BFF1113
Engineering Materials

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Course Guidelines:

1. Introduction to Engineering Materials
2. Bonding and Properties
3. Crystal Structures & Properties
4. Imperfection in Solids
5. Mechanical Properties of Materials
6. Physical Properties of Materials
7. Failure & Fundamental of Fracture
8. Metal Alloys
9. Phase Diagram
10. Phase Transformation – Heat Treatment
11. Processing and Application of Metals
12. Ceramic Materials
13. Polymer Materials
14. Composite Materials
15. Corrosion & Degradation of Materials
16. Environment and Sustainability

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METAL

1. INTRODUCTION TO METALS & ALLOYS : GENERAL PROPERTIES & APPLICATIONS
2. PHASE DIAGRAM
3. **FABRICATION & THERMAL PROCESSES OF METALS**

By the end of this lecture..

- You should be able to explain the concept of solid state transformation in austenitic steel and relate the microstructure of the steel to its properties.

- You should be able to state the purpose and describe heat treatment process in metal

- You should be able to name and describe processes involve in metal fabrications

- You should be able to provide a suitable process to form engineering components

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FABRICATION & HEAT TREATMENT PROCESS

Chapter Outline

1. **Metal fabrication in general**
2. **Heat treatment process**

Fabrication of Metals - Methods

Metal Fabrication Methods

1. FORMING

Shape of metal piece changed by plastic deformation. Only metal with certain ductility can be formed.

2. CASTING

Molten metal is poured into a mould cavity having desired shape. Suitable for hard/brittle metal.

3. JOINING

Two or more parts are joined to for a single piece

Miscellaneous

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1. Forming Operations

FORMING

Hot Working

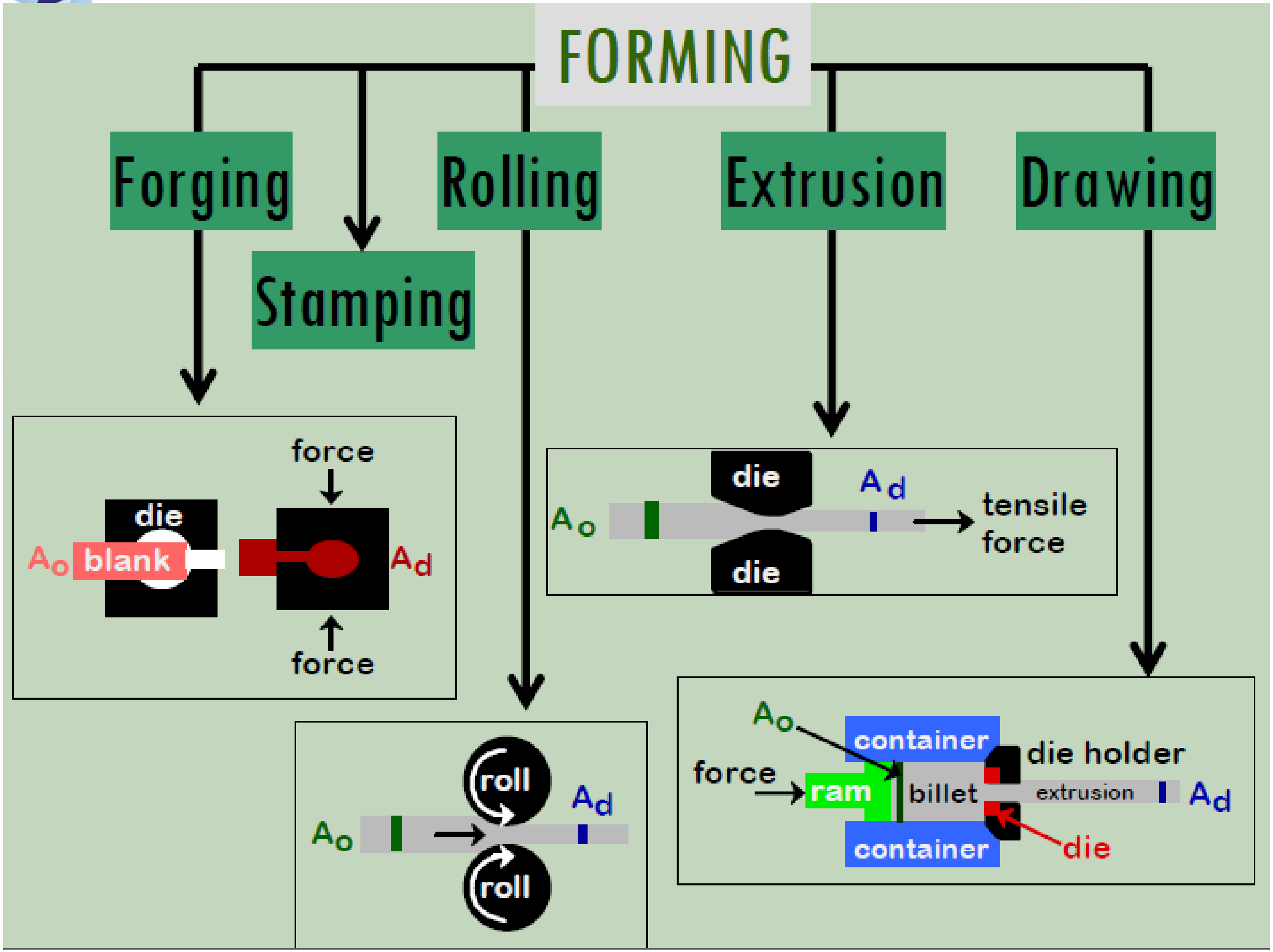
Deformation is achieved at temperature at which recrystalisation can occurs

- Large deformation is possible.
- Deformation can be repeated (soft and ductile)
- Less deformation energy required
- Oxidation might occurs – bad surface finish

Cold Working

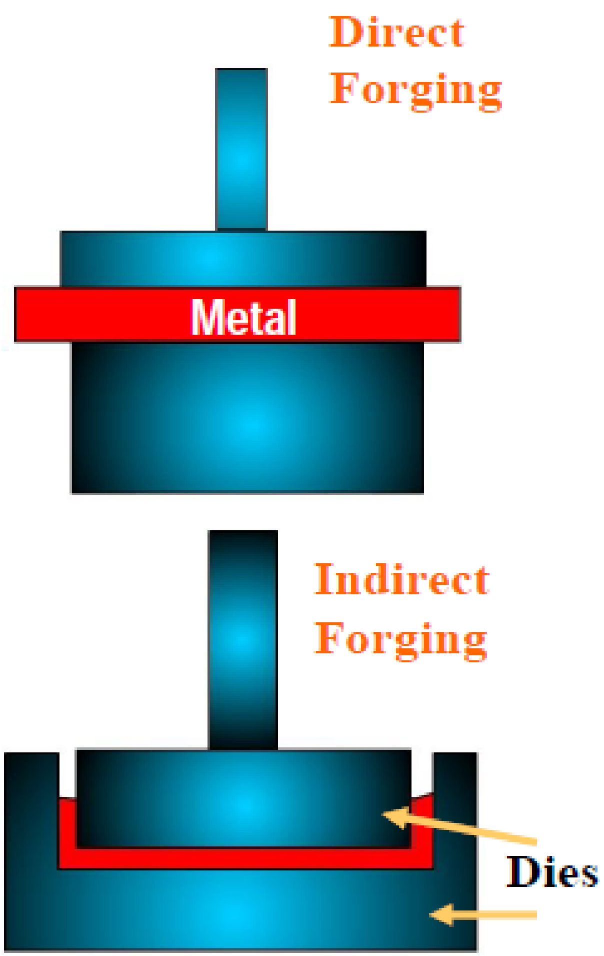
Deformation is achieved below the recrystalisation temperatures

- Metals strain hardened
- Higher quality surface finish
- Better mechanical properties
- Variety of mechanical properties can be formed
- Closer dimension control of the final piece


FORMING
Forging
Stamping
Rolling
Extrusion
Drawing
force
die
Ao
blank
Ad
force
die
Ao
Ad
tensile
force
die
roll
Ao
Ad
roll
Ao
container
force
ram
billet
die holder
extrusion
Ad
container
die

Forging

- Mechanically working or deforming a single piece of a hot metal
- Start with billet of metal then formed
- Hammered or pressed into a desired shape
- Mould used to place hot metal in before being shaped into desired shape
- Use for producing large parts; steel shafts for steam turbine engine, automobile connecting rods, or tools like wrench

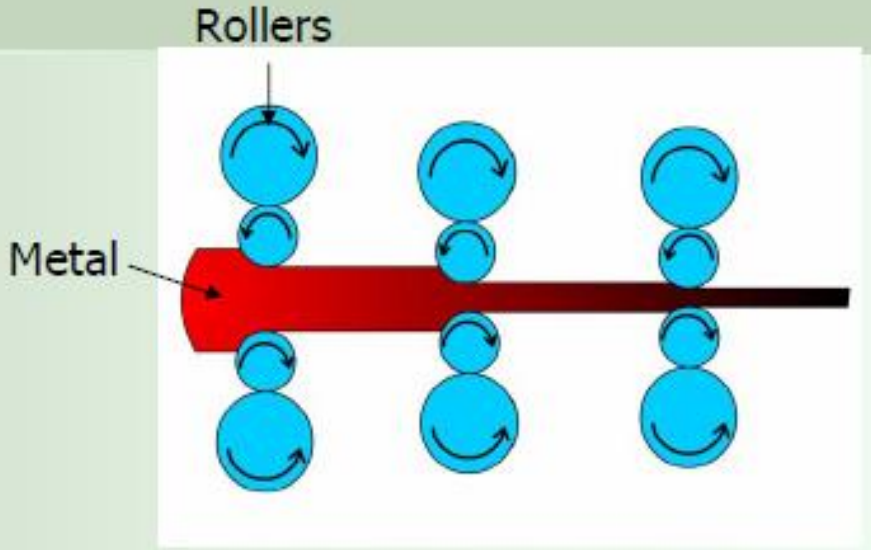


Stamping

- Mechanically working or deforming a sheet of metal
- The metal sheet will be stamped to desired shape and size
- Use to make parts like automotive body (car body), car doors, metal plates etc

