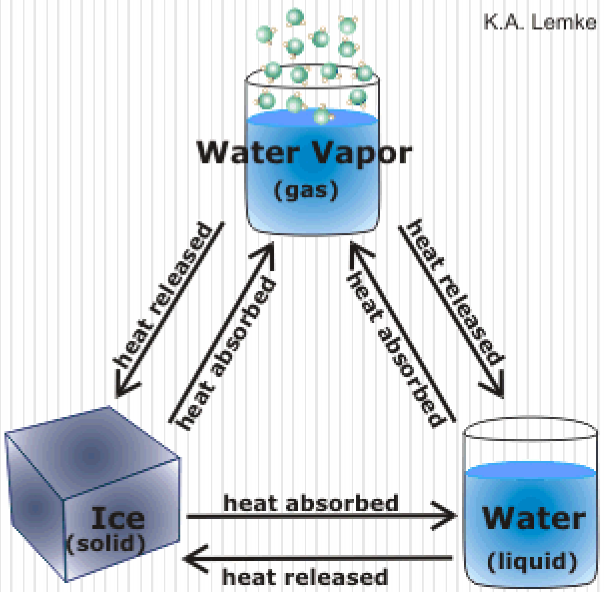
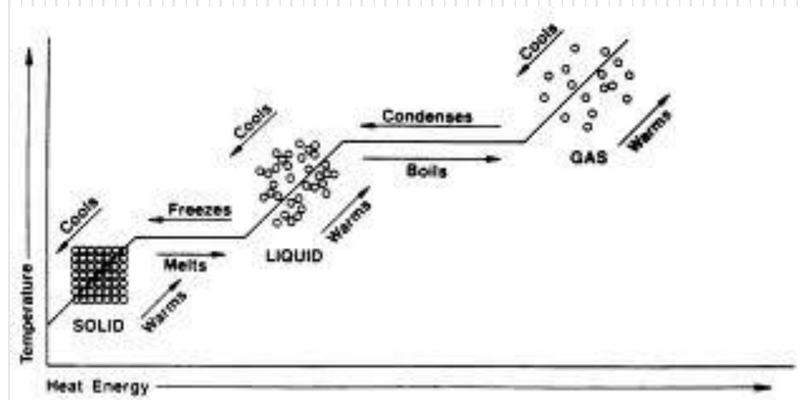
Phase change processes for material property manipulation





BY PROF.A.CHANDRASHEKHAR

Introduction

- The phase of a material is defined as a chemically and structurally homogeneous state of material.
- Any material can exists in any one of the following state solid, liquid and gaseous phases depending on the temperature and other conditions.
- A material in which two or more phases are present known as polyphase material.
- In poly phase, the overall properties of the material depend on the :
  - Number of phases present
  - Relative amount of each phase
  - Composition and microstructure of each phase
  - Size and distribution of the phases in the microstructure

Phase Diagram

- It is the graphical representation of the phase present, their compositions and temperature.
- It is also known as equilibrium diagram or constitutional diagrams.
- The term equilibrium denotes a state of rest, implying that for a particular temperature and composition no change in constituents will occur with time.
- The equilibrium diagrams are useful for determining the correct temperatures for heat treating alloys as well as for indicating the constituents which will exist at the room temperature.

- **Phase:** A region in a material that differs in structure and function from other regions.
- **Phase diagrams:**
  - **Represents phases present in metal at different conditions (Temperature, pressure and composition).**
  - **Indicates equilibrium solid solubility of one element in another.**
  - **Indicates temperature range under which solidification occurs.**
  - **Indicates temperature at which different phases start to melt.**

Solid Solution

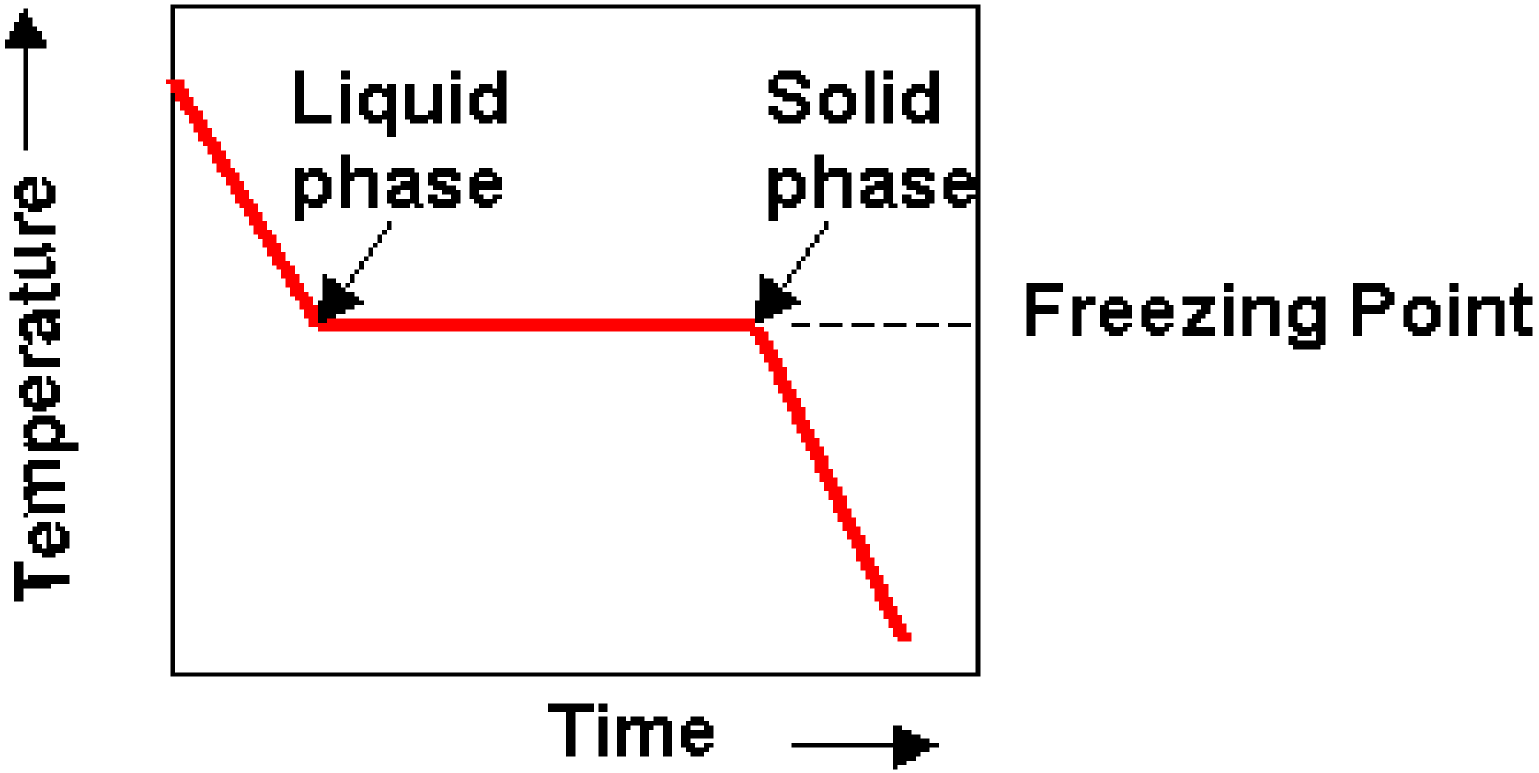
- The solution which is present in major proportion is called solvent.
- The solution which is present in minor proportion is called solute
- A **solid solution** is a solid-state solution of one or more solutes in a solvent.

- **Pure substance exist as solid, liquid and vapor.**
- **Phases are separated by phase boundaries.**
- **Example : Water, Pure Iron.**
- **Different phases coexist at *triple point*.**

