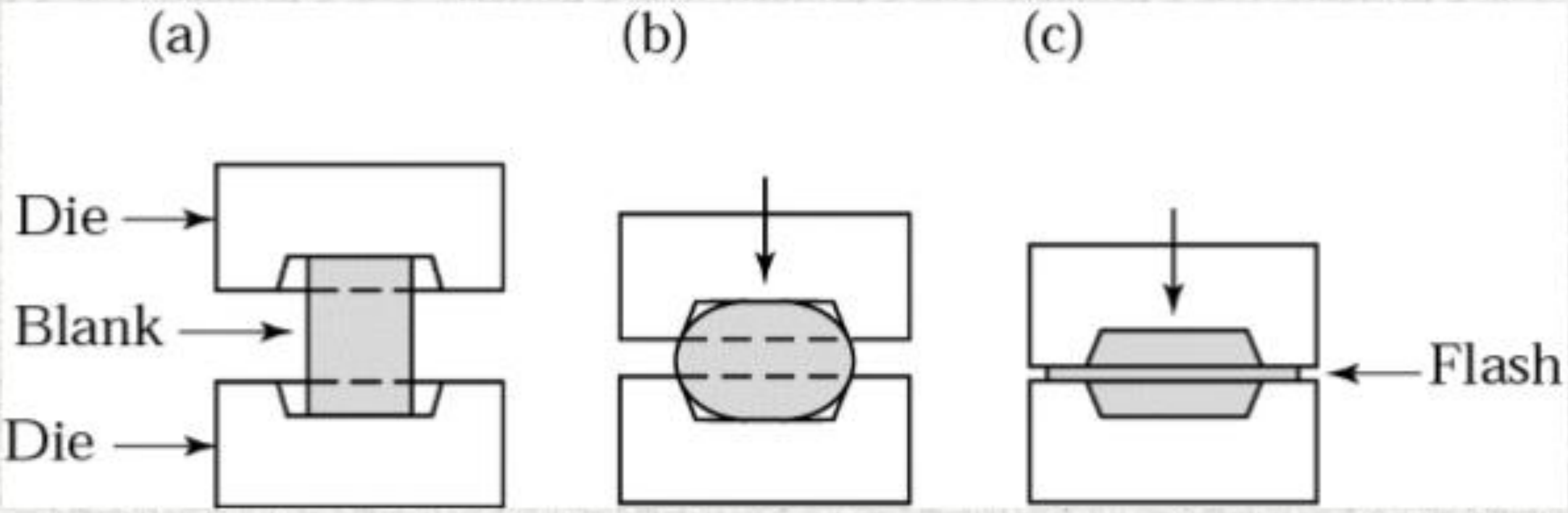


Figure 14.6 Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off (see Fig. 14.8).

The workpiece takes the shape of the die cavity while being forged between two shaped dies
This process usually is carried out at elevated temperatures to lower the required forces and attain enhanced ductility in the workpiece

Video

Metal extrusion process

- In extrusion, a cylindrical billet is forced through a die in a manner similar to squeezing toothpaste from a tube or extruding Play-Doh in various cross sections in a toy press.

- A wide variety of solid or hollow cross sections may be produced by extrusion, which essentially are semi-finished parts.

- A characteristic of extrusion (from the Latin extrudere, meaning “to force out”) is that large deformations can take place without fracture.

- Typical products made by extrusion are railings for slide doors, window frames, tubing, almunium ladder frames.

- Commonly extruded materials are aluminum, copper, steel, magnesium, and lead; other metals and alloys also can be extruded, with various levels of difficulty.

Direct Extrusion

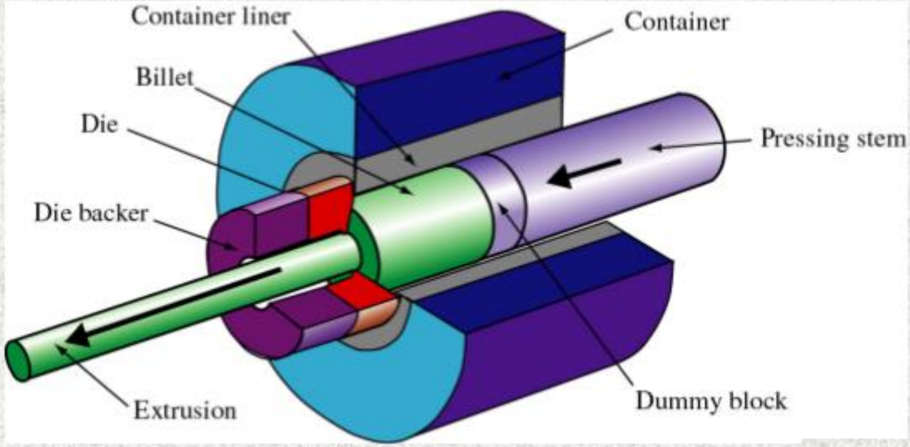


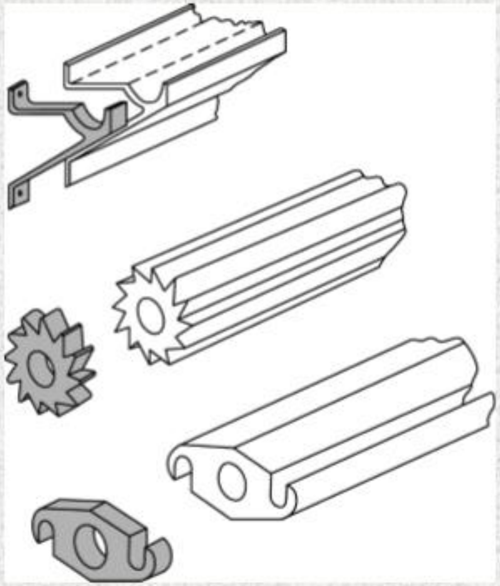
Figure 15.1 Schematic illustration of the direct extrusion process.

A billet is placed in a chamber (container) and forced through a die opening by a hydraulically driven ram (pressing stem or punch).

The die opening may be round, or it may have various shapes, depending on the desired profile

Extrusions

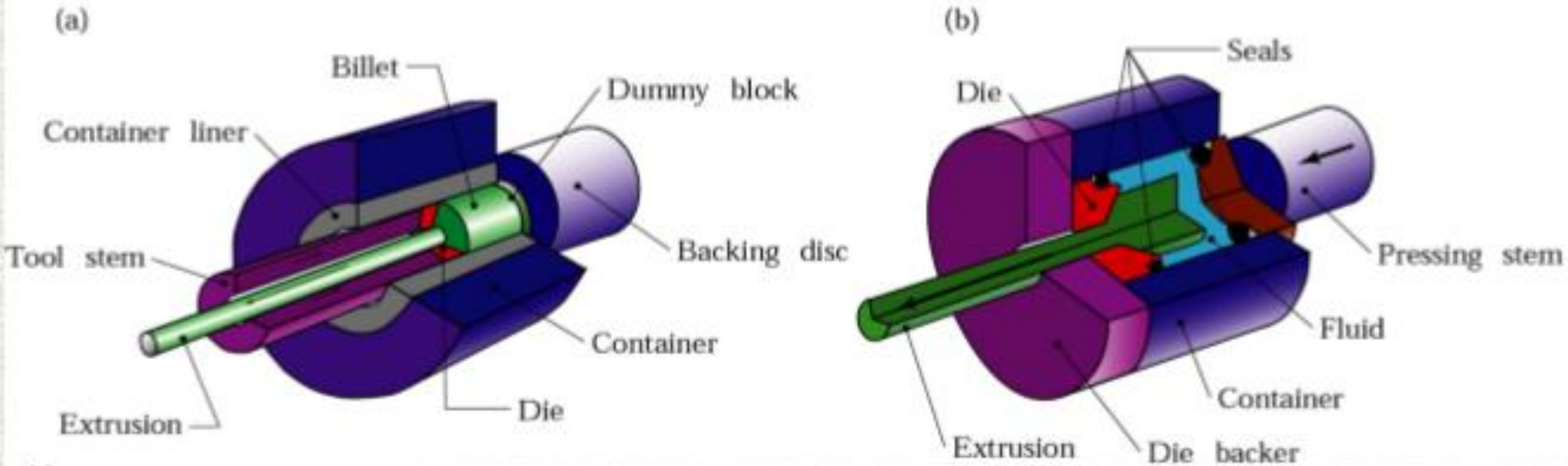
Figure 15.2 Extrusions, and examples of products made by sectioning off extrusions. *Source*: Kaiser Aluminum.



