

Introduction to Engineering Materials and Metallurgy

Dr. Niraj Bala

Introduction

- **Materials:**

Materials are substances of which something is composed or made.

e.g. wood, concrete, brick, steel, plastic, glass, rubber, Al, Cu and paper

- **Material Science:** Material science is primarily concerned with search for basic knowledge about the internal structure, properties, and processing of materials.

- **Material Engineering:** Material engineering is mainly concerned with the use of fundamental and applied knowledge of materials so that the materials can be converted into products necessary or desired by society.



- Engineering Materials are divided into 3 main classes:

- Metallic

- Polymeric(plastic)

- Ceramic materials

Two more types are composites and electronic materials

Metallic materials

- These materials are inorganic substances which are composed of one or more metallic elements and may also contain some non-metallic elements.
- E.g. iron, Al, Ni Ti
- Metals and alloys are divided into two categories
 - Ferrous metals: that contain a large percentage of iron such as the steels and cast irons
 - Non ferrous metals and alloys: that do not contain iron or only relatively small amount of iron. E.g. Al, Ni, Zn.

Polymeric (plastic) materials

- Most polymeric materials consist of organic (carbon-containing) long molecular chains or networks.

Ceramic materials

- Ceramic materials are inorganic materials which consist of metallic and non-metallic elements chemically bonded together.

Composite Materials

- Composite materials are mixture of two or more materials. These consist of selected filler or reinforcing material and a compatible resin binder to obtain specific characteristics and properties desired.

Circuit board: polymeric materials



Weight percentage of materials used in an automobile



Ceramic materials for advanced engine applications



Summary:

- Materials
- Material Science
- Material Engineering
- Types of Materials

References

- Book referred:
- Fundamentals of Materials Science and Engineering by William Smith

CRYSTAL STRUCTURE

BY

NIRAJ BALA

CRYSTAL STRUCTURE

- ✘ **Crystal:** a solid composed of atoms, ions, or molecules arranged in a pattern that is repeated in three dimensions.
- ✘ **Crystal Structure:** a regular three-dimensional pattern of atoms or ions in space.
- ✘ **Space lattice:** three dimensional array of points each of which has identical surroundings.
- ✘ **Lattice point:** one point in an array in which all the points have identical surroundings.
- ✘ **Unit cell:** a convenient repeating unit of a space lattice.

IN 3D WE HAVE SEVEN CRYSTAL SYSTEMS

Crystal System	Unit Cell Parameters	Crystal System Diagram
Cubic	$a = b = c$ $\alpha = \beta = \gamma = 90^\circ$	
Trigonal	$a = b = c$ $\alpha = \beta = \gamma = 120^\circ$	
Orthorhombic	$a \neq b \neq c$ $\alpha = \beta = \gamma = 90^\circ$	