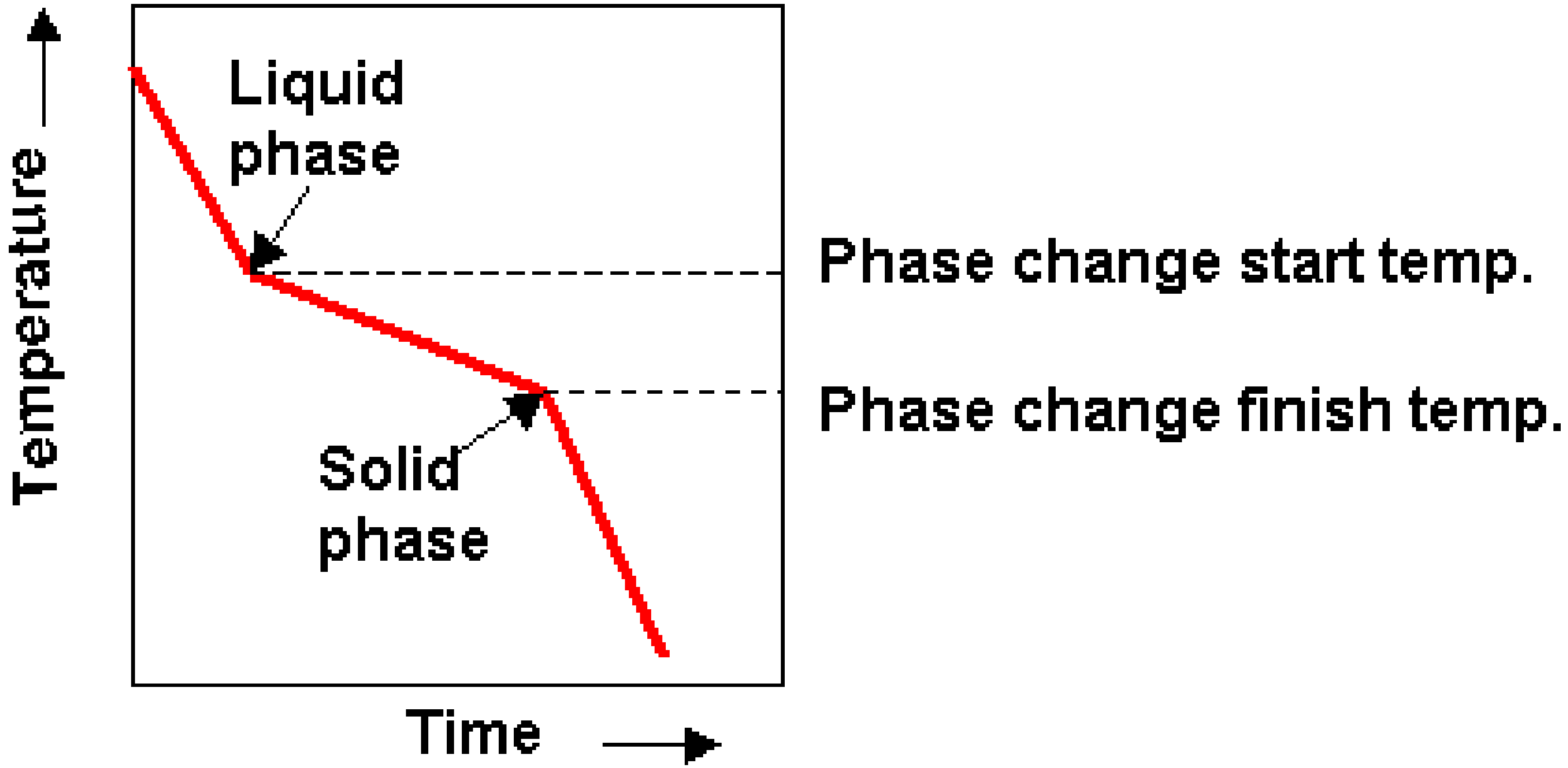
Cooling Curves

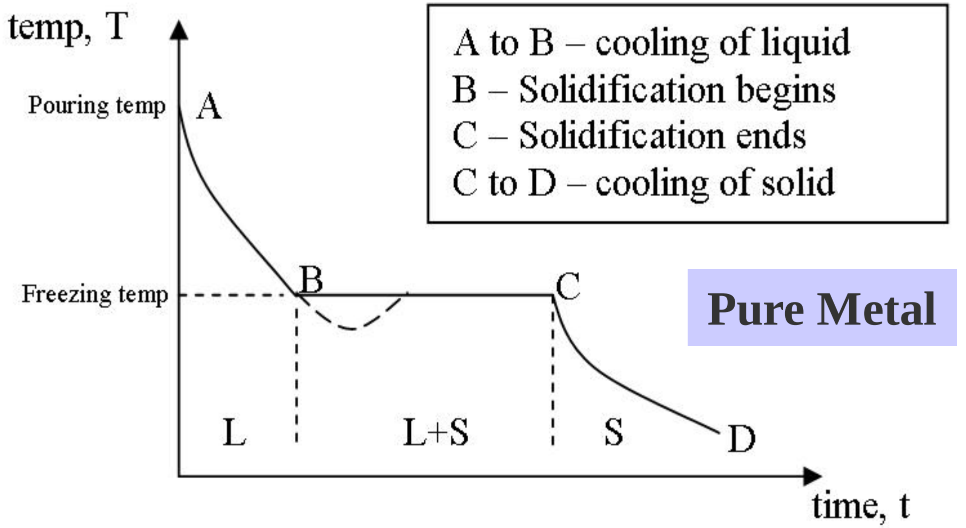
- Used to determine phase transition temperature.
- Temperature and time data of cooling molten metal is recorded and plotted.
- Thermal arrest : heat lost = heat supplied by solidifying metal
- Alloys solidify over a range of temperature (no thermal arrest)

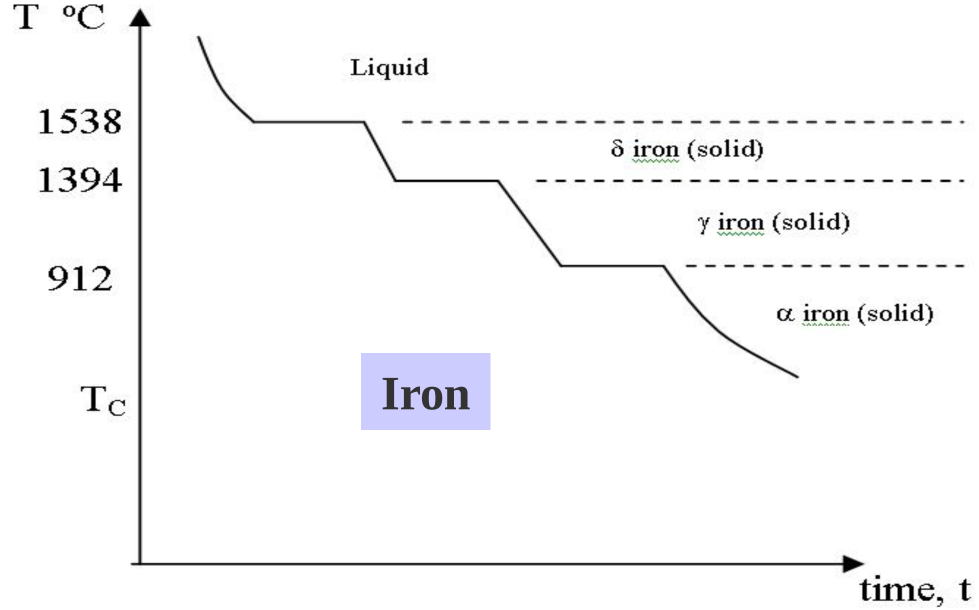
Cooling curve for the solidification of a pure metal.

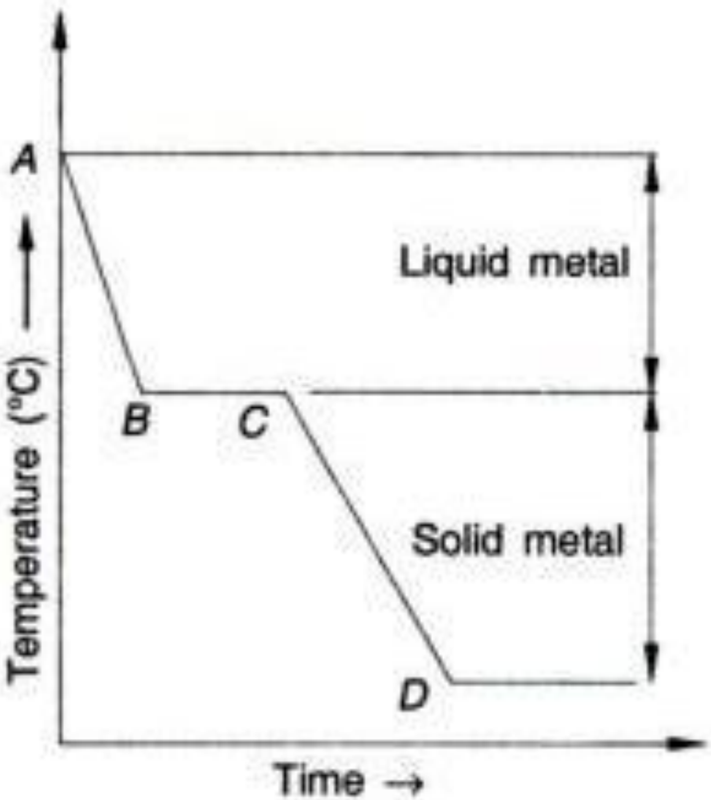


Cooling curve for a solid solution.

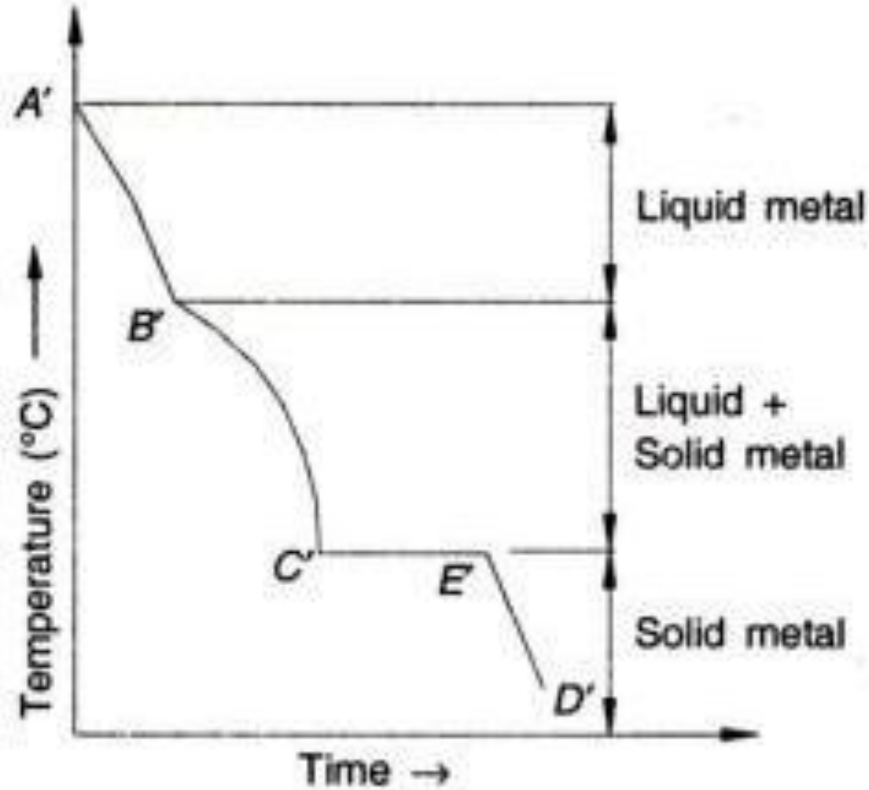



temp, T
Pouring temp
A
A to B – cooling of liquid
B – Solidification begins
C – Solidification ends
C to D – cooling of solid
Freezing temp
B
C
Pure Metal
L
L+S
S
D
time, t