Extrusions can be cut into desired lengths, which then become discrete parts, such as brackets, gears, and coat hangers

Video

Types of Extrusion



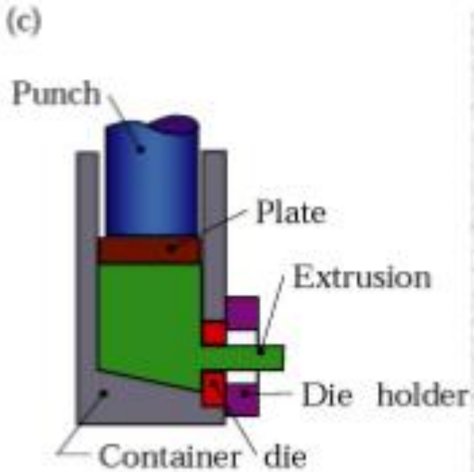


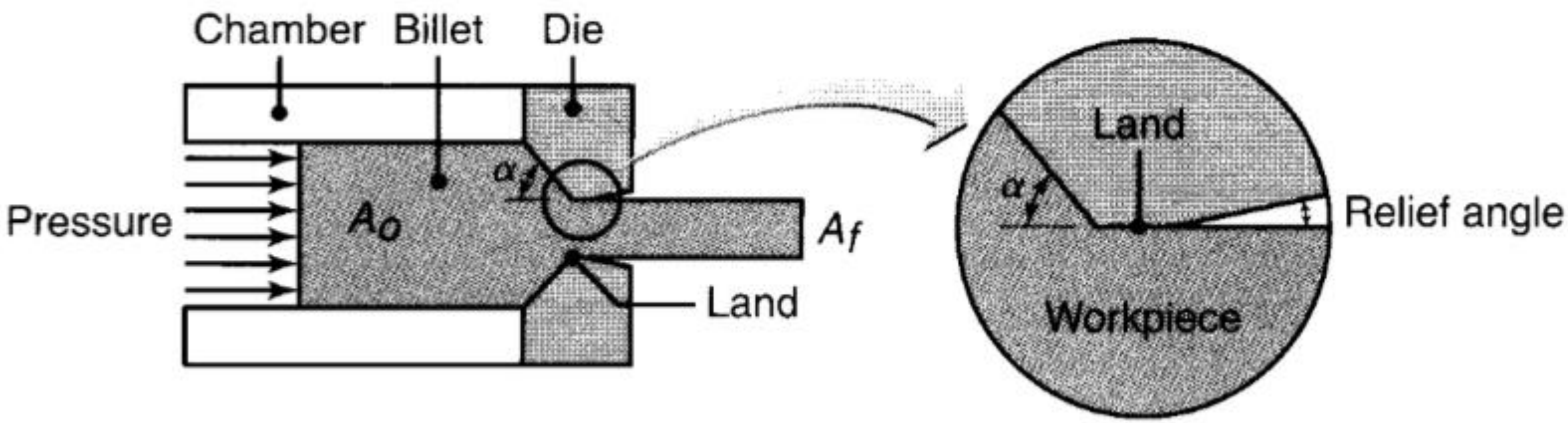
Figure 15.3 Types of extrusion: (a) indirect; (b) hydrostatic; (c) lateral.

In indirect extrusion (also called reverse, inverted, or backward extrusion), the die moves toward the unextruded billet

Indirect extrusion has the advantage of having no billet-container friction, since there is no relative motion. Thus, indirect extrusion is used on materials with very high friction, such as high strength steels.

Video

Extrusion force



The force required for extrusion depends on
(a) the strength of the billet material,
(b) The extrusion ratio
(c) The friction between the billet and the chamber and die surface.
(d) Temperature and speed of extrusion

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right),$$

where k is the **extrusion constant** (which is determined experimentally) and A_o and A_f are the billet and extruded product areas, respectively. The k value in Eq. (15.1) is thus a measure of the strength of the material being extruded and the frictional conditions.

Extrusion constant for different materials

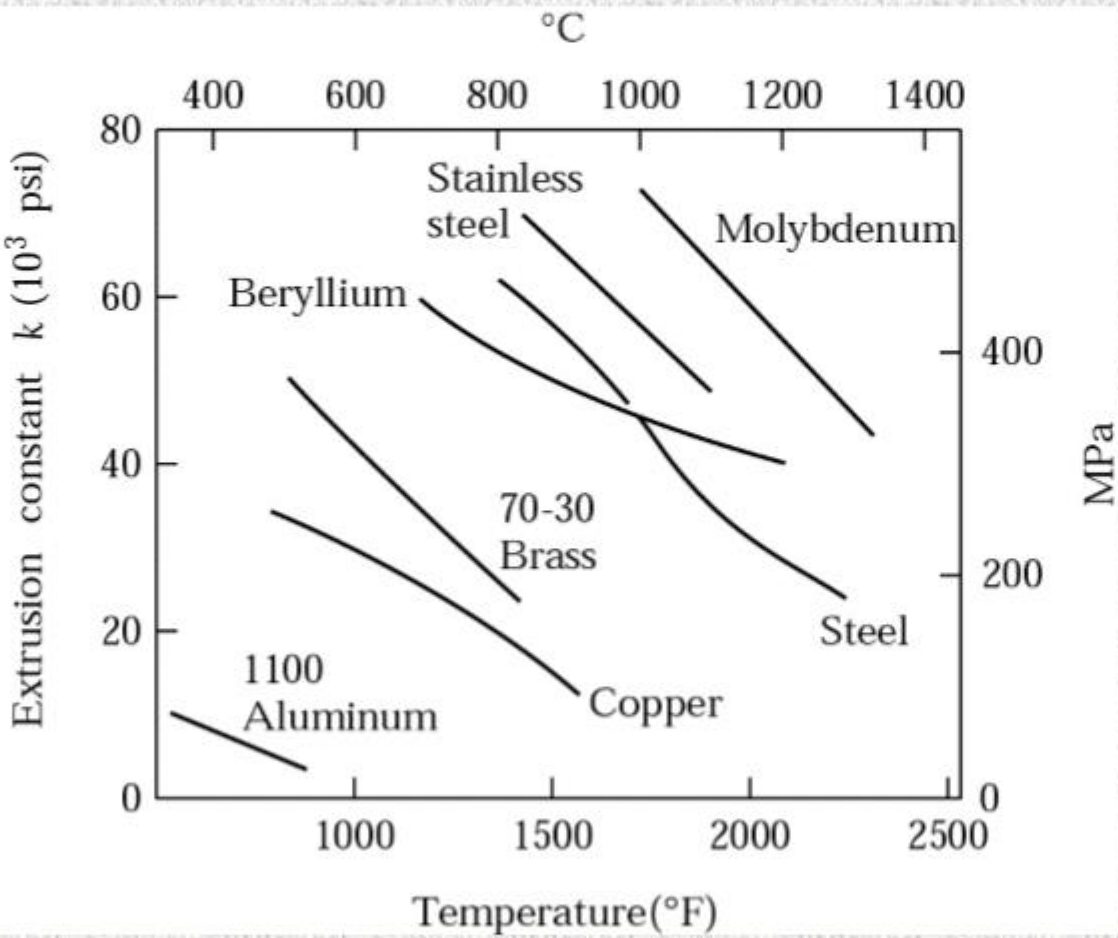


Figure 15.6 Extrusion constant *k* for various metals at different temperatures. *Source*: P. Loewenstein.