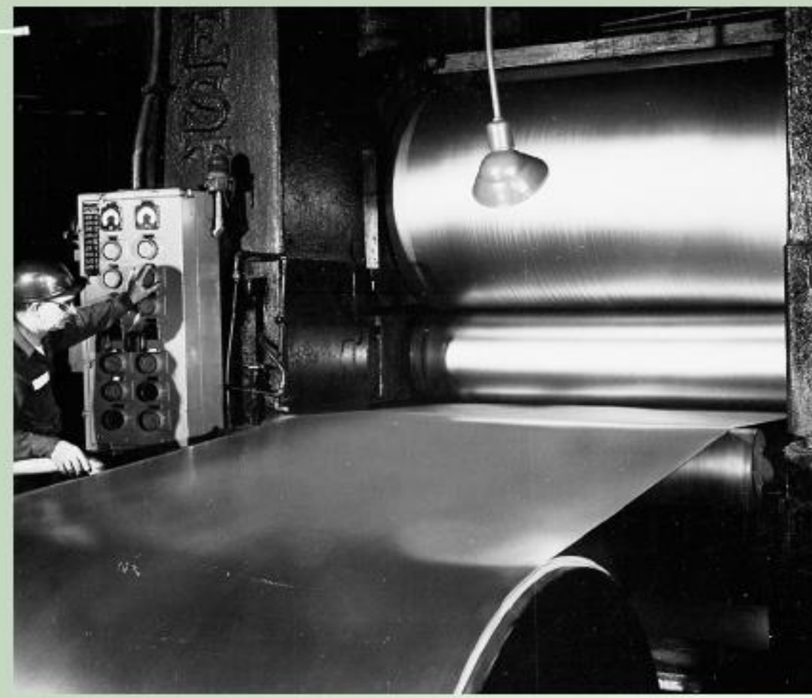
Rolling

- Passing a piece of metal between two rolls
- Thickness reduced with rolling pass
- Cold or hot rolling.
- Cold rolling produces sheet, strips, foils which can be recrystallised after rolling



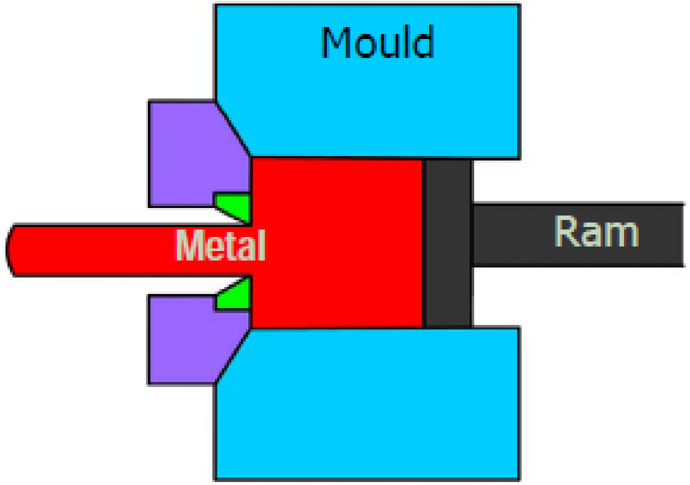
Rolling Machine

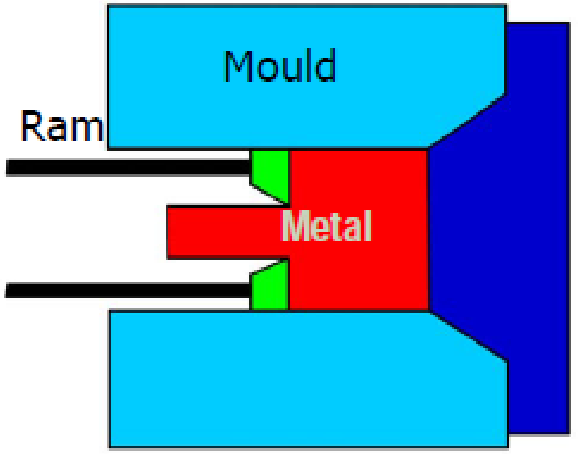
Rolling Machine



Extrusion

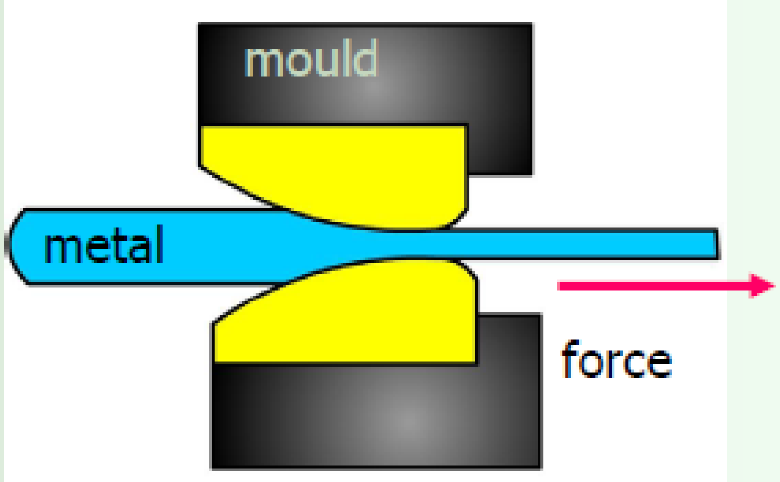
- A bar of metal is forced through a die orifice by a compressive force that is applied to a ram
- Rods, tubing, wires, pipes
- Anything with symmetrical shape





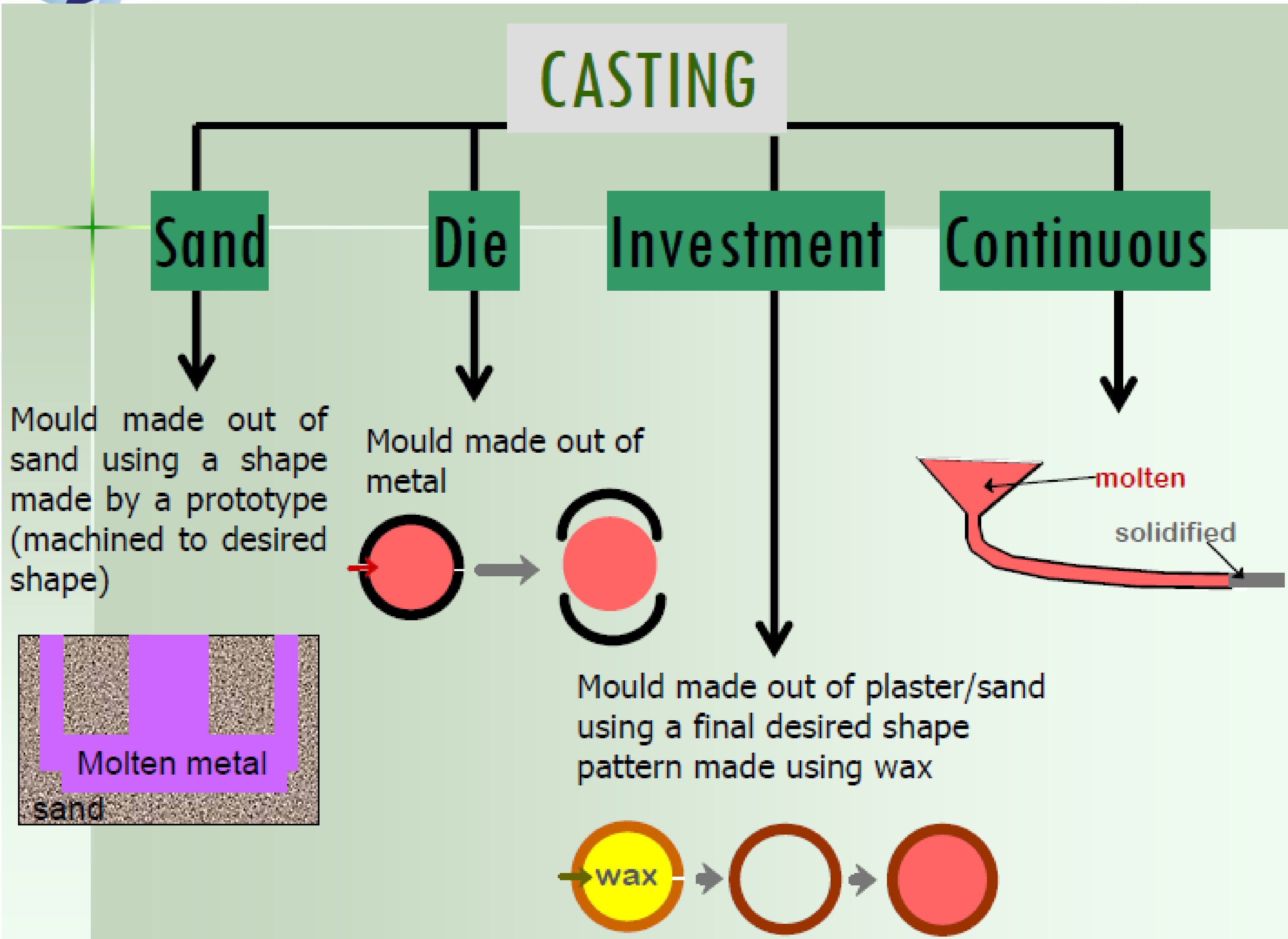
Wire Drawing

- A bar of metal is drawn through a die orifice by a compressive force that is applied to a ram
- Start with rods to form wires



2. Casting

- Molten metal is poured into a mould cavity having the desired shape. Upon solidification, the metal assumes the shape of the mould but experiences some shrinkage.
- Casting is best used:
  - To produce metal product of complex shape and size. Other method is not applicable.
  - For metal alloys having low ductility that forging is impossible
  - To cut cost as the process is very economical


CASTING
Sand
Die
Investment
Continuous
Mould made out of sand using a shape made by a prototype (machined to desired shape)
Molten metal
sand
Mould made out of metal
Mould made out of plaster/sand using a final desired shape pattern made using wax
wax
molten
solidified

Example of product produced by casting

Sand Casting

The mould is made out sand using a shape from a prototype. Economical!

2-piece mould

Large parts; Automotive cylinder blocks, fire hydrants, large pipe fittings

Molten metal is placed at one opening and once the metal is solidified, mould is broken to release the product from the moulds.