T °C
Liquid
1538
δ iron (solid)
1394
γ iron (solid)
912
α iron (solid)
Iron
TC
time, t

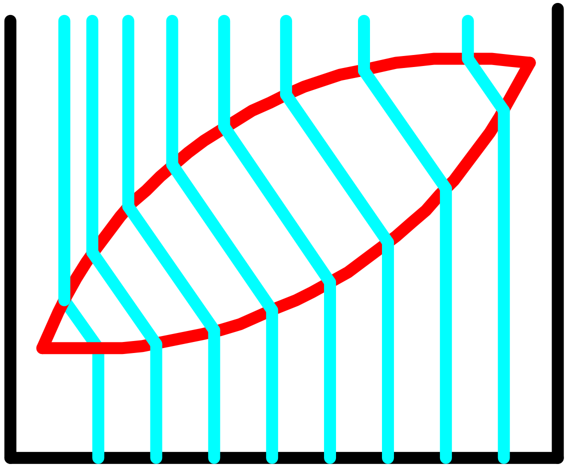


(a) a pure metal

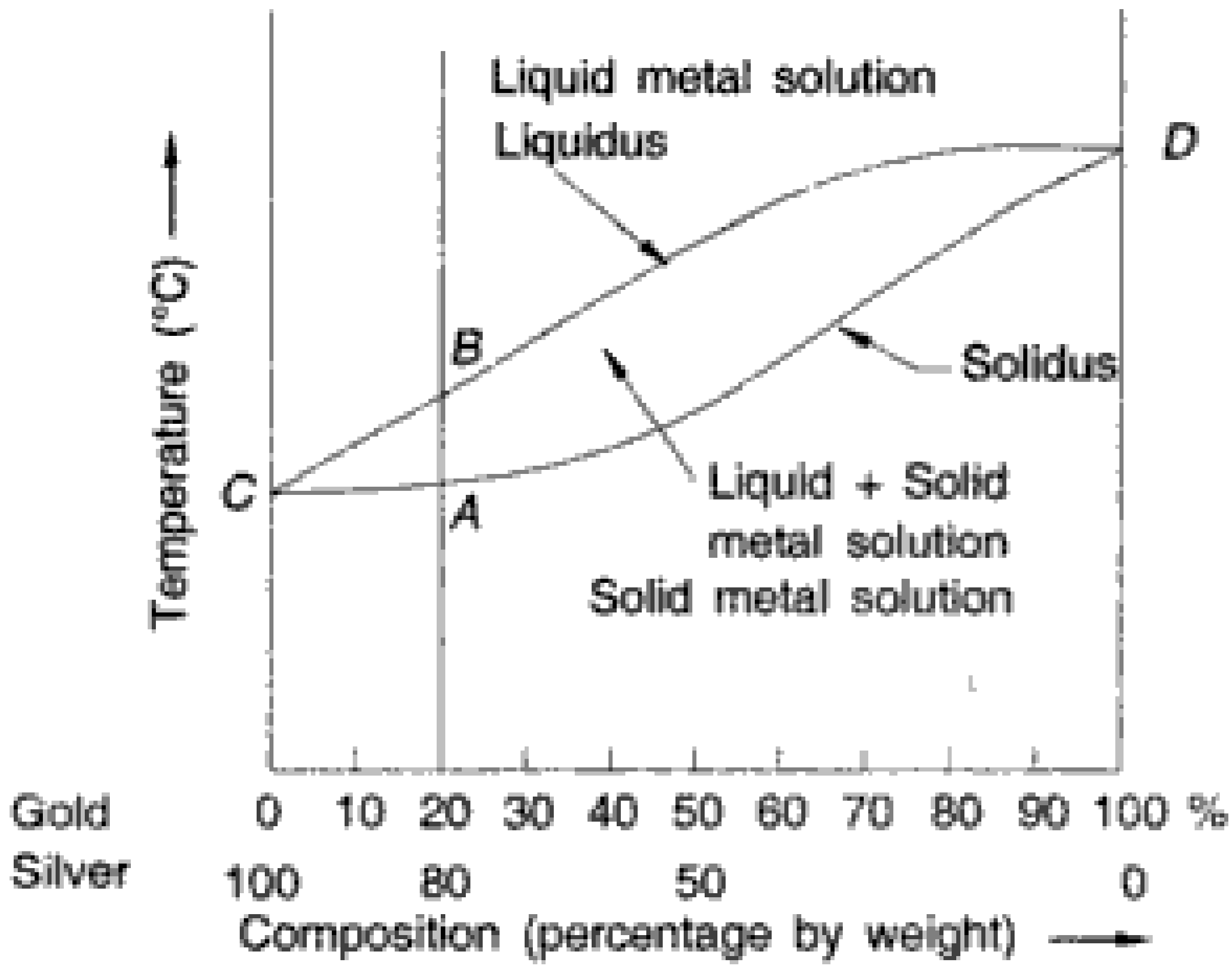


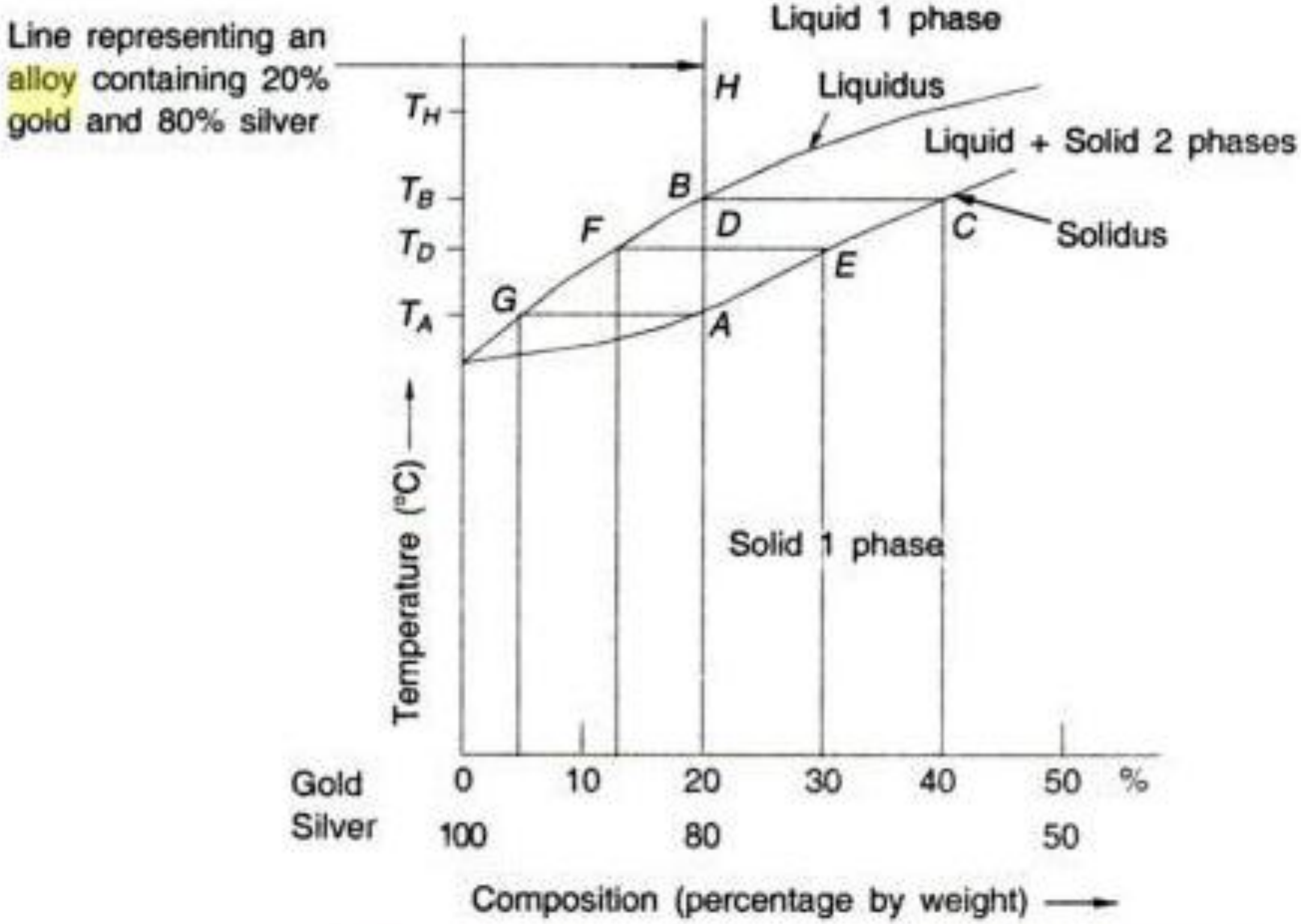
(b) an alloy

Construction Of Phase Diagram



Phase diagram for a binary alloy.





Enlarged portion of gold-silver alloy phase diagram.