The drawing process

- In **drawing**, the cross section of a long rod or wire is reduced or changed by *pulling* (hence the term drawing) it through a die called a draw die.
- The difference between drawing and extrusion is that in extrusion the material is **pushed** through a die, whereas in drawing it is **pulled** through it.
- The major processing variables in drawing are similar to those in extrusion that is, reduction in cross-sectional area, die angle, friction along the die-workpiece interface, and drawing speed. *The die angle influences the drawing force and the quality of the drawn product.*

Process Variables in Wire Drawing

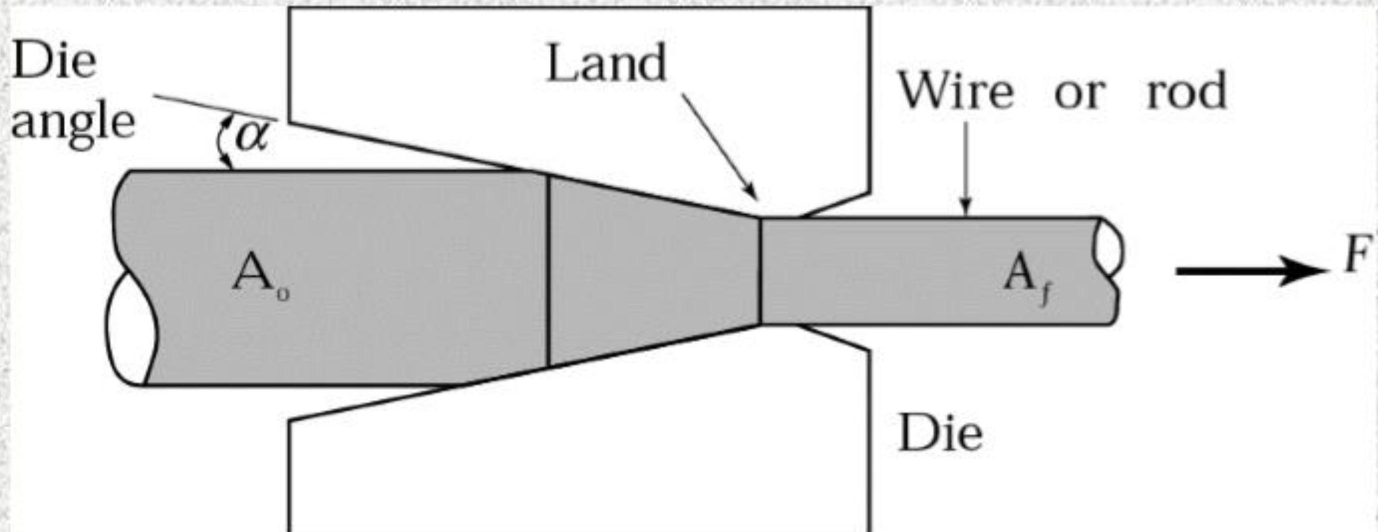


Figure 15.18 Process variables in wire drawing. The die angle, the reduction in cross-sectional area per pass, the speed of drawing, the temperature, and the lubrication all affect the drawing force, *F*.

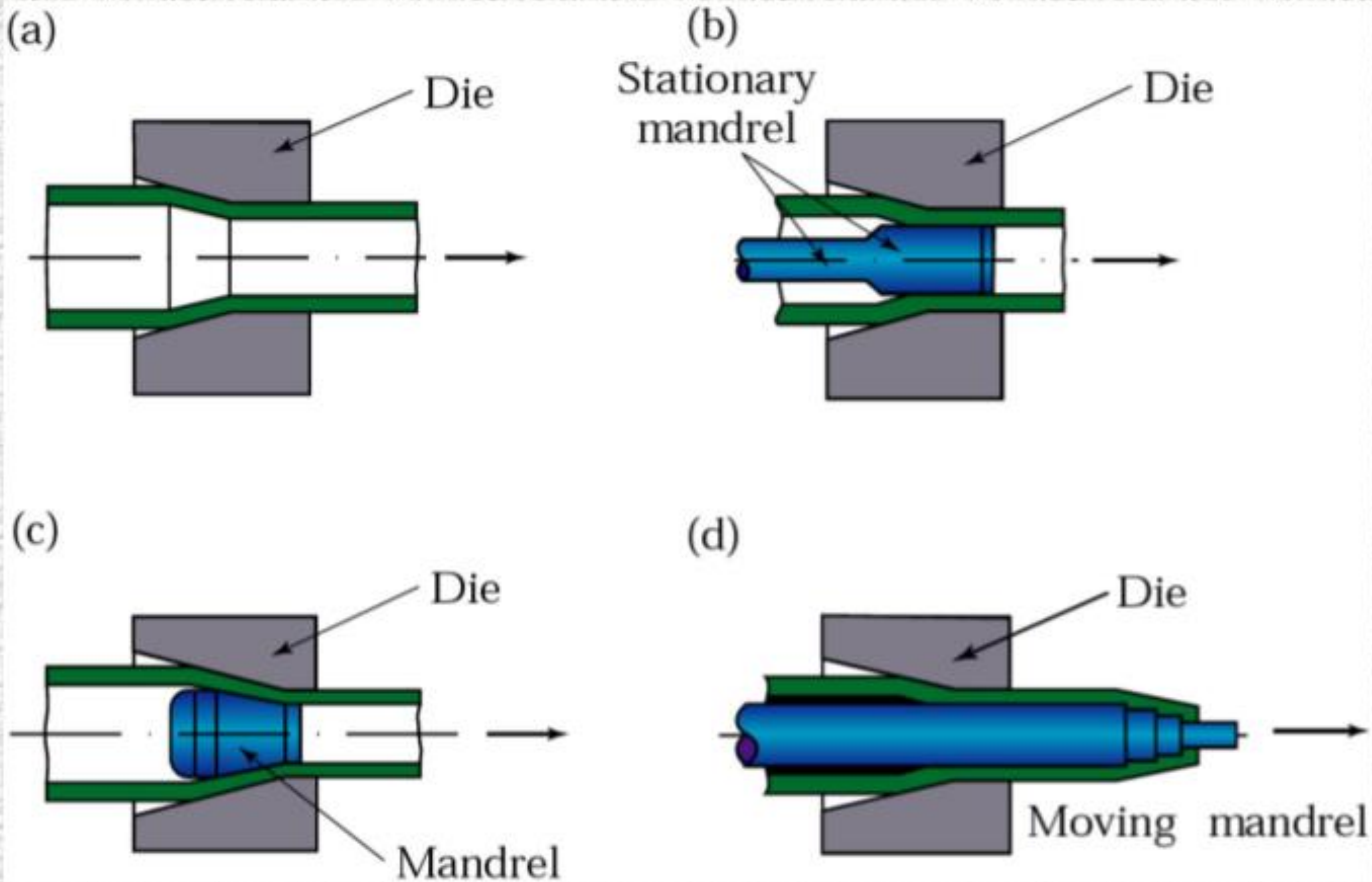
Drawing force $$F = Y_{avg} A_f \ln\left(\frac{A_o}{A_f}\right),$$

where Y_{avg} is the average true stress of the material in the die gap.

Video

Examples of Tube-Drawing Operations

Figure 15.19 Examples of tube-drawing operations, with and without an internal mandrel. Note that a variety of diameters and wall thicknesses can be produced from the same initial tube stock (which has been made by other processes).



Machining Processes

The turning process

- One of the most basic machining processes is turning where the part is rotated while it is being machined.

- The starting material is generally a workpiece that has been made by other processes, such as casting, forging, extrusion, or drawing.

- Turning processes, which typically are carried out on a lathe or by similar machine tools.