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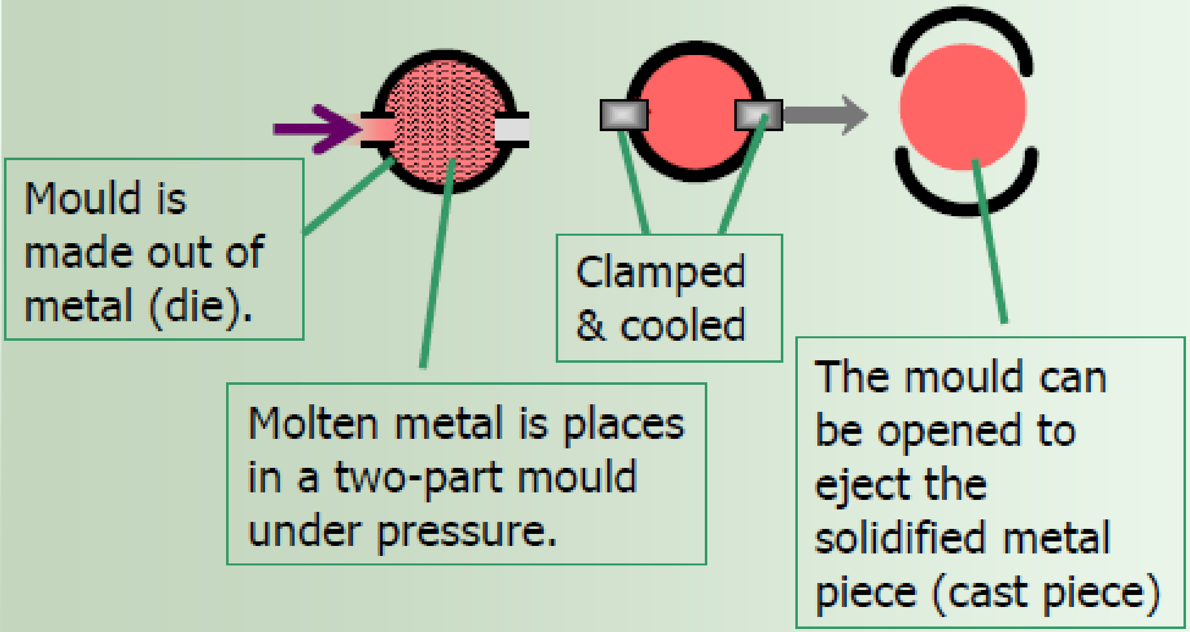
Die Casting

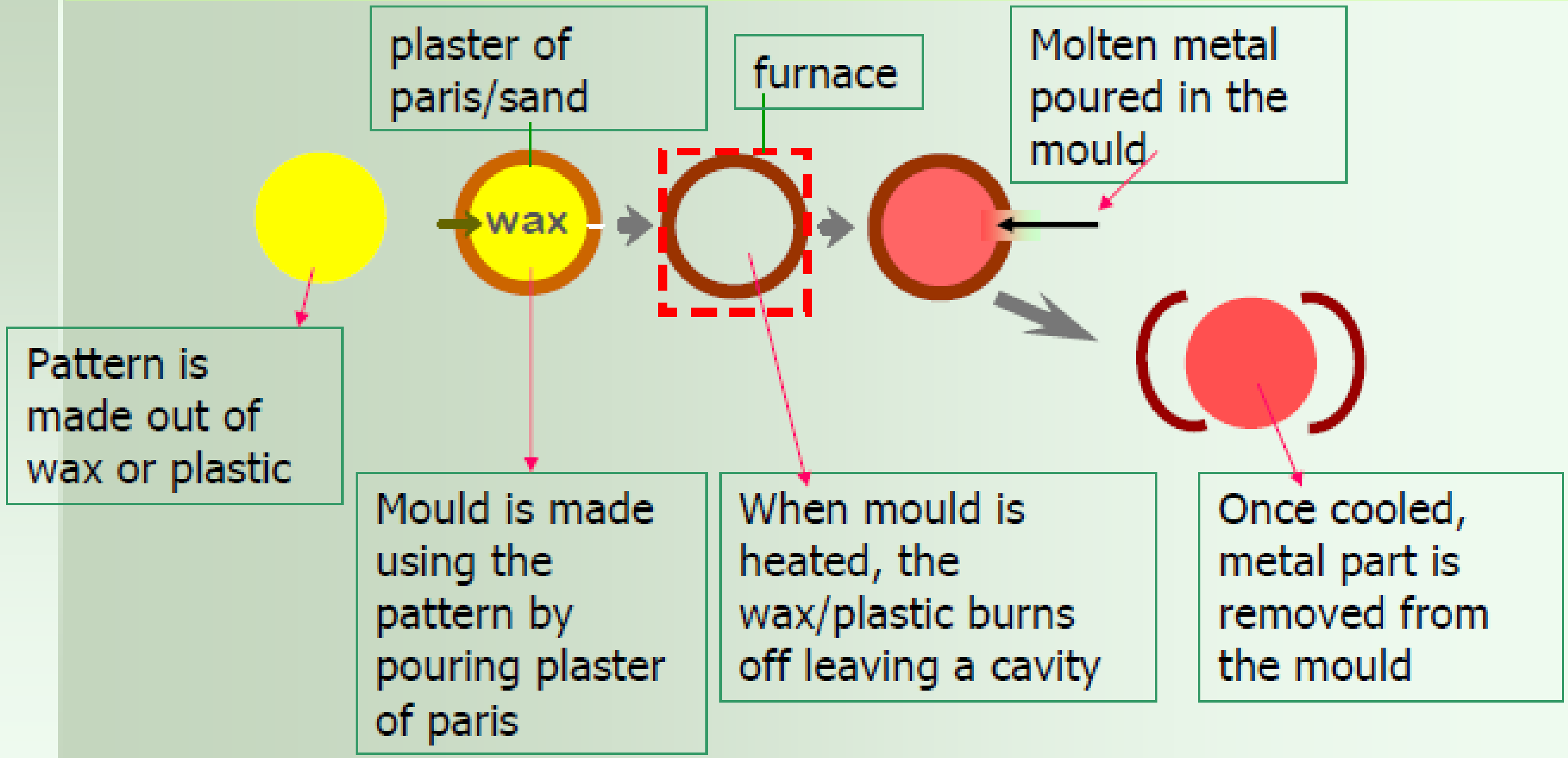
To produce high volume products, low melting point alloys (e.g. Zn, Al and Mg) and small products



Examples of die casting

Investment Casting

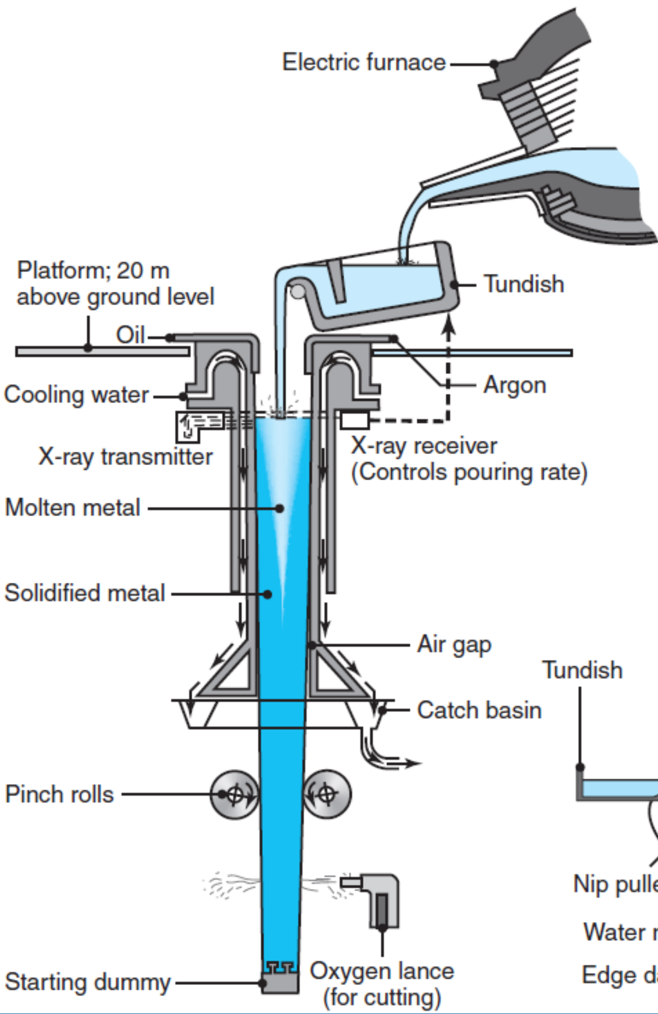
This process is capable of producing precise detail and dimensional accuracy in parts weighing many pounds to just a few ounces. Precision investment castings are able to reduce costs in many cases due to reduced machining and less material waste.



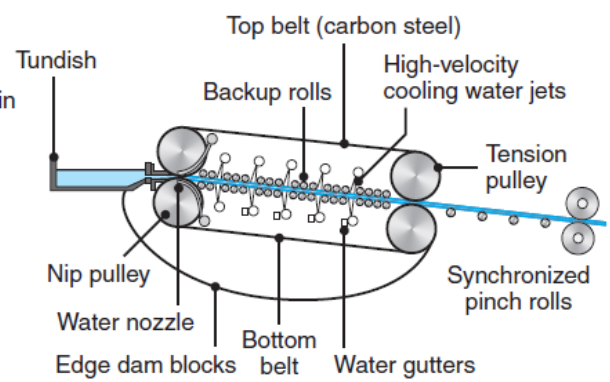
Investment Casting

Investment Casting is suitable for low volume, complex shapes like jewelry, dental crown, turbine blades, weaponry,

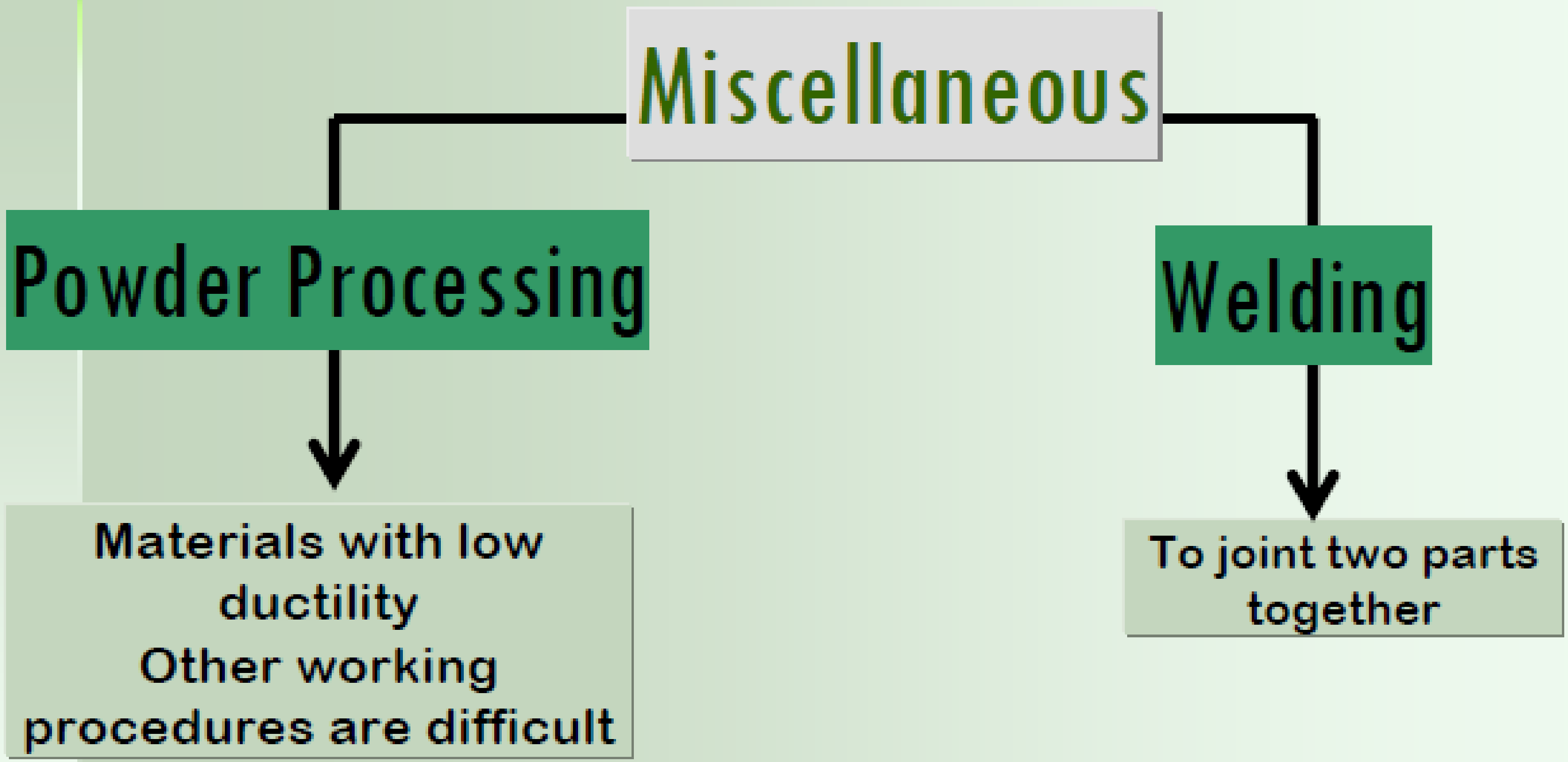
Continuous Casting



- *Continuous casting* is the process whereby molten metal is solidified into a "semifinished" billet, bloom, or slab for subsequent rolling in the finishing mills
- *Continuous casting* process produces higher quality steels at reduced costs