The Lever rule gives the weight % of phases in any two phase regions.

$$\% \text{ Liquid present} = \frac{\text{Length } DE}{\text{Length } FE} \times 100$$

$$\% \text{ Solid present} = \frac{\text{Length } FD}{\text{Length } FE} \times 100$$

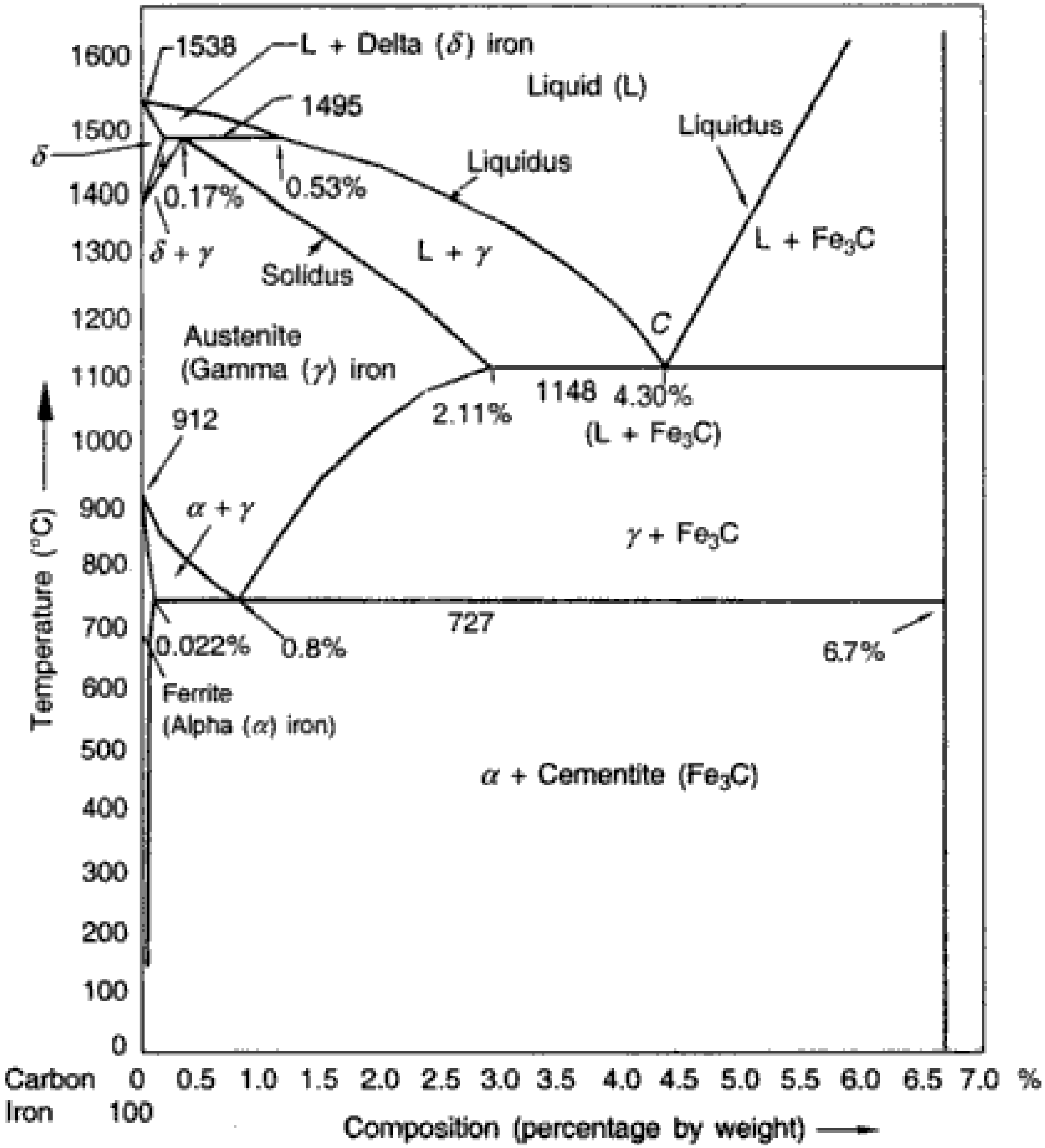
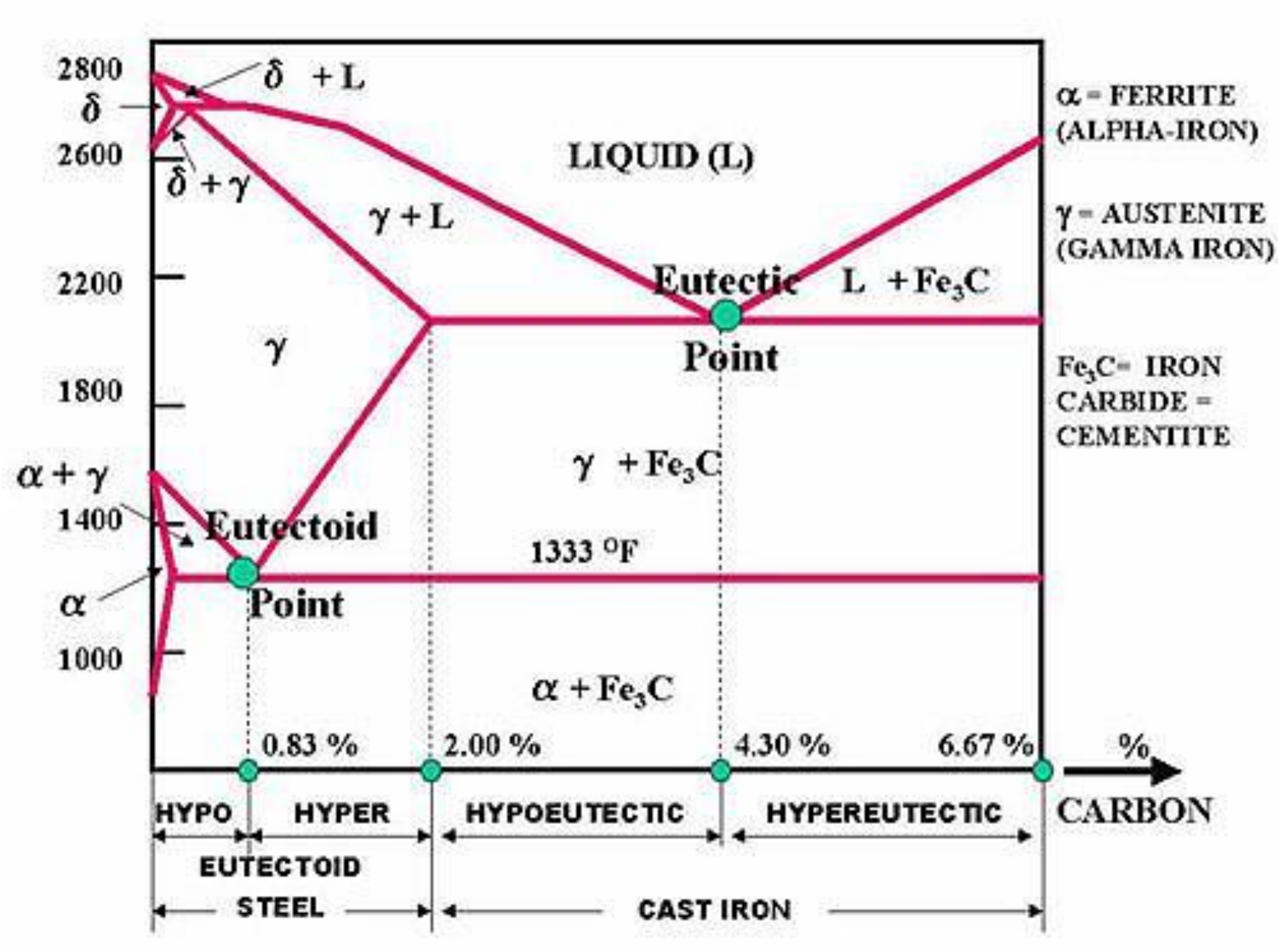
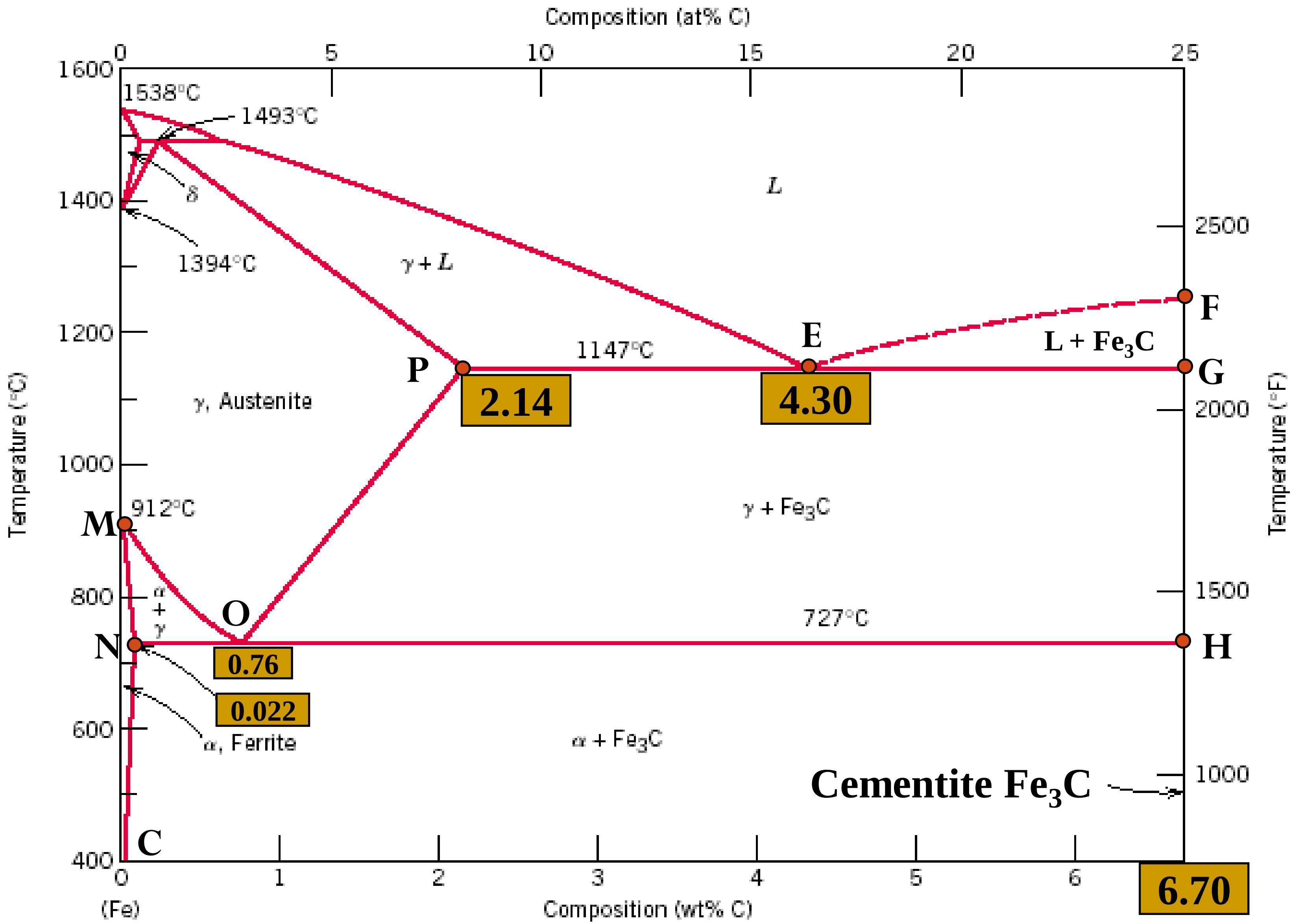