Components of a Lathe

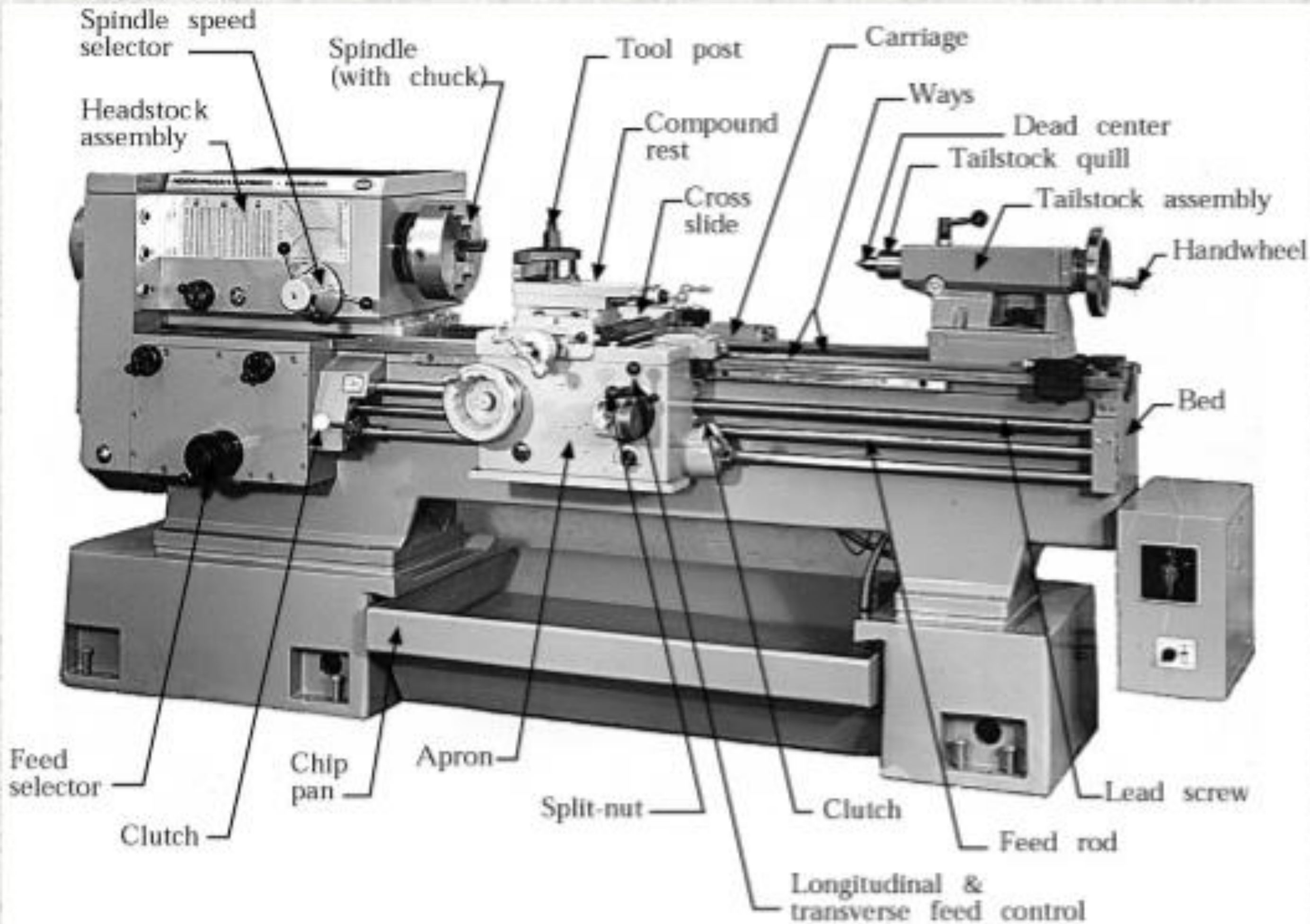


Figure 22.2 Components of a lathe. *Source*: Courtesy of Heidenreich & Harbeck

Cutting Tool Material Hardnesses

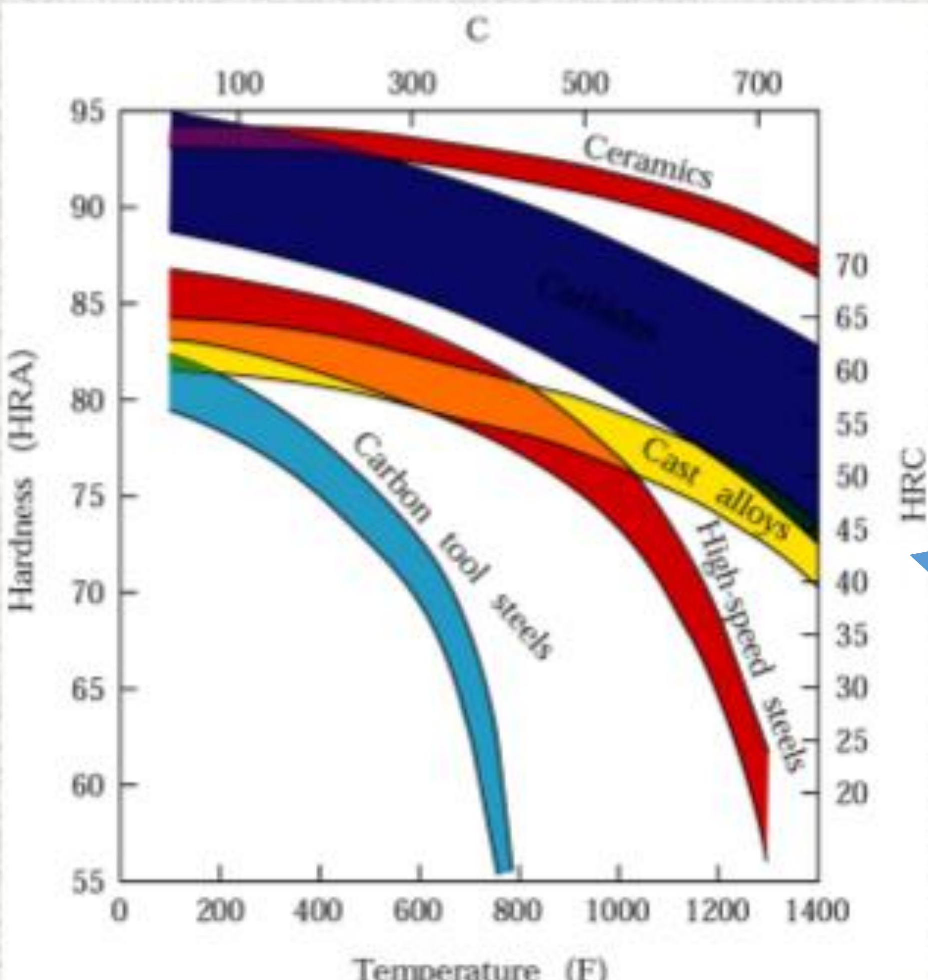
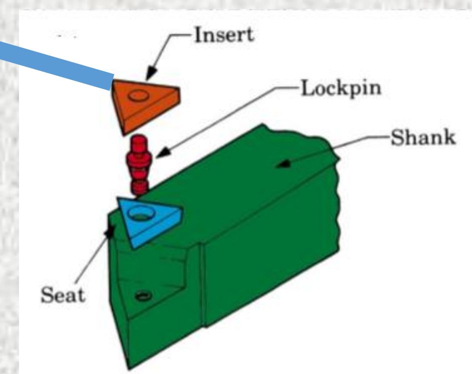
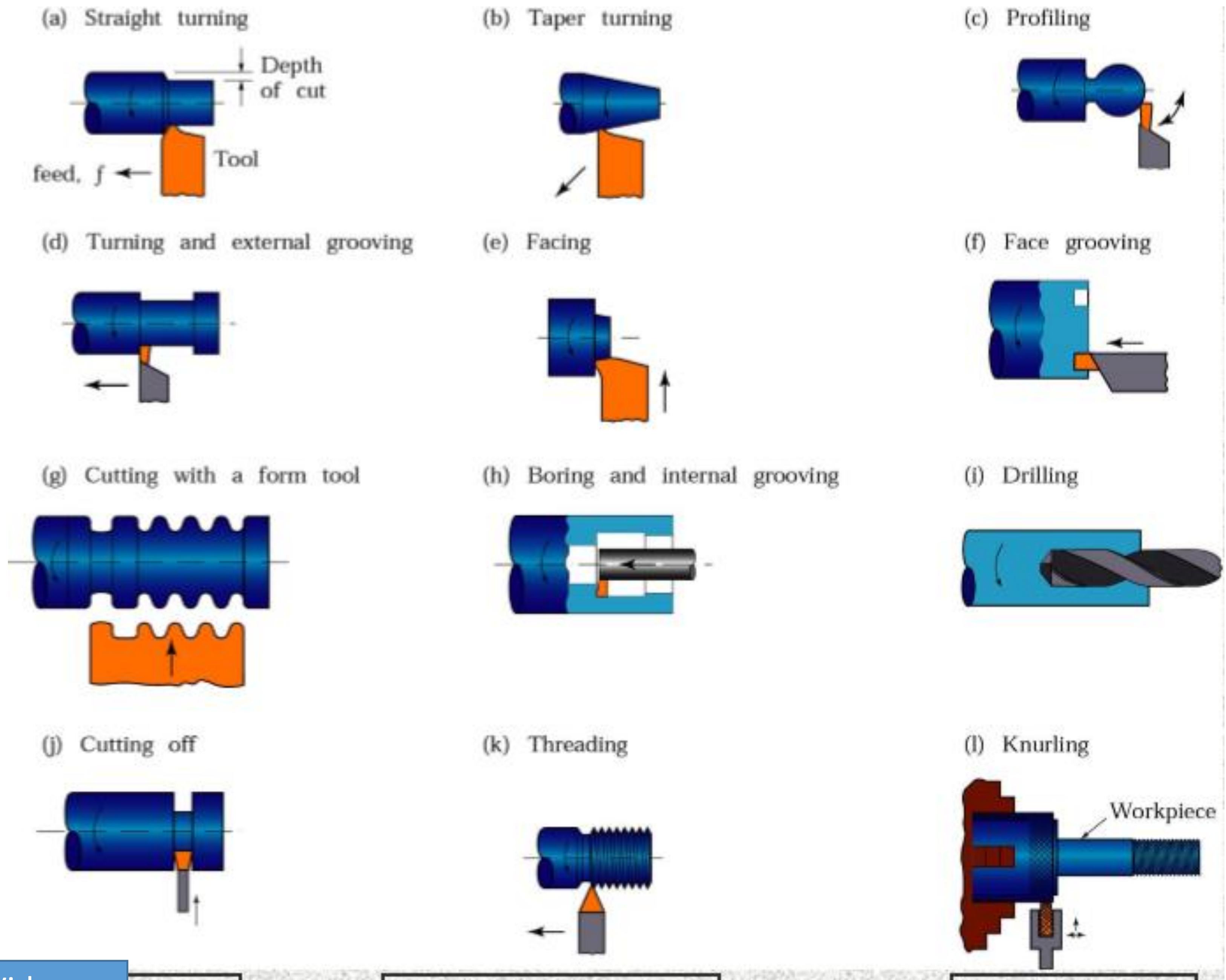