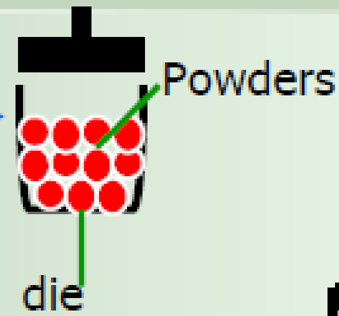


3. Miscellaneous

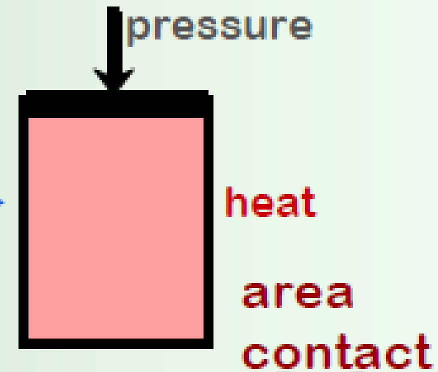


Powder Metallurgy

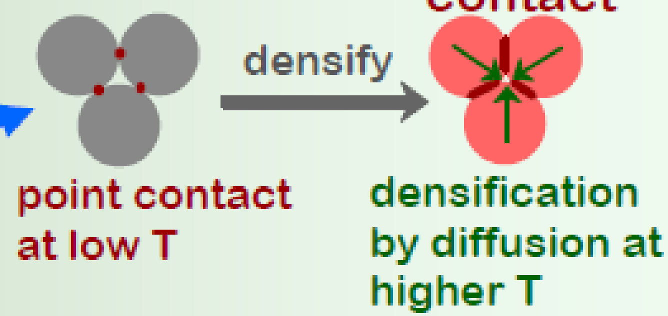
- Micron sized or nano sized metal powders are placed in a die



- Pressure applied to compact the powders
- Uniaxial press
- Heat sometimes applied during compaction – hot press



- During heating, particles started to be densified assist by high temperature and solidify



- Finish product will be removed from the die

Welding

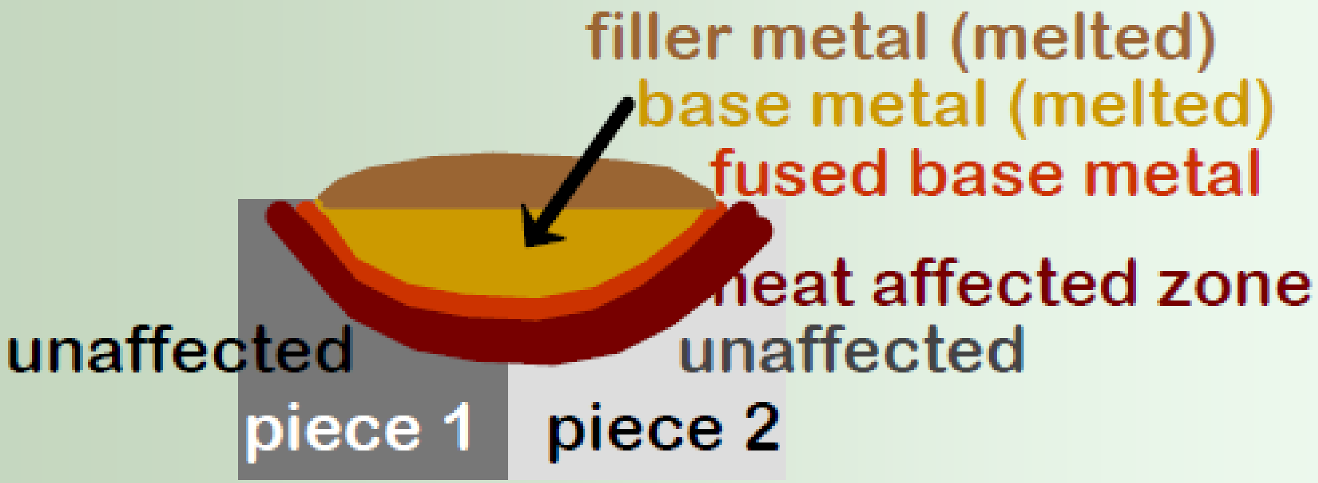
- Similar or dissimilar metals can be joined.
- Joining bond is metallurgical not mechanical
- Arch, gas welding, soldering and brazing

Done by melting work pieces and adding a filler material to form a pool of molten material (the weld puddle) that cools to become a strong joint.

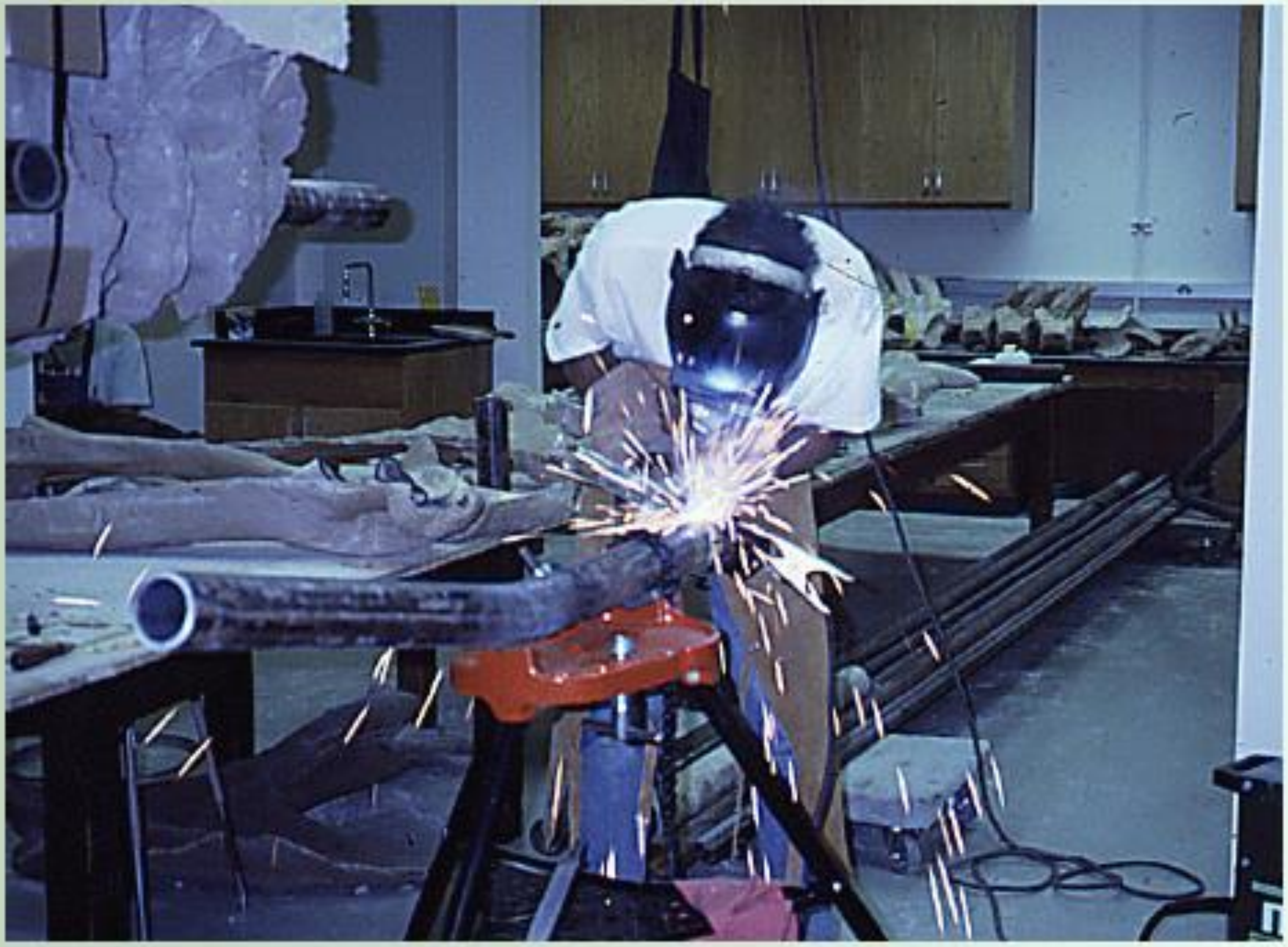
Arc welding refers to a group of welding processes that use a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point.

Heat Effected Zone

- Workpieces are joined by a filler material which is heated to a high temperature.
- This resulted in fusion joint between the 2 parts
- The region adjacent to the weld will experience microstructure and property alterations.
- Heat-affected-zone (HAZ). Knowledge of HAZ is required to make sure the joining stays intact and not failed



Welding



Thermal Processing of Metals

Annealing

- Definition:

A heat treatment process where a material will be heated at high temperature, leave at that temperature for a period of time follow by cooling

In other word:

- **Annealing** is the restoration of a cold-worked or heat-treated alloy to its original properties
- Increase ductility, reduce the hardness

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Reasons of Annealing

1. Process annealing – heat treatment to negate (counteract) effects of cold work. During cold work, metal suffers severe deformation (hence it strain-hardens) and with process annealing, recovery and recrystalisation occurs
2. Internal residual stress formed in metal because of plastic deformation (machining, grinding) and non-uniform cooling. Annealing can reduce the internal residual stress.