Figure 10.4 Iron-carbon equilibrium diagram.

Iron-Iron Carbide Diagram





Composition (at% C)
0
5
10
15
20
25
1600
1538°C
1493°C
δ
1400
1394°C
L
2500
γ + L
F
E
L + Fe3C
1200
P
1147°C
G
2.14
4.30
γ, Austenite
2000
Temperature (°C)
Temperature (°F)
1000
M
912°C
γ + Fe3C
800
α + γ
O
1500
727°C
N
H
0.76
0.022
600
α, Ferrite
α + Fe3C
Cementite Fe3C
1000
C
400
0
1
2
3
4
5
6
6.70
(Fe)
Composition (wt% C)

CEMENTITE (Fe3C):

- **Cementite is also known as iron carbide which has a chemical formula, Fe_3C.**
- **It contains 6.67 % Carbon by weight. It is a typical hard and brittle interstitial compound of low tensile strength (approximately 5,000 psi) but high compressive strength.**
- **Its crystal structure is orthorhombic.**

FERRITE (α iron):

- **It is also known as (α) alpha -iron, which is an interstitial solid solution of a small amount of carbon dissolved in iron with a Body Centered Cubic (B.C.C.) crystal structure. It is the softest structure on the iron-iron carbide diagram.**

AUSTENITE (γ iron):

- **It is also known as (γ) gamma-iron, which is an interstitial solid solution of carbon dissolved in iron with a face centered cubic crystal (F.C.C) structure.**

(δ) DELTA IRON:

- **Delta iron exists between 1400 and 1538 ^{o}c. It may exist in combination with the melt to about 0.50 % Carbon, in combination with austenite to about 0.18 % Carbon and in a single phase state out to about 0.10 % carbon. Delta iron has the Body Centered Cubic (B.C.C) crystal structure and is magnetic.**

PEARLITE (α + Fe_3C)

- **It is the eutectoid mixture containing 0.83 % Carbon and is formed at 727^{o}c on very slow cooling. It is very fine plate like or lamellar mixture of ferrite and cementite. The structure of pearlite includes a white matrix (ferritic background) which includes thin plates of cementite.**

LEDEBURITE (α + Fe_3C)

- It is the eutectic mixture of austenite and cementite. It contains 4.3 % Carbon and represents the eutectic of cast iron. Ledeburite exists when the carbon content is greater than 2 %, which represents the dividing line on the equilibrium diagram between steel and cast iron.

Heat Treatment

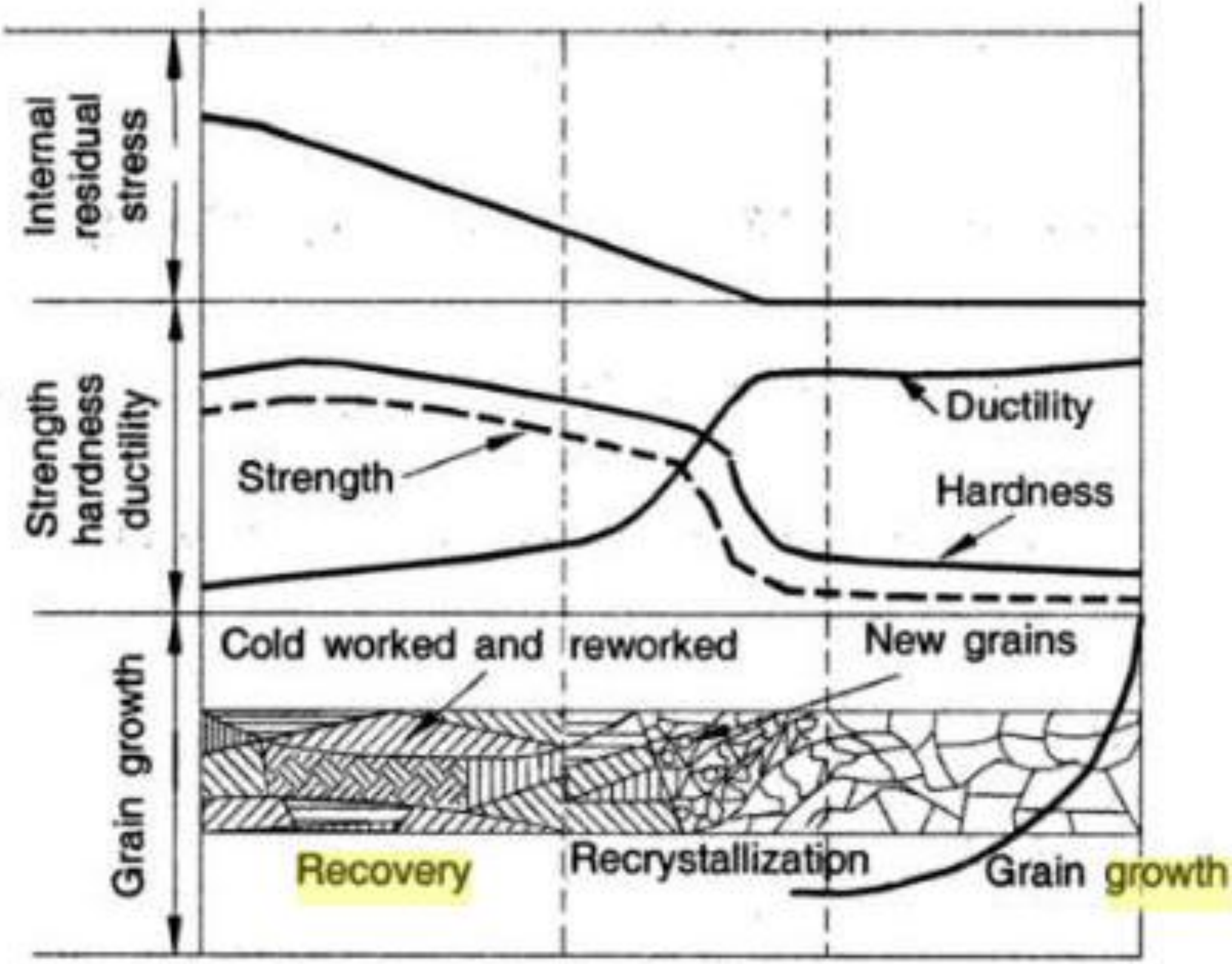
•Heat treatment: an operation, or series of operations, involving the heating and cooling of steel in the solid state and in a controlled atmosphere.

Various types of heat treatment processes are used to change the following properties or conditions of the steel:

- Improve the toughness
- Increase the hardness
- Increase the ductility
- Improve the machinability
- Refine the grain structure
- Remove the residual stresses
- Improve the wear resistance

Work hardening, strain hardening, or cold work

- All metals get hardened when plastically deformed in cold condition.
- An increase in the hardness, yield point or tensile strength takes place when a metal is plastically strained. This is called strain hardening or work hardening.
- Strain hardening reduces the formability of the material.



Recovery, recrystallization and grain growth.

Recovery, Recrystallization and grain growth

- Recovery :

  The partial restoration of the original properties, produced by reducing the distortion of the crystal lattice without noticeable changes in the microstructure, is called recovery.