Figure 21.1 The hardness of various cutting-tool materials as a function of temperature (hot hardness). The wide range in each group of materials is due to the variety of tool compositions and treatments available for that group. See also Table 21.1 for melting or decomposition temperatures of these materials.




(a) Straight turning
Depth of cut
Tool
feed, f
(b) Taper turning
(c) Profiling
(d) Turning and external grooving
(e) Facing
(f) Face grooving
(g) Cutting with a form tool
(h) Boring and internal grooving
(i) Drilling
(j) Cutting off
(k) Threading
(l) Knurling
Workpiece

Video

- **Turning:** to produce straight, conical, curved, or grooved workpieces ,such as shafts, spindles, and pins.
- **Facing:** to produce a flat surface at the end of the part and perpendicular to its axis ,useful for parts that are assembled with other components. Face grooving produces grooves for applications such as O-ring seats
- **Cutting with form tools:** to produce various axisymmetric shapes for functional or aesthetic purposes.
- **Boring:** to enlarge a hole or cylindrical cavity made by a previous process or to produce circular internal grooves
- **Drilling:** to produce a hole which may be followed by boring to improve its dimensional accuracy and surface finish.
- **Parting:** also called cutting off, to cut a piece from the end of a part, as is done in the production of slugs or blanks for additional processing into discrete products.
- **Threading:** to produce external or internal threads.
- **Knurling:** to produce a regularly shaped roughness on cylindrical surfaces, as in making knobs and handles.

General characteristics of machining processes

Process	Characteristics	Typical dimensional tolerances, ± mm
Turning	Turning and facing operations on all types of materials, uses single-point or form tools; engine lathes require skilled labor; low production rate (but medium-to-high rate with turret lathes and automatic machines) requiring less skilled labor	Fine: 0.025–0.13 Rough: 0.13
Boring	Internal surfaces or profiles with characteristics similar to turning; stiffness of boring bar important to avoid chatter	0.025
Drilling	Round holes of various sizes and depths; high production rate; labor skill required depends on hole location and accuracy specified; requires boring and reaming for improved accuracy	0.075
Milling	Wide variety of shapes involving contours, flat surfaces, and slots; versatile; low-to-medium production rate; requires skilled labor	0.013–0.025
Planing	Large flat surfaces and straight contour profiles on long workpieces, low-quantity production, labor skill required depends on part shape	0.08–0.13
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; low-quantity production; labor skill required depends on part shape	0.05–0.08
Broaching	External and internal surfaces, slots, and contours; good surface finish; costly tooling; high production rate; labor skill required depends on part shape	0.025–0.15
Sawing	Straight and contour cuts on flat or structural shapes; not suitable for hard materials unless saw has carbide teeth or is coated with diamond; low production rate; generally low labor skill	0.8

Schematic Illustration of a Turning Operation

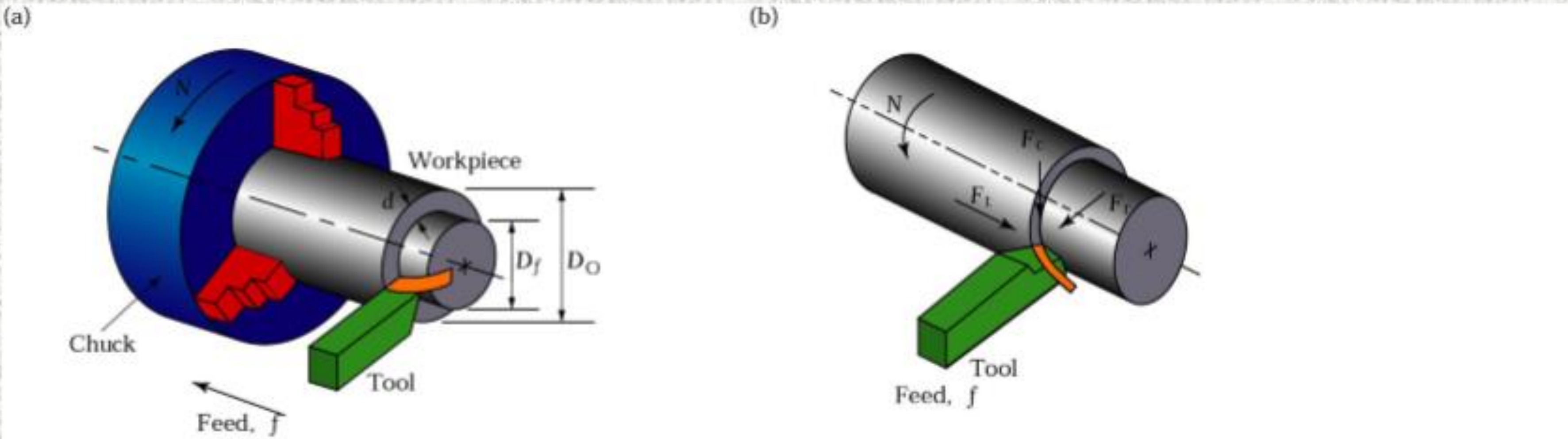


Figure 22.3 (a) Schematic illustration of a turning operation showing depth of cut, *d*, and feed, *f*. Cutting speed is the surface speed of the workpiece at the F_c is the cutting force, F_t is the thrust or feed force (in the direction of feed, F_r is the radial force that tends to push the tool away from the workpiece being machined. Compare this figure with Fig. 20.11 for a two-dimensional cutting operation.