IN 3D WE HAVE SEVEN CRYSTAL SYSTEMS



PRINCIPAL UNIT CELLS



(A) BCC (B) FCC (C) HCP

BCC UNIT CELL



BCC UNIT CELL



FCC UNIT CELL



FCC UNIT CELL



HCP UNIT CELL



MILLER INDICES

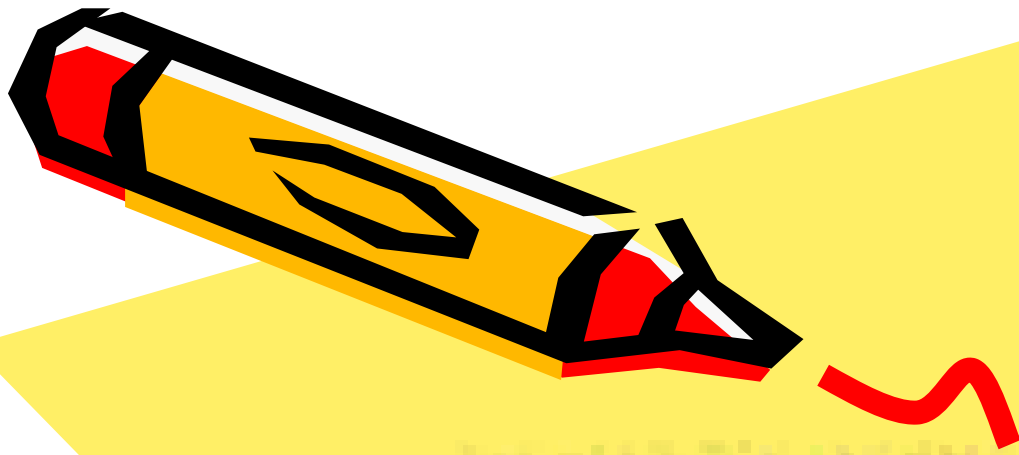


MILLER INDICES



REFERENCES

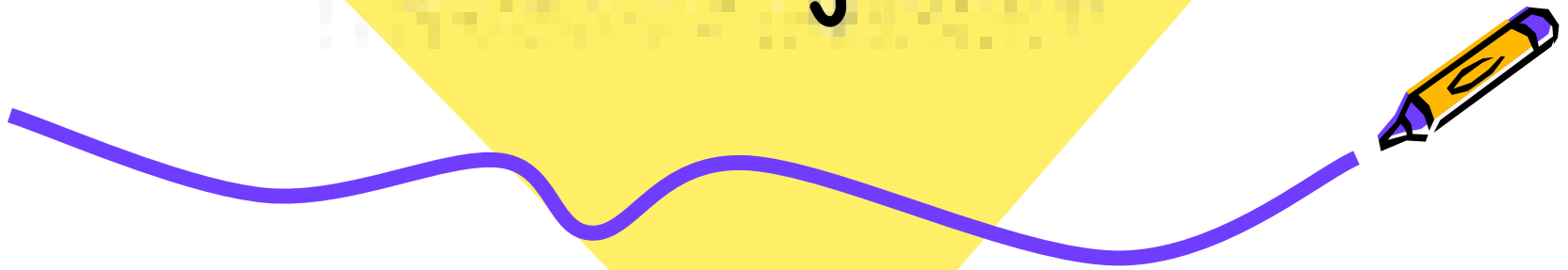
- ✘ Book referred:
- ✘ Fundamentals of Materials Science and Engineering by William Smith.



Phase Diagrams

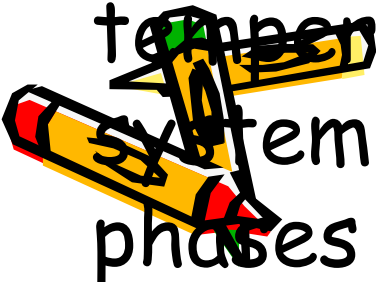
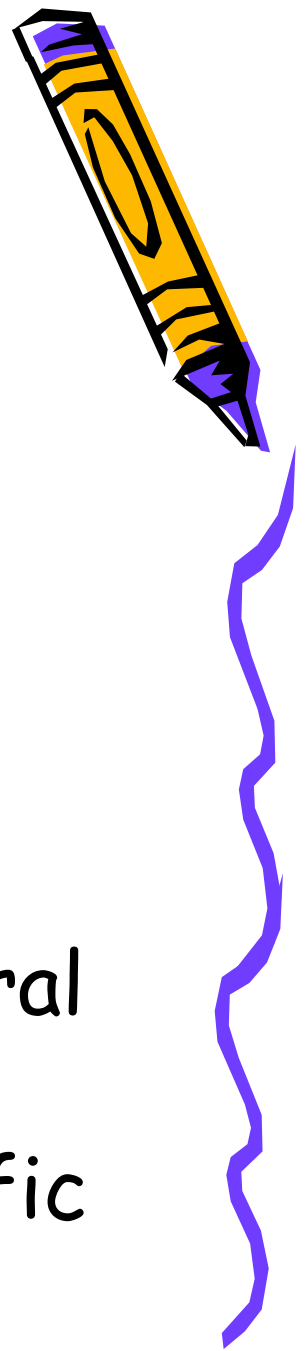
By

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Introduction

- A phase diagram is a graphical way to depict the effects of pressure and temperature on the phase of a substance:
- Phase diagrams provide a graphical means of presenting the results of experimental studies of complex natural processes, such that at a given temperature and pressure for a specific system at equilibrium the phase or phases present can be determined.



SYSTEM - Any portion of the universe which is of interest and can be studied experimentally.