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Methods of Annealing

1. You need an oven (furnace)
2. Place the metal samples which you wish to anneal in the oven
3. Heat the furnace to desired temperature
4. Make sure you use the right heating rate to aid thermal shock
5. Set the annealing time (i.e. how long you would want to anneal your samples) - soaking
6. Once the annealing is done, cool down the furnace
7. Make sure the cooling rate is right

In summary, Annealing process consists of:

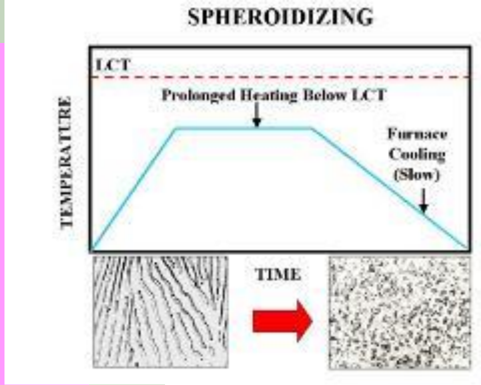
1. **Heating the workpiece to a specific range of temperature in a furnace**
2. **Holding temperature for a period of time (*soaking*)**
3. **Cooling the workpiece**

Types of Annealing

Annealing: Heat to high temperature, T_{anneal}, then cool slowly.

- **Stress Relief:** Reduce stress caused by:
  - -plastic deformation
  - -nonuniform cooling
  - -phase transform.

- **Spheroidize (steels):** Make very soft steels for good machining. Heat just below T_E & hold for 15-25 h.



Types of Annealing

- **Full Anneal (steels):** Make soft steels for good forming by heating to get γ, then cool in furnace to get coarse P.

- **Process Anneal:** Negate effect of cold working by (recovery/ recrystallization)

- **Normalize (steels):** Deform steel with large grains, then normalize to make grains small.

Process Annealing

- *Process annealing* is where workpiece is annealed to restore its ductility

Stress-relief Annealing

- *Stress-relief annealing* is to reduce residual stresses
- Stress relieving promotes dimensional stability and reduces the tendency to stress-corrosion cracking

Spherodize Annealing

- *Spheroidizing annealing* improves the cold workability and machinability of steels

Full Annealing

- Structure obtained through full annealing is coarse pearlite, which is soft and ductile and has small, uniform grain

Normalize Annealing

- To avoid excessive softness from the annealing of steels, the cooling cycle is done completely in still air, called **normalizing**

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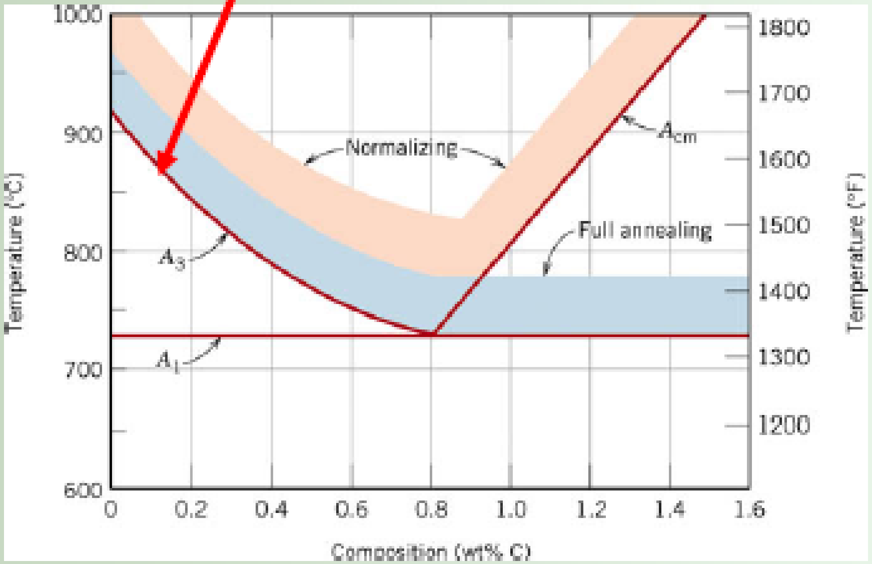
Normalizing

- Heat treatment to refine the grains (decrease grain size)
- Produces more uniform grains (size and distribution)
- Strength of steel also increases
- Heating to temperature > upper critical temperature (see phase diagram)



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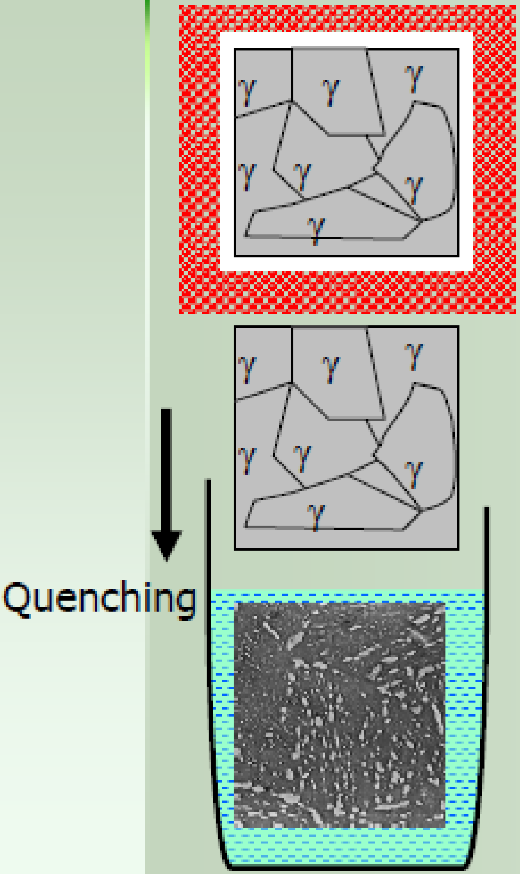
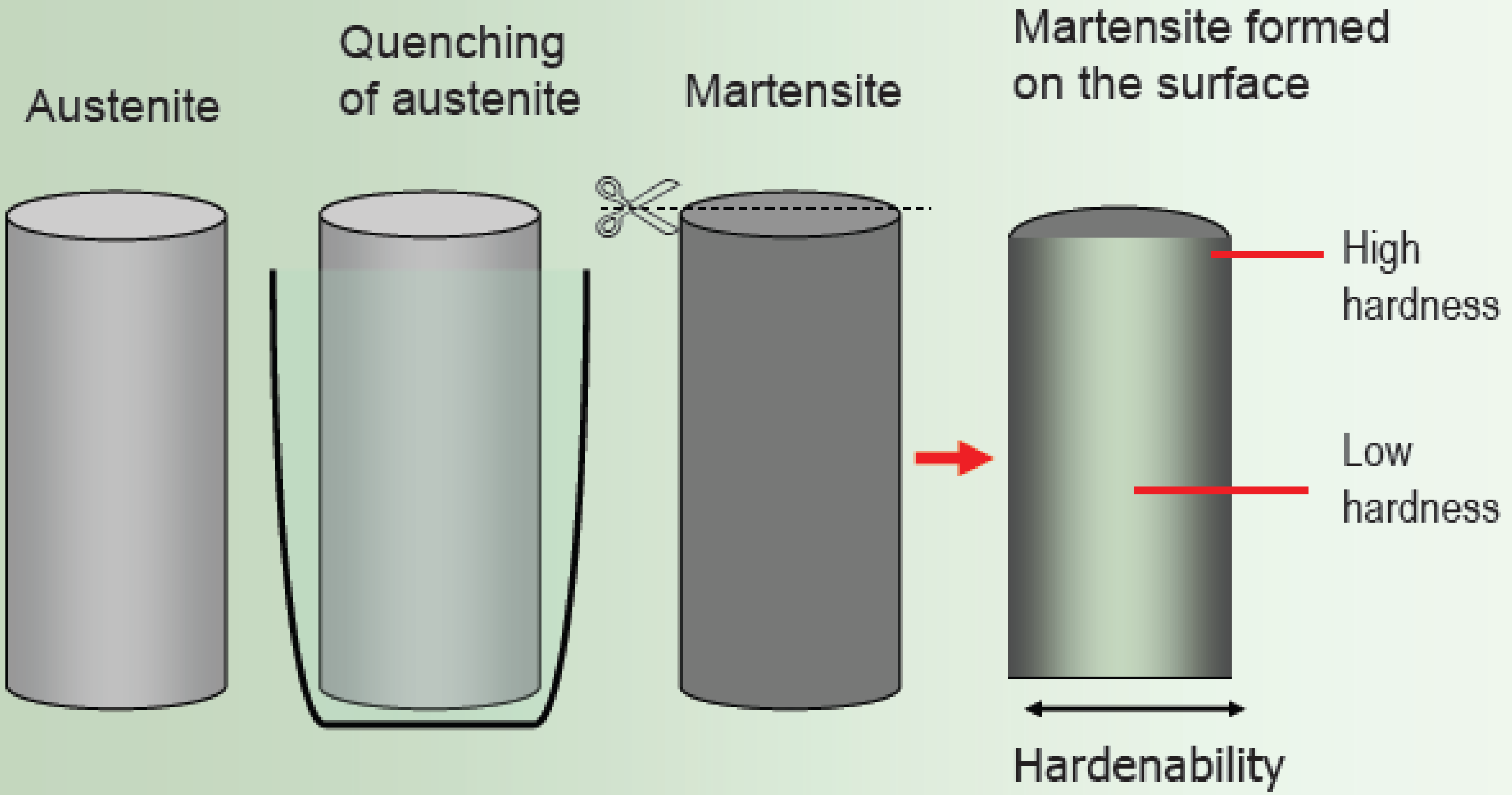
QUENCHING



- Quench austenite >726°C (in water, air or oil)
- Upon quenching, martensite formed
- Cooling is not uniform.
- The outer part of the metal will cooled quicker compared to the inner part
- Hardenability → property which determines the depth and distribution of hardness induced by quenching from austenite conditions
- It is a parameter which measure the rate at which hardness drops off the distance into the interior of a specimen as a result of diminished martensite content.

Formation of Martensite



HEAT TREATMENT OF FERROUS ALLOY

- Microstructures can be modified by **heat-treatment** techniques using controlled heating and cooling of the alloys at various rates
- Treatments induce **phase transformations** that greatly influence such mechanical properties
- Heat-treatment processes are annealing, quenching, and tempering.