Material removal rate is the volume of material removed per unit time (mm^3/min)

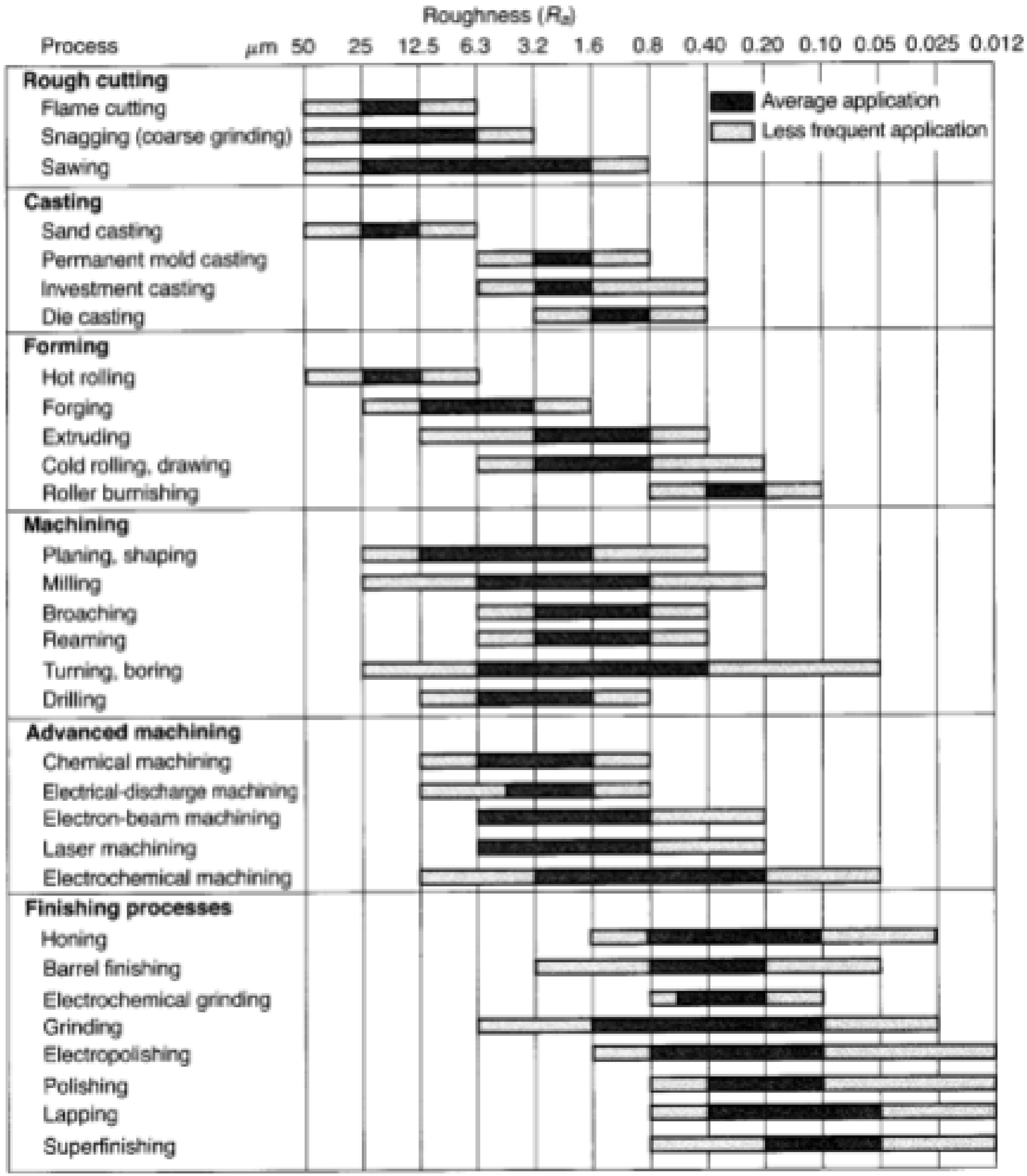
$$\text{MRR} = \pi D_{\text{avg}} d f N.$$

d = depth of cut (mm)

f=feet rate (mm/rev)

N= rotation speed of the workpiece (rev/min)

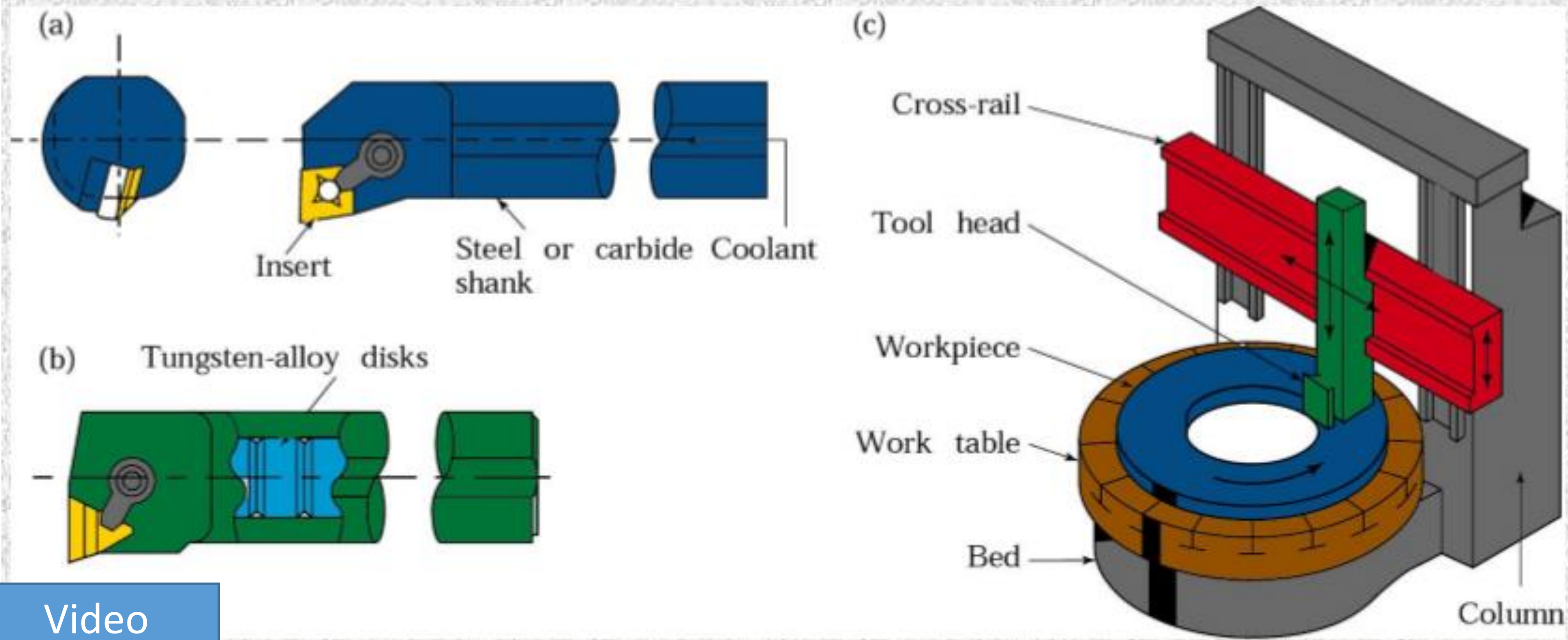
$$D_{\text{avg}} = \frac{D_o + D_f}{2}.$$


Roughness (R_a)
Process
μm 50 25 12.5 6.3 3.2 1.6 0.8 0.40 0.20 0.10 0.05 0.025 0.012
Average application
Less frequent application
Rough cutting
Flame cutting
Snagging (coarse grinding)
Sawing
Casting
Sand casting
Permanent mold casting
Investment casting
Die casting
Forming
Hot rolling
Forging
Extruding
Cold rolling, drawing
Roller burnishing
Machining
Planing, shaping
Milling
Broaching
Reaming
Turning, boring
Drilling
Advanced machining
Chemical machining
Electrical-discharge machining
Electron-beam machining
Laser machining
Electrochemical machining
Finishing processes
Honing
Barrel finishing
Electrochemical grinding
Grinding
Electropolishing
Polishing
Lapping
Superfinishing

Boring

Boring enlarges a hole made previously by some other process or produces circular internal profiles in hollow workpieces. The cutting tools are similar to those used in turning and are mounted on a boring bar.

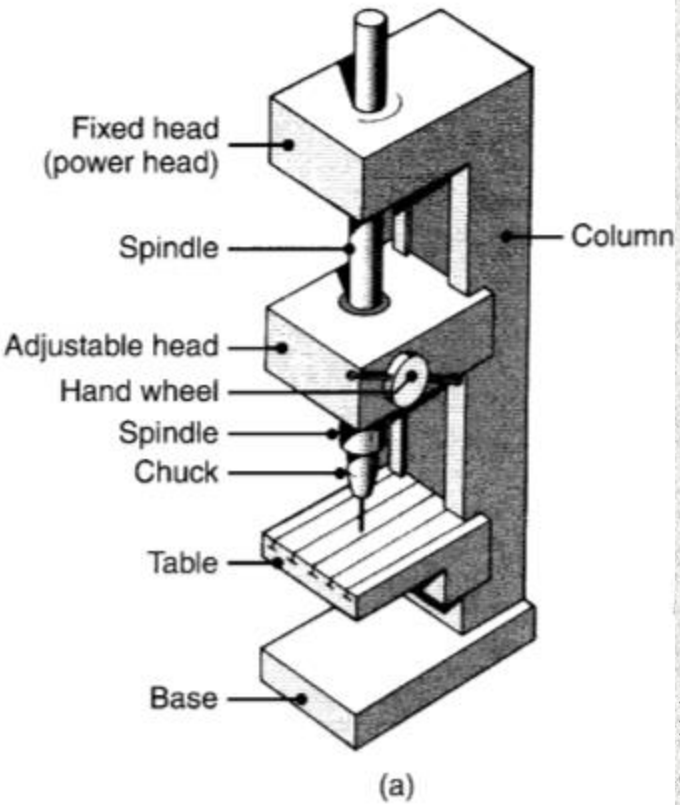
Figure 22.20 (a) Schematic illustration of a steel boring bar with a carbide insert. Note the passageway in the bar for cutting fluid application. (b) Schematic illustration of a boring bar with tungsten-alloy "inertia disks" sealed in the bar to counteract vibration and chatter during boring. This system is effective for boring bar length-to-diameter ratios of up to 6. (c) Schematic illustration of the components of a vertical boring mill. *Source*: Kennametal Inc.