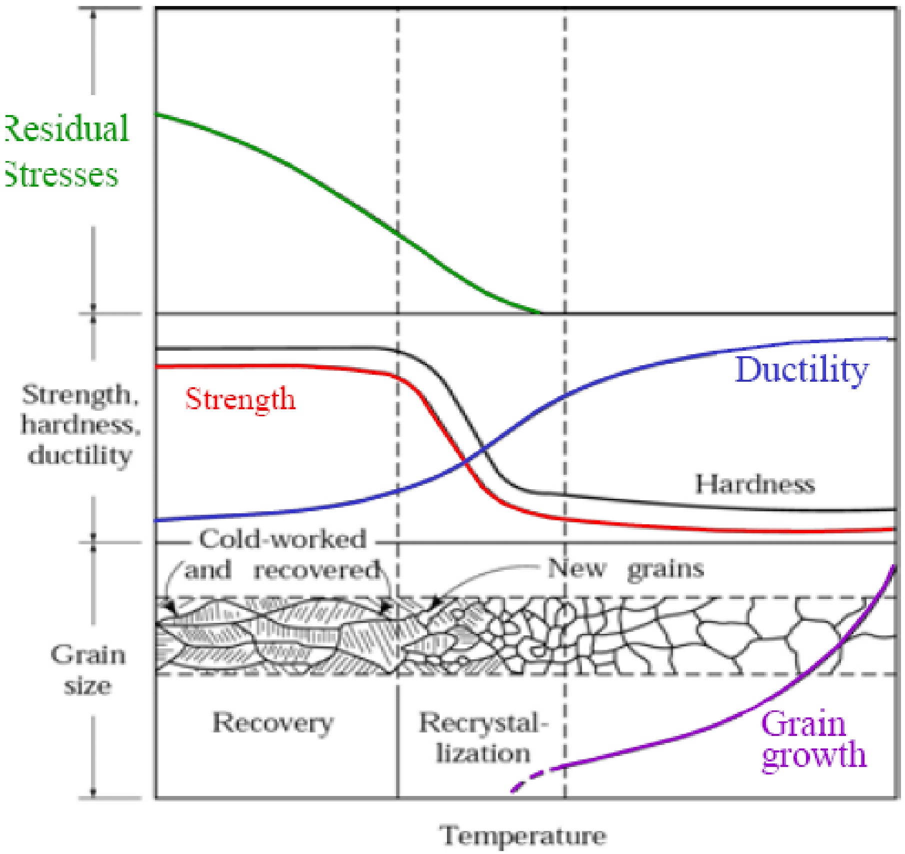
Recrystallization

- At high temperatures, new grains start growing and if the temperature is sufficiently high, growth of new grains is accelerated and continuous until the formation of new grains takes place.
- The temperature at which the process of recrystallization is said to complete is known as recrystallization temperature.
- recrystallization temperature is different for different materials.

Grain Growth

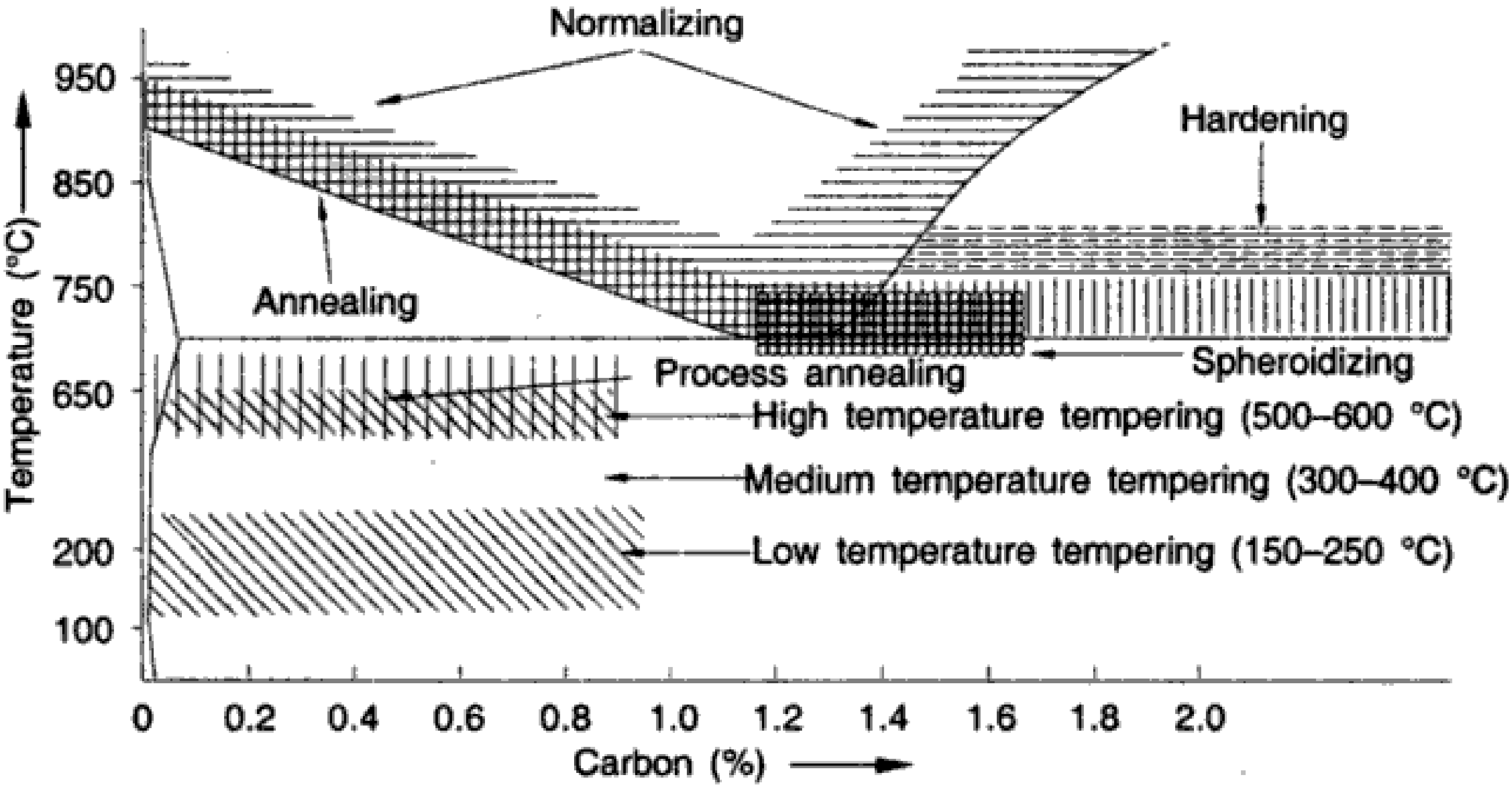
- After a material has recrystallized, the grains are smaller and some what regular in shape. The grains will grow, if the temperature is high enough or if the temperature is allowed to exceed the minimum required for recrystallization.
- This growth is the result of the tendency to return to more stable and larger state, and appears to depend primarily on the shape of the grain.

Annealing-Recrystallization in Metals



Schematic illustration of the effects of recovery, recrystallization, and grain growth on mechanical properties and on the shape and size of grains.

- Formation of new strain-free grains is called *recrystallization*
- Recrystallization takes time - the recrystallization temperature is specified as the temperature at which new grains are formed in about …………
- Heating a metal to its recrystallization temperature prior to deformation allows a greater amount of straining, and lower forces and power are required to perform the process



Changes that occur in the microstructure of steel.

Stages of Heat Treatment

- Heating slowly to ensure a uniform temperature
  - prevent distortion/cracking
- Soaking the metal at a given temperature for a given time
  - promote internal structural change
- Cooling the metal to room temperature
  - Cooling medium (gas, liquid, solid) determines the cooling rate

- **Critical Temperature or Transformation Range**
  - temperature(s) at which metal undergoes internal atomic changes, which radically affects the properties

The Various processes used for heat treatment are:

- Annealing

  It is a process of heating the steel to a temperature at or near the critical temperature range, then cooling at a predetermined rate, and employing usually a relatively slow cooling.