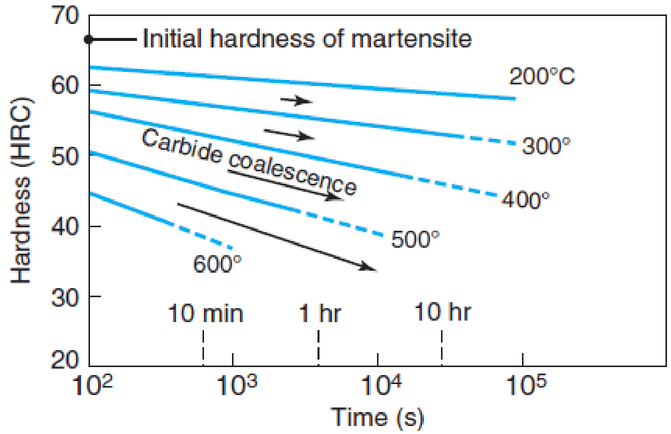
Heat Treatment of Ferrous Alloys

Retained Austenite

- When alloy temperature is not quenched sufficiently low, only a portion of the structure is transformed to martensite
- The rest is **retained austenite** which can cause dimensional instability and cracking
- Lower the hardness and strength of the alloy

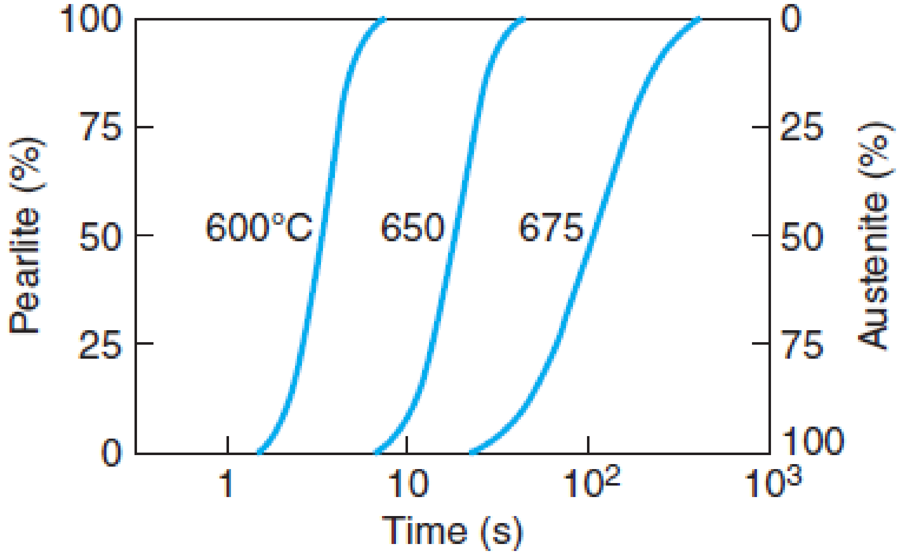
Tempered Martensite

- Tempered to improve its mechanical properties
- **Tempering** is a heating process to reduce hardness and improve toughness
- With increasing tempering time and temperature, the hardness of tempered martensite decreases

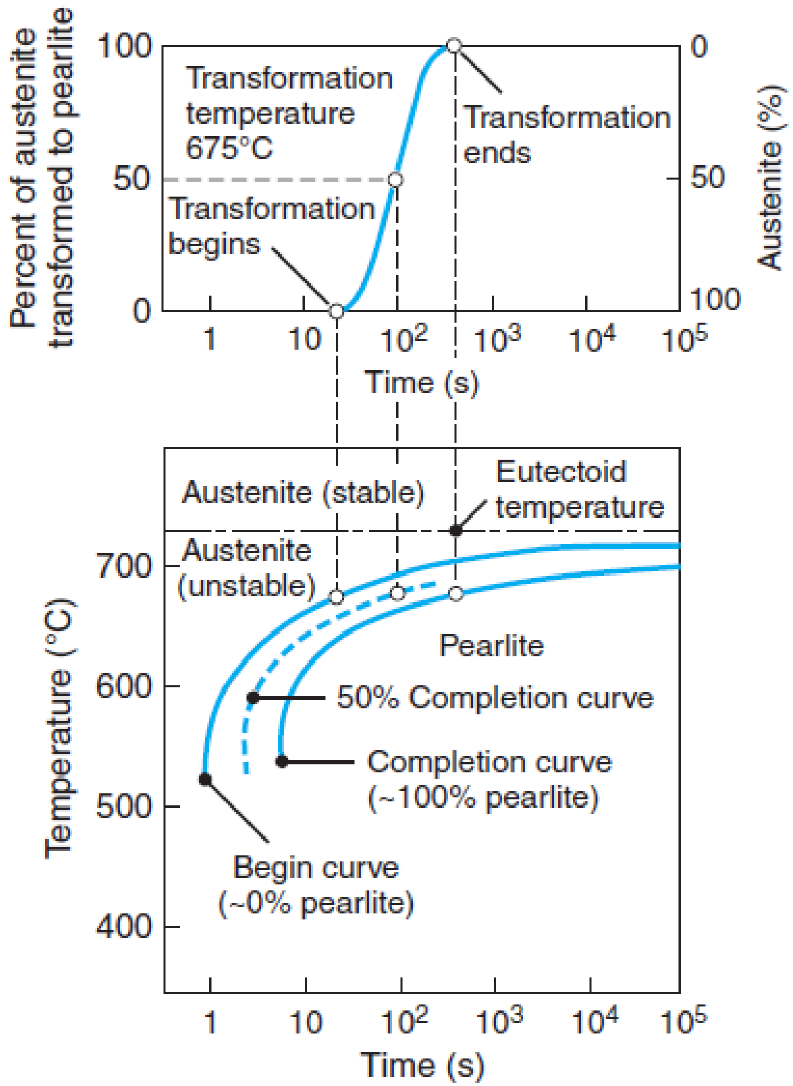


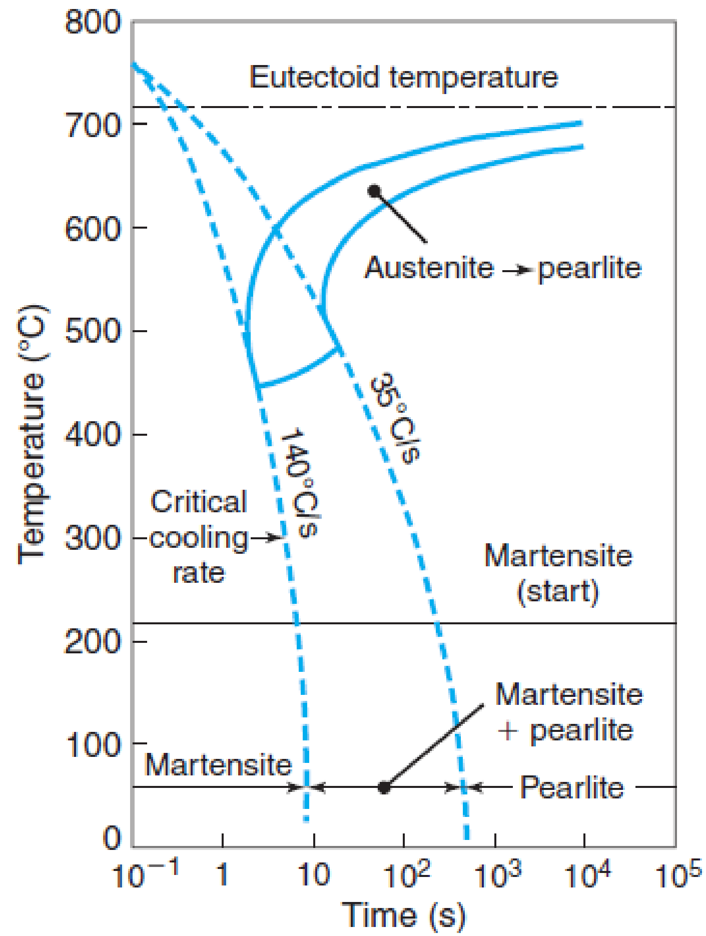
Time–Temperature-Transformation Diagrams

- Transformation from austenite to pearlite is shown in **isothermal transformation (IT) diagrams**, or *time–temperature-transformation* (TTT) *diagrams*