Video

Drilling

-Making Holes like (a) rivets on an airplane's wings and fuselage, (b) the bolts in engine blocks and heads, and (c) numerous consumer and industrial products.
-Hole making is among the most important operations in manufacturing, and drilling is a major and common hole-making process.



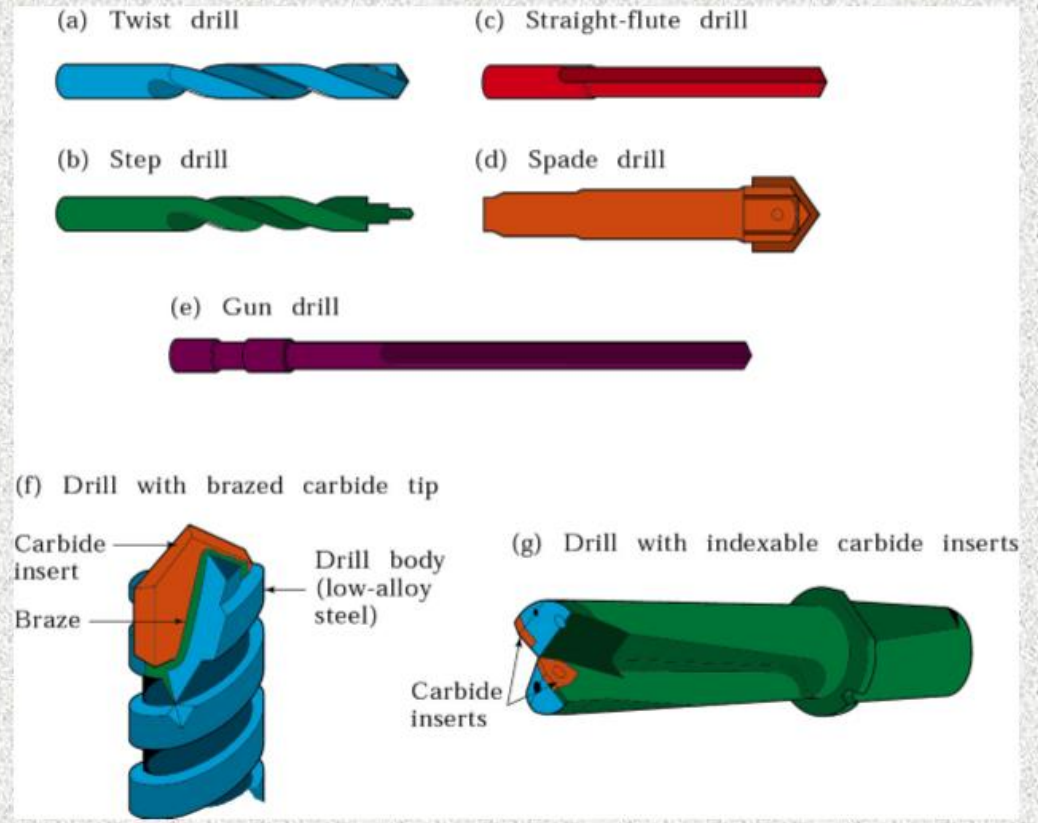


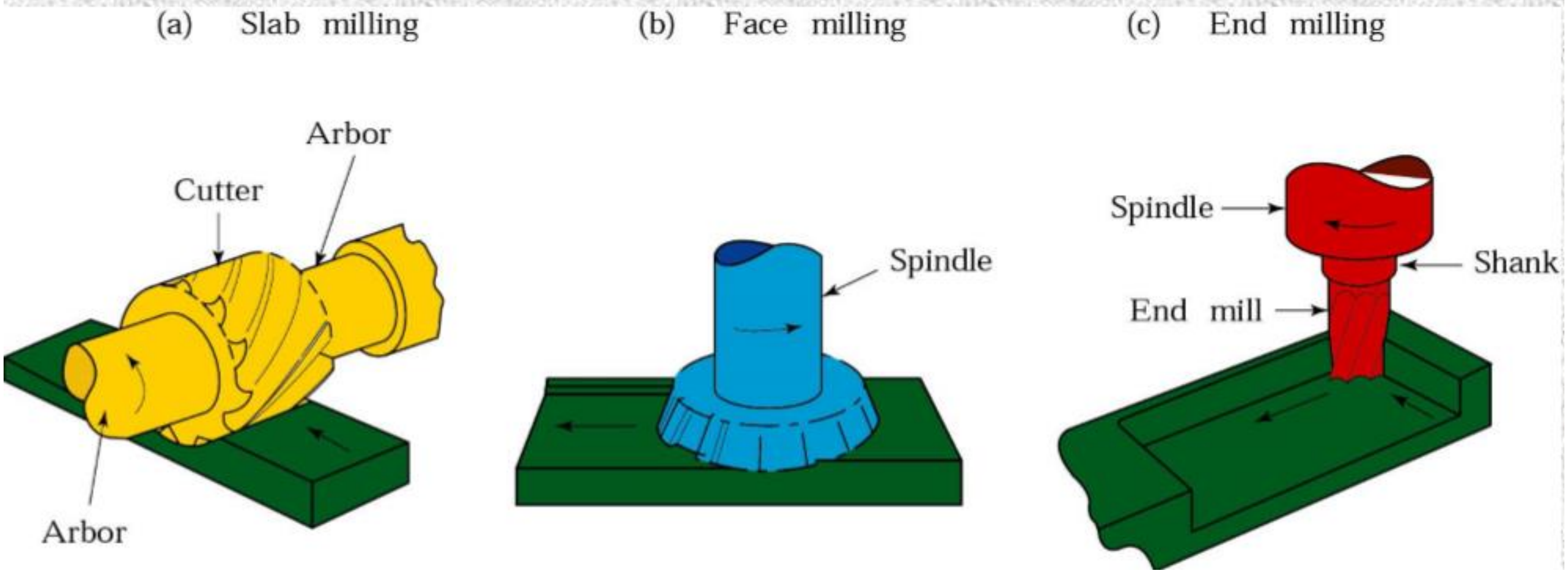
Figure 22.2 Various types of drills

Video

Milling operations

Milling includes a number of highly versatile machining operations taking place in a variety of configurations , with the use of a milling cutter-a multitooth tool that produces a number of chips in one revolution

Figure 23.2 Some of the basic types of milling cutters and milling operations.



Video

Video

Video

Milling operations

- In **slab milling** (also called plain milling), the axis of cutter rotation is *paralle*l to the workpiece surface.

- In **face milling**, the cutter is mounted on a spindle having an axis of rotation *perpendicular* to the workpiece surface

- **End milling** is an important and common machining operation because of its *versatility* and capability to produce various profiles and curved surfaces. The cutter, called an end mill has either a straight shank (for small cutter sizes) or a tapered shank (for larger sizes) and is mounted into the spindle of the milling machine. End mills may be made of high-speed steels or with carbide inserts, similar to those for face milling. The cutter usually rotates on an axis *perpendicular* to the workpiece surface, and it also can be tilted to conform to machine-tapered or curved surfaces.