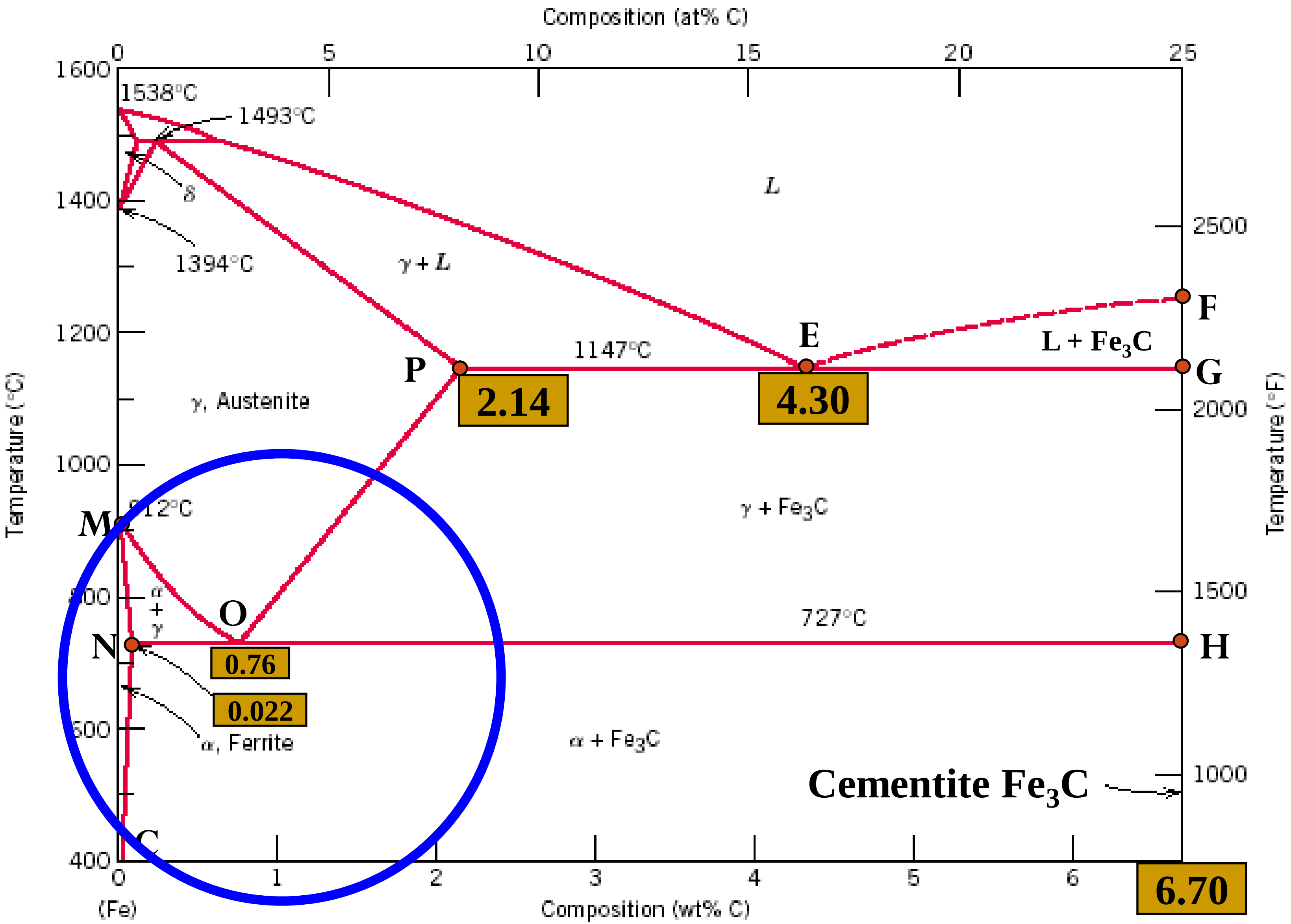
Annealing

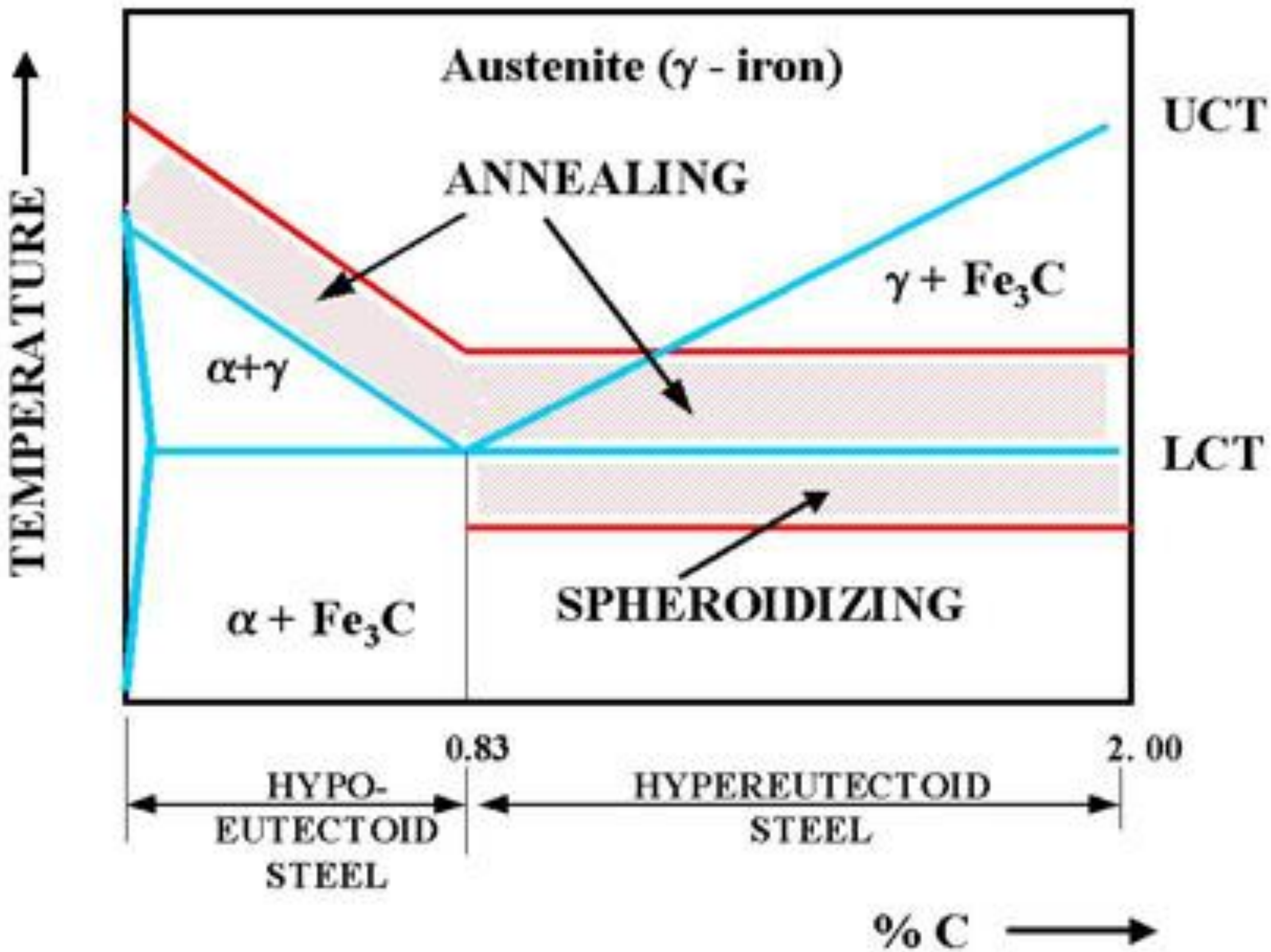
- Procedure (heating/soaking/cooling)
- Objectives
  - relieve internal stresses
  - Soften the material
  - Make them more ductile
  - Refine their grain structures
- Examples

  Treat welding area to relieve internal stress

  Softening ferrous/nonferrous materials

The Iron–Iron Carbide Phase Diagram





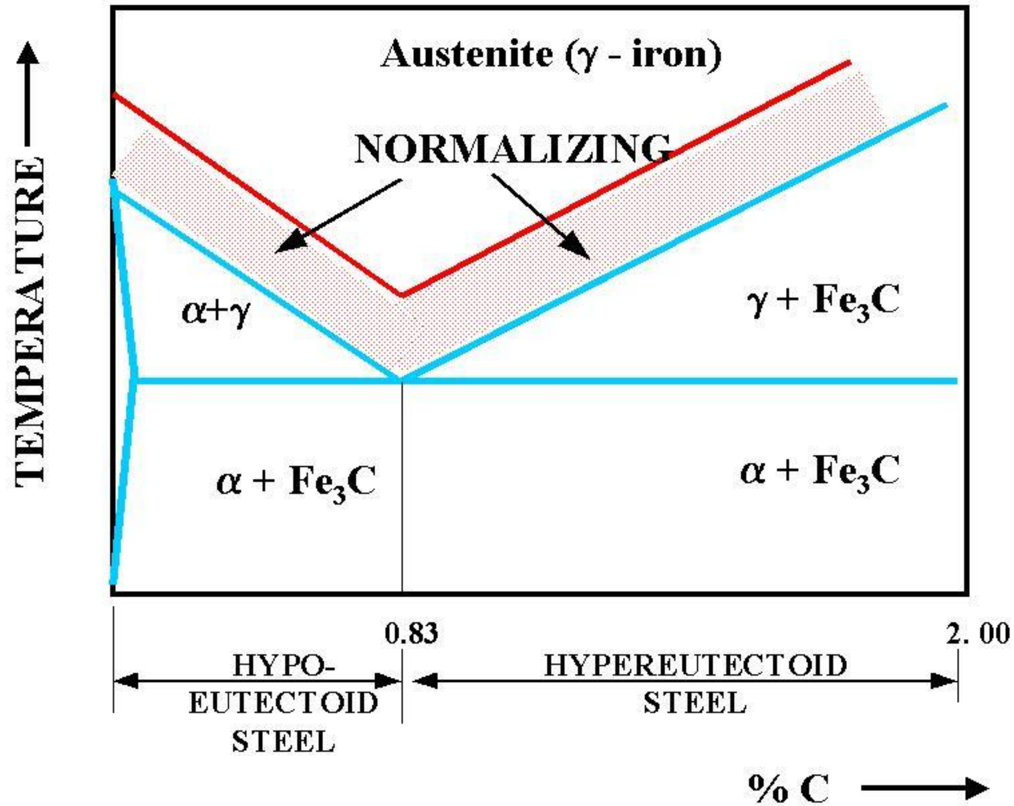
Austenite (γ - iron)
UCT
ANNEALING
γ + Fe3C
α+γ
LCT
SPHEROIDIZING
α + Fe3C
TEMPERATURE
0.83
2. 00
HYPO-
EUTECTOID
STEEL
HYPEREUTECTOID
STEEL
% C

Spheroidizing

- It is the process of heating the steel just under 700^0c and holding at that temperature for at least an hour per inch thickness so that grains change into small spheres.
- It improves the machinability and toughness of the sphere.

Normalizing

- It is a process where by steel is heated approximately 38 to 60 ^{0}c above the critical range followed by cooling to below that range in still air.



Normalizing

- Procedure (heating/soaking/cooling)
- Higher temperature than annealing
- Air cooling
- **Objectives**

  Remove internal stresses induced by heat treating such as welding, casting, forging, machining, etc
- **Results**

  Harder and tougher than annealed parts

  Good for parts subject to impact

Hardening

- The process of hardening is accomplished by first heating the steel to a temperature above critical temperature and keeping at this temperature for a long time, transforming the steel to austenite. Then it is cooled at rapid rate by quenching in water, oil or any other quenching medium.