Time–Temperature-transformation Diagrams



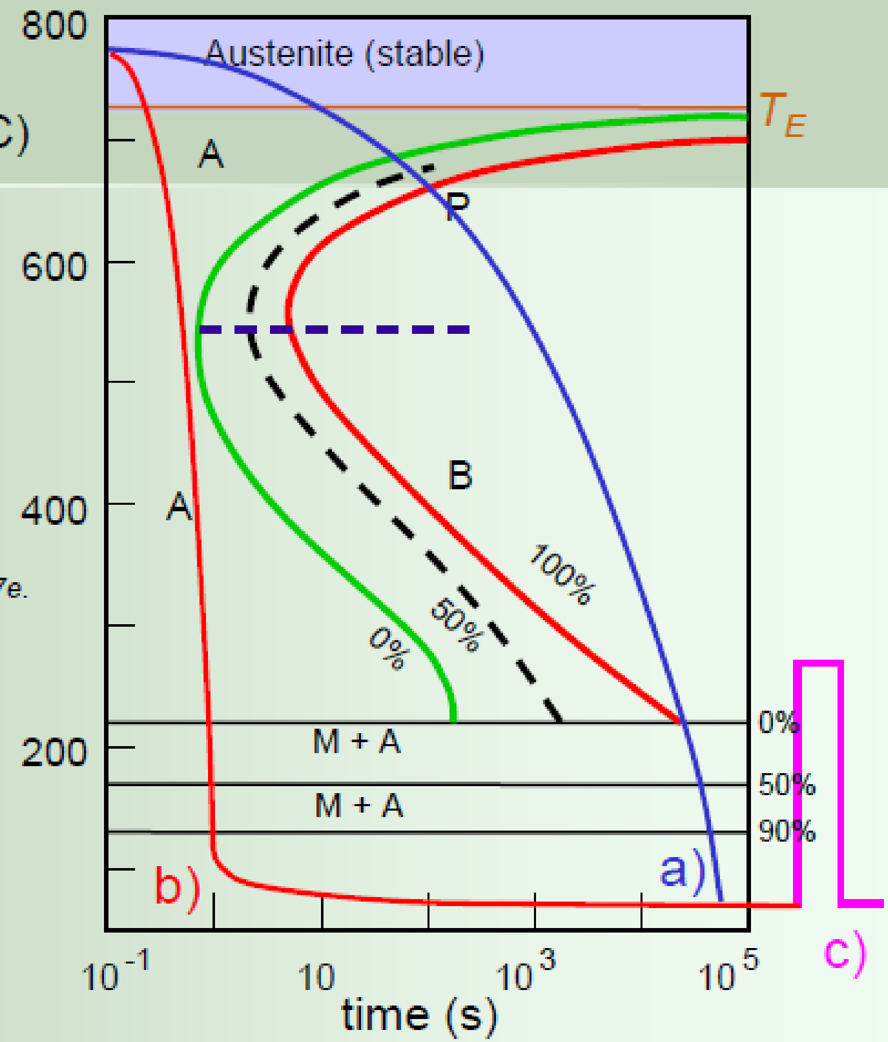


Heat Treatments

a) **Annealing**

b) Quenching

c) Tempered Martensite



Adapted from Fig. 10.22, *Callister 7e.*

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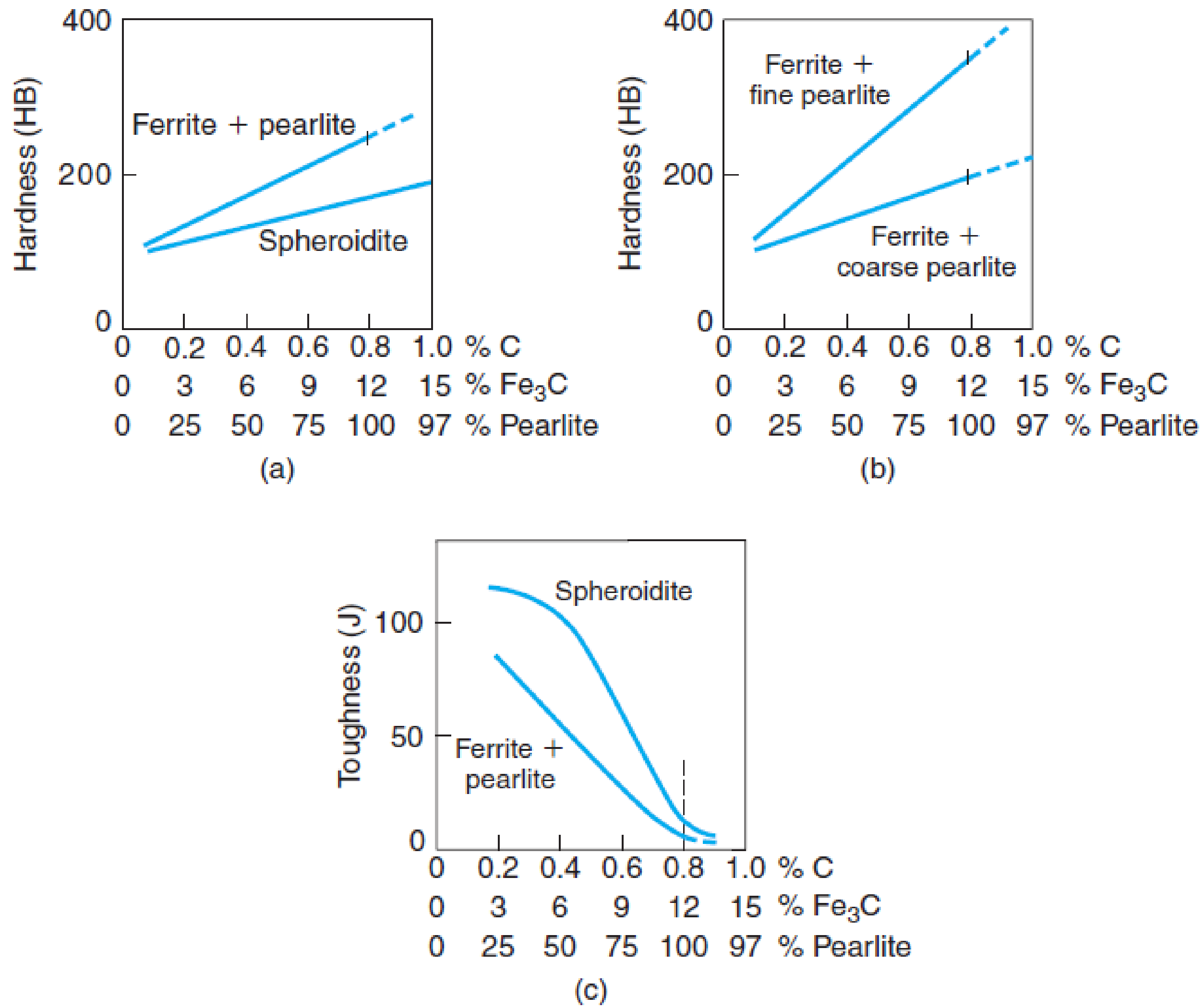
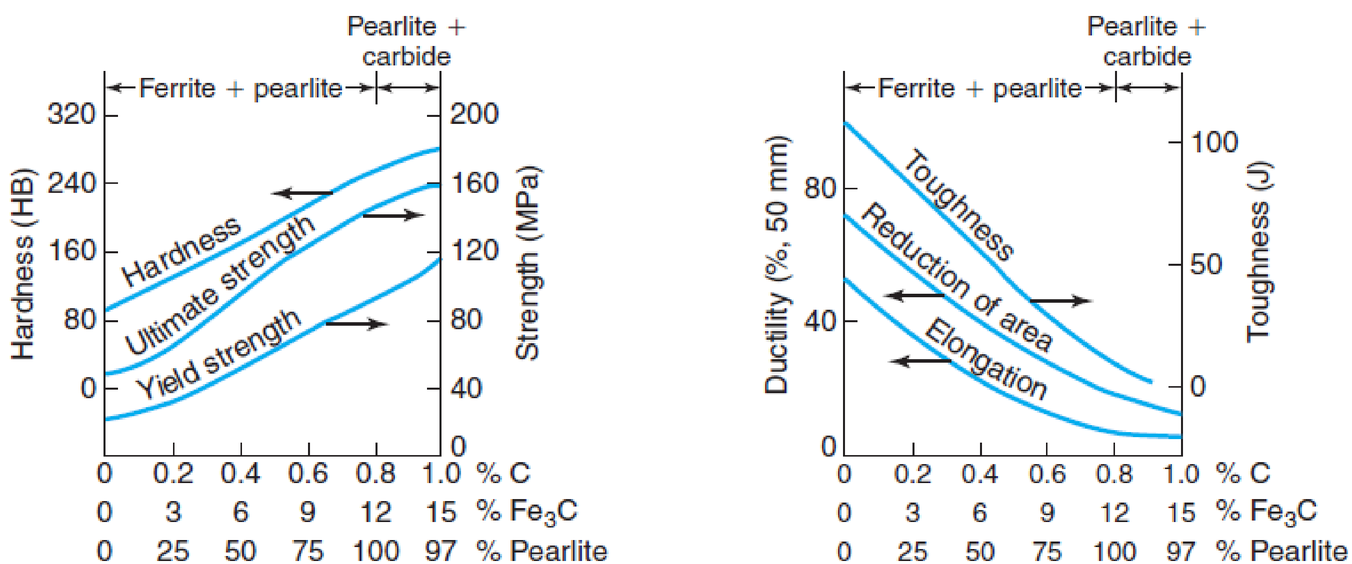
- Differences in hardness and toughness are shown



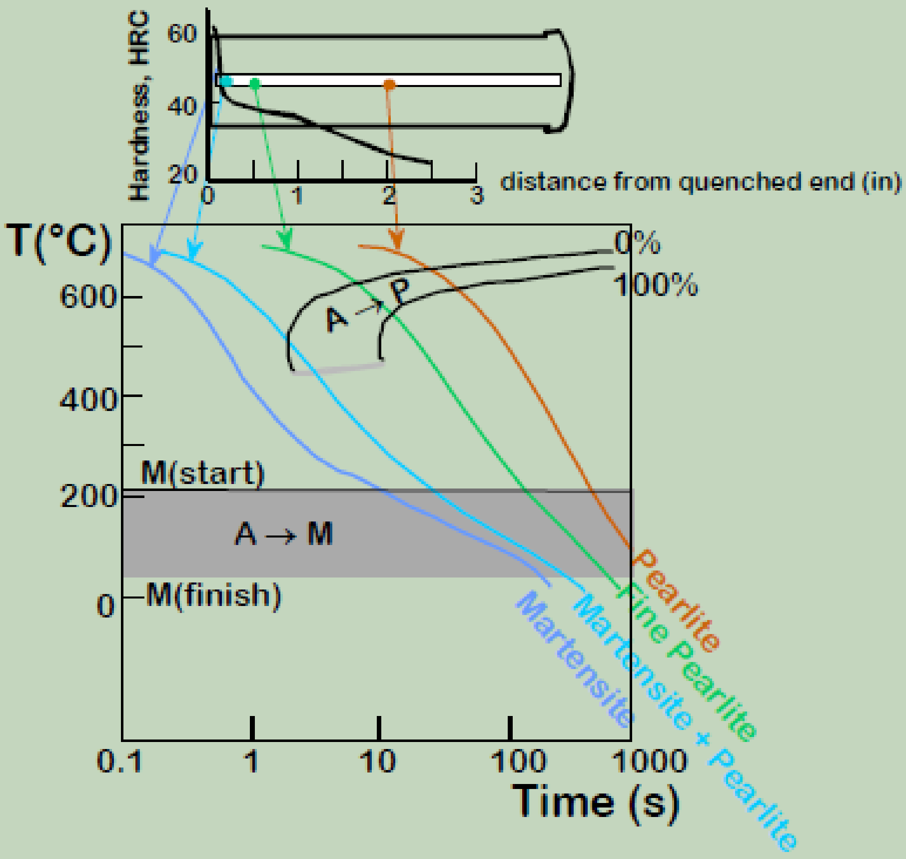
- Fine pearlite is harder and less ductile than coarse pearlite
- Effects of various percentages of carbon, cementite, and pearlite on other mechanical properties of steels are shown

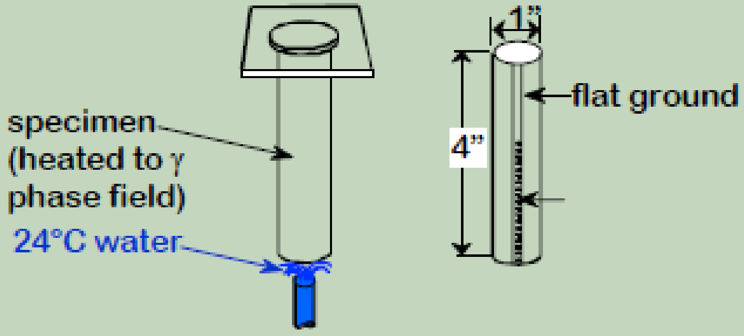


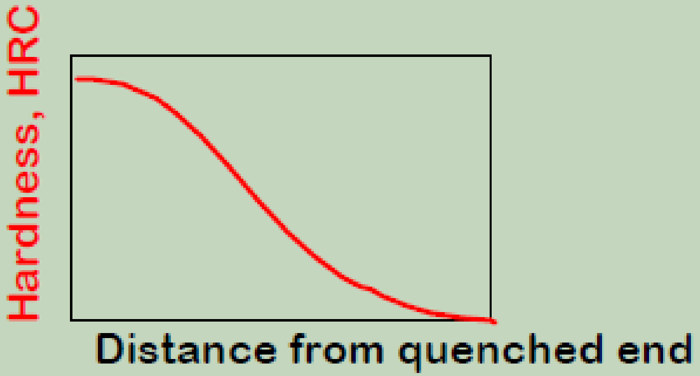
Hardenability of Ferrous Alloys

- Capability of an alloy to be hardened by heat treatment is called its **hardenability**
- A measure of the *depth* of hardness
- While hardness is the resistance of a material to indentation or scratching