Some advanced machining processes

- The machining processes described in the preceding chapters involved material removal by mechanical means: chip formation, abrasion, or microchipping. However, there are situations in which mechanical methods are not satisfactory, economical, or even possible, for the following reasons:

(1) The hardness of the workpiece material are very high, typically above 400 HB

(2) The workpiece material is too brittle to be machined without damage to the workpiece. This is typically the case with highly heat treated alloys, glass, ceramics, and powder-metallurgy parts.

(3) The workpiece is too flexible or too slender to withstand forces in machining or grinding, or the parts are difficult to clamp in fixtures and work-holding devices.

(4) The shape of the part is complex , including such features as internal and external profiles or holes with high length-to-diameter ratios in very hard materials.

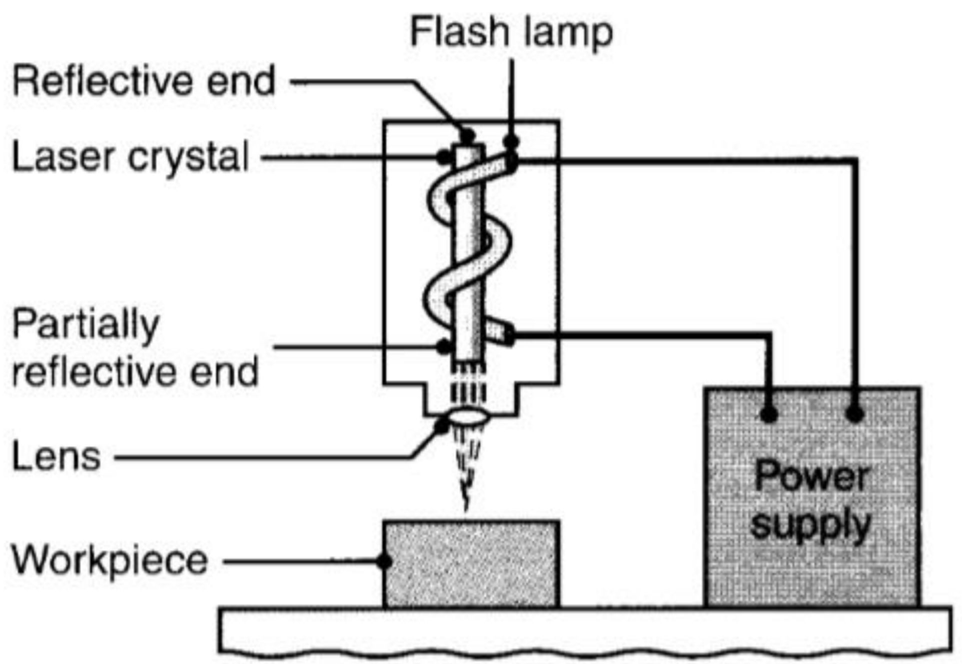
(5) Special surface finish and dimensional tolerance requirements exist that cannot be obtained by other manufacturing processes

(6) The temperature rise during processing and residual stresses developed in the workpiece are not desirable or acceptable.

Process	Characteristics	Process parameters and typical material-removal rate or cutting speed
Chemical machining (CM)	Shallow removal on large flat or curved surfaces; blanking of thin sheets; low tooling and equipment cost; suitable for low-production runs	0.0025–0.1 mm/min.
Electrochemical machining (ECM)	Complex shapes with deep cavities; highest rate of material removal among other nontraditional processes; expensive tooling and equipment; high power consumption; medium-to-high production quantity	V: 5–25 DC; A: 1.5−8 A/mm^2; 2.5–12 mm/min, depending on current density
Electrochemical grinding (ECG)	Cutting off and sharpening hard materials, such as tungsten-carbide tools; also used as a honing process; higher removal rate than grinding	A: 1−3 A/mm^2; typically 25 mm^3/s per 1000 A
Electrical-discharge machining (EDM)	Shaping and cutting complex parts made of hard materials; some surface damage may result; also used as a grinding and cutting process; expensive tooling and equipment	V: 50–380; A: 0.1–500; typically 300 mm^3/min
Wire electrical-discharge machining	Contour cutting of flat or curved surfaces; expensive equipment	Varies with material and thickness
Laser-beam machining (LBM)	Cutting and hole making on thin materials; heat-affected zone; does not require a vacuum; expensive equipment; consumes much energy	0.50–7.5 m/min
Electron-beam machining (EBM)	Cutting and hole making on thin materials; very small holes and slots; heat-affected zone; requires a vacuum; expensive equipment	1−2 mm^3/min
Water-jet machining (WJM)	Cutting all types of nonmetallic materials; suitable for contour cutting of flexible materials; no thermal damage; noisy	Varies considerably with material
Abrasive water-jet machining (AWJM)	Single-layer or multilayer cutting of metallic and nonmetallic materials	Up to 7.5 m/min
Abrasive-jet machining (AJM)	Cutting, slotting, deburring, etching, and cleaning of metallic and nonmetallic materials; tends to round off sharp edges; can be hazardous	Varies considerably with material

Laser beam machining

In laser-beam machining (LBM), the source of energy is a laser (an acronym for light amplification by stimulated emission of radiation), which focuses optical energy on the surface of the workpiece . The highly focused, high-density energy source melts and evaporates portions of the workpiece in a controlled manner. This process is used to machine a variety of metallic and nonmetallic materials.



Video

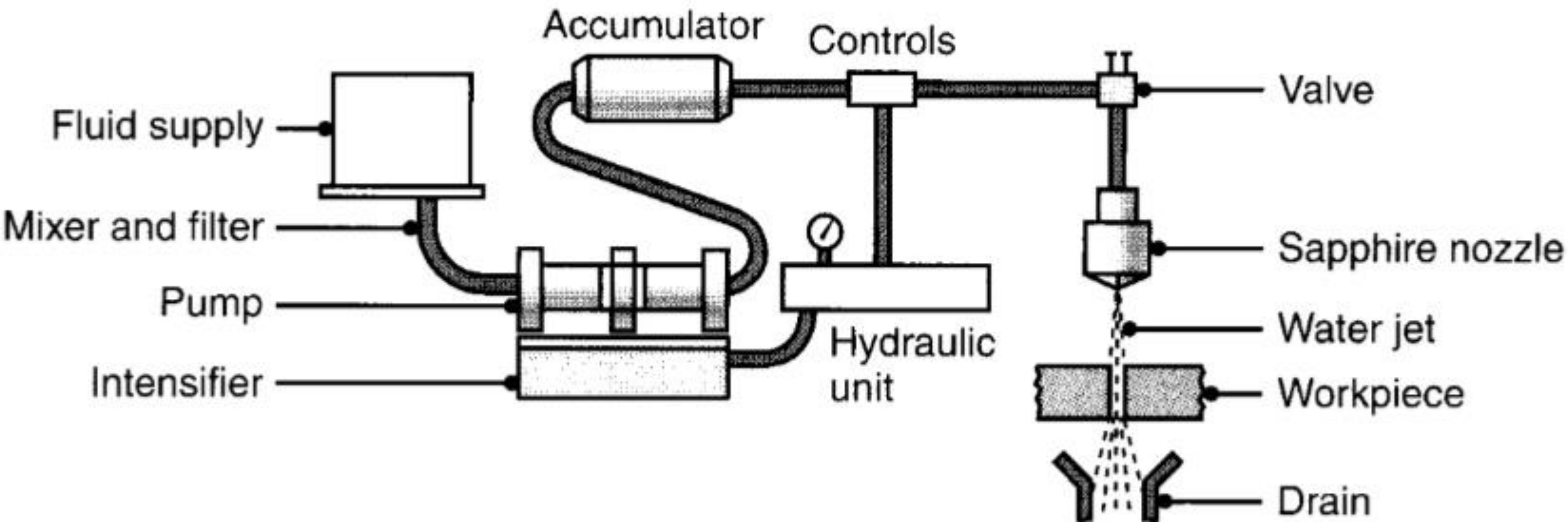
Water jet machining

In water-jet machining (WJM) (also called hydrodynamic machining), the force is utilized in cutting and deburring operations .

The water jet acts like a saw and cuts a narrow groove in the material

The advantages of this process are as follows:
(1) Cuts can be started at any location without the need for predrilled holes.
(2) No heat is produced.
(3) No deflection of the rest of the workpiece takes place; thus, the process is suitable for flexible materials.
(4) Little wetting of the workpiece takes place.
(5) The burr produced is minimal.
(6)It is an environmentally safe manufacturing process.

Water jet machining



Video