Hardening

- Procedure (heating/soaking/cooling)

  Cooling rapidly by plunging into oil/water/brine
- Objectives

  Increase hardness/strength (less ductile)
- Categories

  Case hardening

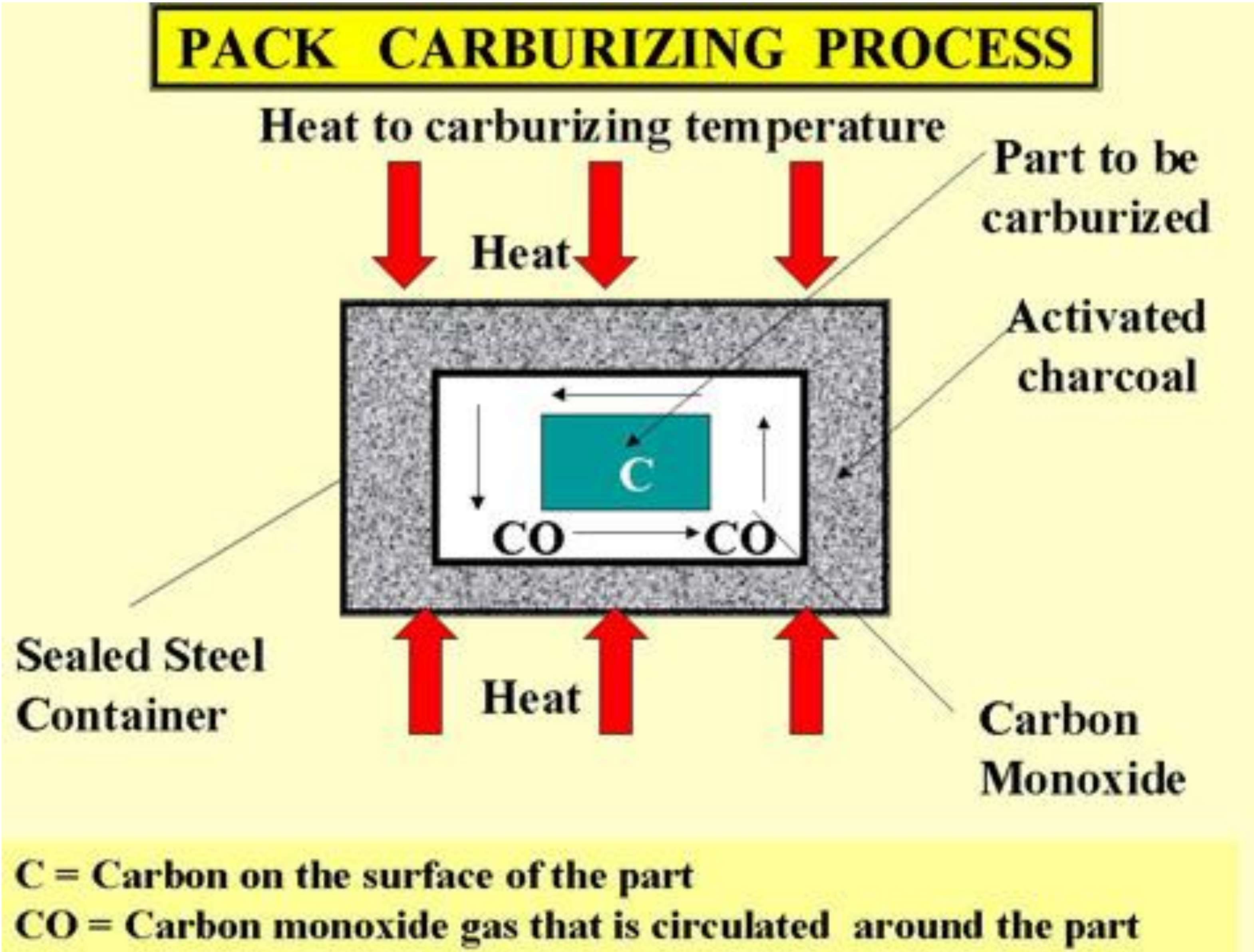
  Flame hardening

Hardenability

the ability of steel to become hardened to a specified depth below its surface is known as its hardenability.

Case Hardening

- Oldest method of producing a hard surface on steel is case hardening or carburizing.
- If a low carbon steel is placed in a high carbon atmosphere at high temperature and pressure, carbon will diffuse in to the outer layers of the steel.
- The case hardening process consists of heating steel parts in gas-tight cast-iron or alloy steel boxes packed with charcoal. This boxes are heated in a suitable furnaces to proper temperature. the oxygen with in the box combines with the carbon from charcoal to form carbon monoxide. When in contact with heated steel, carbon monoxide gives up carbon which diffuses in to the surface.


PACK CARBURIZING PROCESS
Heat to carburizing temperature
Part to be carburized
Heat
Activated charcoal
C
CO
CO
Sealed Steel Container
Heat
Carbon Monoxide
C = Carbon on the surface of the part
CO = Carbon monoxide gas that is circulated around the part

CASE HARDENING

Objectives

Produces a hard, wear-resistant surface

Categories

Carburizing: carbon is added to enhance the surface hardness

Cyaniding: Preheated steel is dipped into a heated cyanide bath; harder than that produced by carburizing; deadly poison

Nitriding: heat-treated and tempered prior to nitriding; then heated in an ammonia gas atmosphere; no quenching required; produce hardest surface (used for producing engine parts). The steel is heated to a temperature of 500 to 600^{o}c in the presence of ammonia for 50 to 100 hours.

Tempering

- Fully hardened steel is unable to withstand impact loads. Therefore some of its hardness and strength must be sacrificed in a compromise to gain sufficient ductility and toughness. This is accomplished by a process called tempering.

Tempering

- Procedure (heating/soaking/cooling)

  Heated below hardening/annealing/normalizing temperature

  Cooling in still air (some cases must be quenched)

  Always following hardening

- Results

  Relieve quenching stress and reduce hardness/brittleness

  Increases softness, ductility, malleability, and impact resistance

Heat treatment Procedure

Step 1: Decide the hardness of the material required depending up on the application.

Step 2: select carbon content and alloying elements that can give the desired hardness.

Step 3: Fabricate the part to oversized (pre-finishing) dimensions.

Step 4: once the part is fabricated, use the hardening process selected to harden the part.

Step 5: finally, the part should be given the finish to the required dimensions by subjecting it to grinding and other finishing processes.

Hot Working and Cold Working

- Materials can be shaped into various sizes in hot condition and cold condition.
- These processes are classified as hot working and cold working.

Hot Working

- It is the plastic deformation of materials above their recrystallization temperature.
- The temperature should not be too high so as to reach the solidus temperature.
- Hot working means working at a temperature, which is as close as possible to the recrystallization temperature but must be slightly higher than it.

Hot Working

- Characteristics:

1. Brings homogeneity in metals and alloys
2. Welding of cracks and blowholes takes place.
3. Grain refinement takes place.
4. In steel, decarburization at the surface layer takes place.

Hot Working

Advantages

1. Because of high temperature, the strength of the metal is low. Hence, less force is required to shape the metal.
2. Impurities in the form of inclusions are broken up and distributed throughout the metal.
3. Ductility and resistance to impact are improved.
4. Blowholes and porosity are eliminated by welding action at the high temperature.

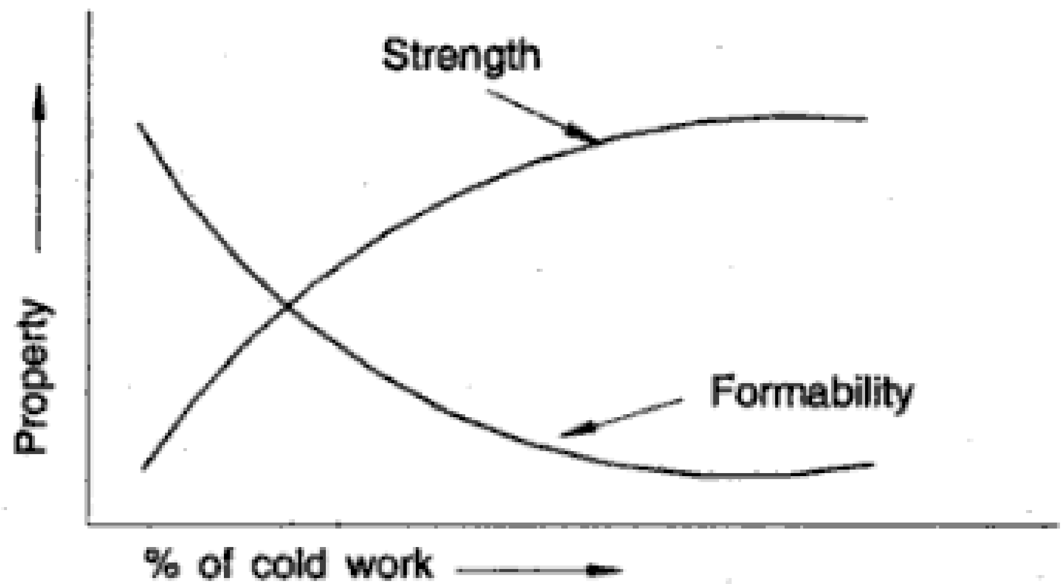
Hot Working

Limitations

1. High temperature heating facilities are required, which increase the investment.
2. Due to scaling and oxidation, there is heavy material loss.
3. Poor dimensional tolerance and surface finish.

Cold Working

- Deforming a material below recrystallization temperature is called cold working, involves higher pressure.
- Grains are distorted permanently and there will be no recrystallization.



Effect of cold work on properties of material.

Cold Working

Advantages

1. No material loss.
2. Surface finish is excellent.
3. Strength and hardness of the material are increased.

Cold Working

Disadvantages

1. Large forces are required for deformation, calling for high capacity machines.
2. Only ductile material can be cold worked.
3. Tooling costs are high.
4. Subsequent heat treatment is required to relieve the internal stresses, which adds cost.