Test used to measure Hardemability Test

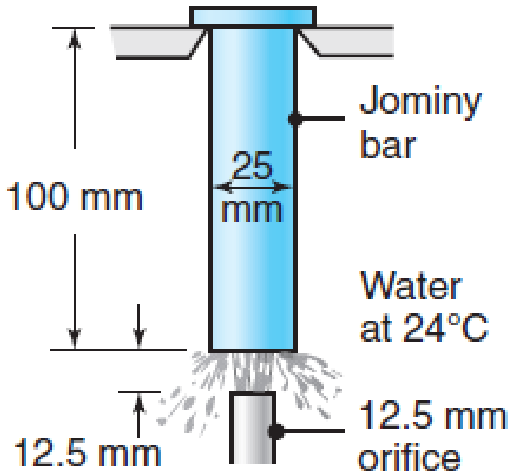


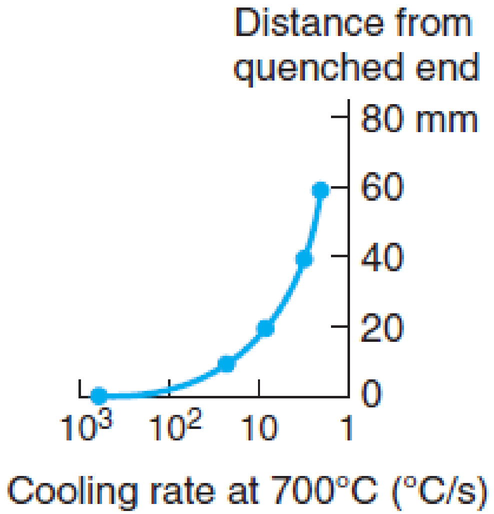




The End-quench Hardenability Test

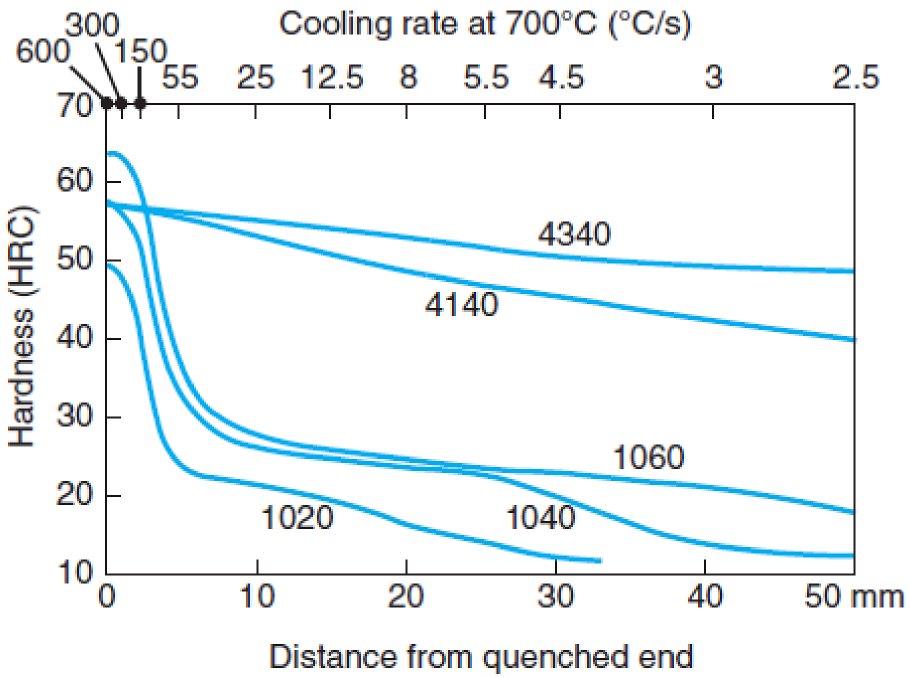
- Alloy heated to the proper temperature to form 100% austenite and then quenched directly at one end with a stream of water at 24° C is called **austenitized**





The End-quench Hardenability Test

- The effects of cooling rates for one end that is quenching is shown



- Greater the depth to which the hardness penetrates, greater the hardenability of the alloy
- Small variations in composition and in grain size can affect the shape of hardenability curves

Hardenability of Ferrous Alloys: Quenching Media

- Cooling rate of the alloy (**severity of quench**) in decreasing order is:

1. Agitated brine
2. Still water
3. Still oil
4. Cold gas
5. Still air

- Heated metal may form a **vapor blanket** due to the watervapor bubbles that form when water boils at the metal–water interface
- Blanket will creates a barrier to heat conduction
- **Polymer quenchants** is used for ferrous and nonferrous alloy quenching

HEAT TREATMENT OF NON-FERROUS ALLOY

- Nonferrous alloys cannot be heat treated by the techniques used for ferrous alloys
- Alloys do not undergo phase transformations
- Heat-treatable structure are hardened and strengthened by **precipitation hardening**
- Process where small particles of a different phase (**precipitates**) are uniformly dispersed in the matrix of the original phase

Precipitation Hardening

- Introducing small uniformly dispersed particles (second phase) within original phase matrix.
- The small particles are called ‘precipitates’ and can be formed by appropriate heat treatment
- The strengthening process → increased in resistance to dislocation motion by lattice strains which are established in the vicinity of small precipitated particles

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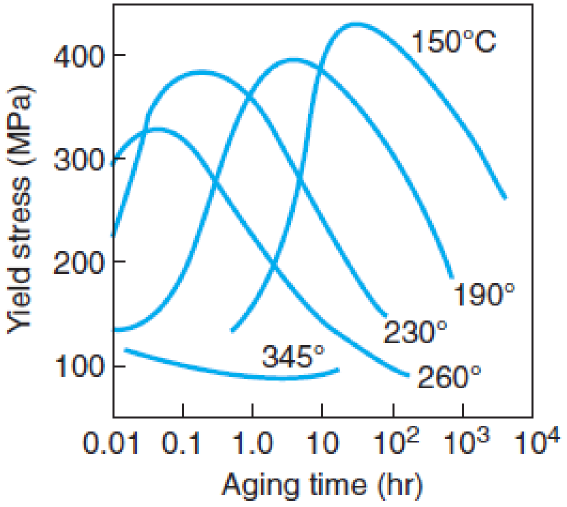
- Alloy is reheated to an intermediate temperature for a period of time and precipitation takes place
- Increase in strength is due to increased resistance to dislocation movement in the region of the precipitates

Aging

- Precipitation process it is also called *aging*,
- Property improvement is known as **age hardening**

Aging

- When carried out above room temperature, it is called **artificial aging**
- Hardening of aluminum alloys over a period of time at room temperature is called **natural aging**
- Natural aging can be slowed by refrigerating the quenched alloy (**cryogenic treatment**)
- An aged alloy can be used only up to a certain maximum temperature in service
- But an over-aged part has better dimensional stability



Maraging

- *Maraging* is a process where one or more intermetallic compounds are precipitated in a matrix of low-carbon martensite
- Hardening by maraging does not depend on the cooling rate

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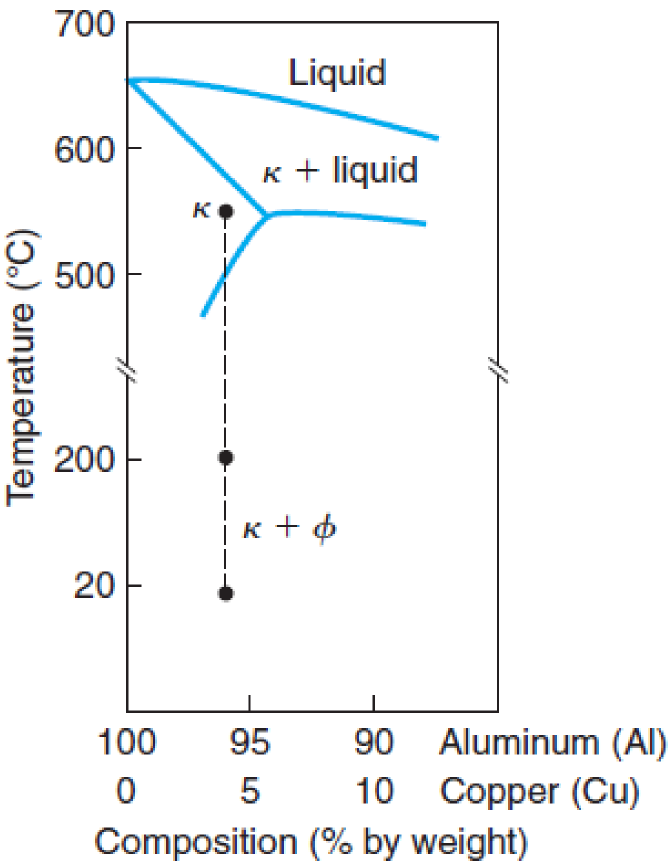
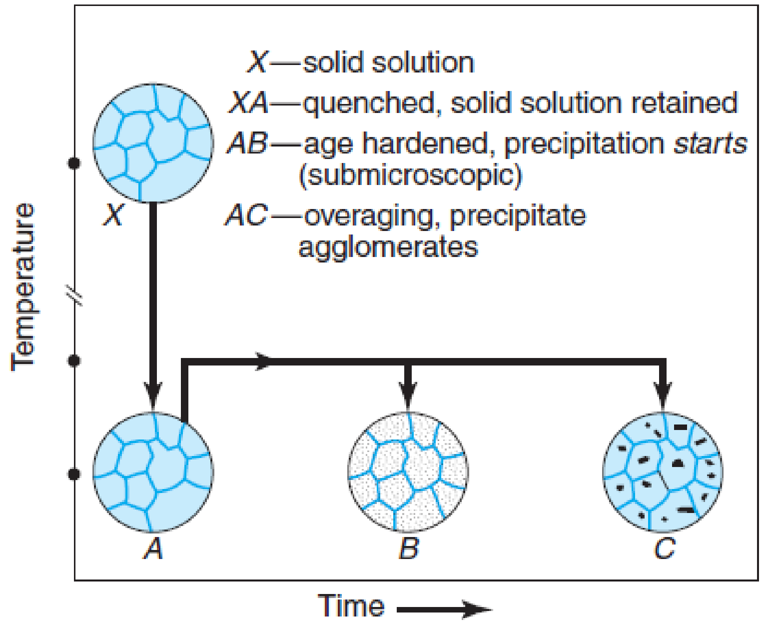
PRECIPITATION HARDENING

- 3 stages are involved in precipitation hardening



In **solution treatment**, the alloy is heated to within the solid-solution kappa phase and then cooled rapidly by quenching



Precipitation Hardening; example (READ)

- Duralumin is an aluminium alloy containing 4wt% copper, as well as smaller amounts of other elements. The impurities in the material changes its properties by changing the microstructure, and since the distribution of the copper atoms can be varied using heat treatments, a variety of microstructures, and hence properties can be produced.

- The copper forms precipitates of $CuAl_2$ within an aluminium matrix. These precipitates hinder the movement of dislocations and substantially strengthens the alloy. This process is widely used to make strong aluminium alloys for structural purposes, and is known as precipitation hardening .