PHASE- any particular portion of a system, which is physically homogeneous, has a specific composition, and can be mechanically removed or separated from any other phase in the system.

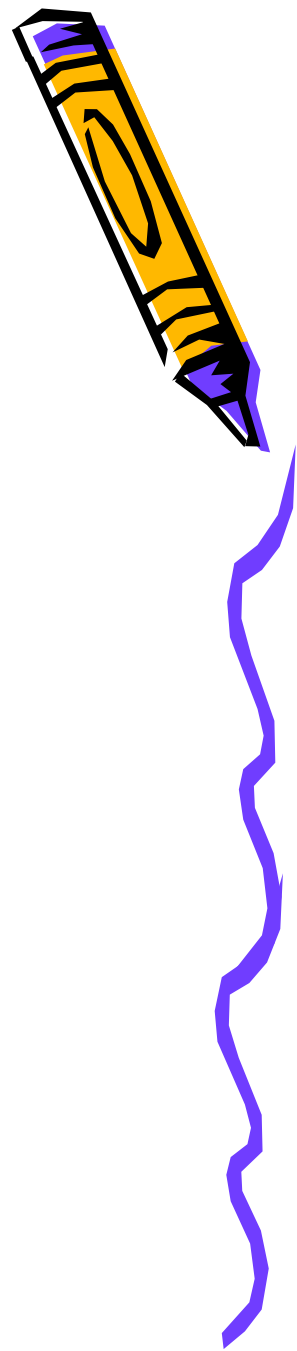
e.g. A system containing a mixture of ol and pl in equilibrium contains two phases - ol and pl.

In petrology we generally deal with primary phases - any crystalline phase which can coexist with liquid, i.e. it formed/crystallized directly from the liquid.

EQUILIBRIUM - The condition of minimum energy for the system such that the state of a reaction will not change with time provided that pressure and temperature are kept constant.



LEVER RULE



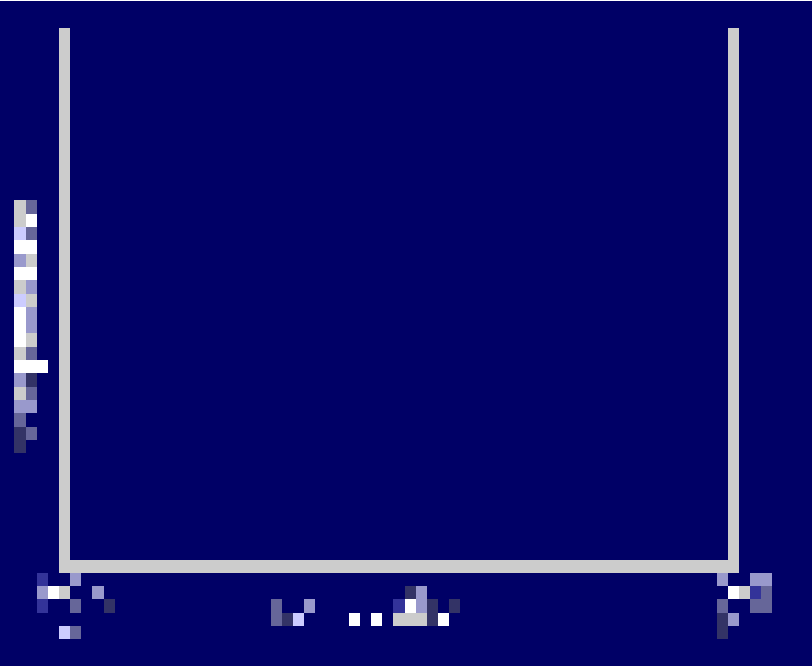
- To determine compositions of phases and the relative proportions of phases to each other in Binary diagrams the **LEVER RULE** is used.

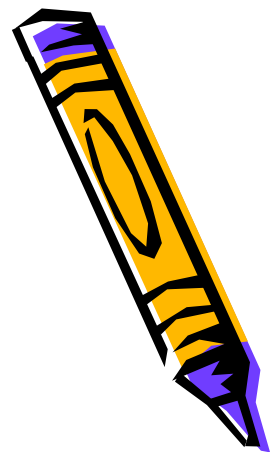
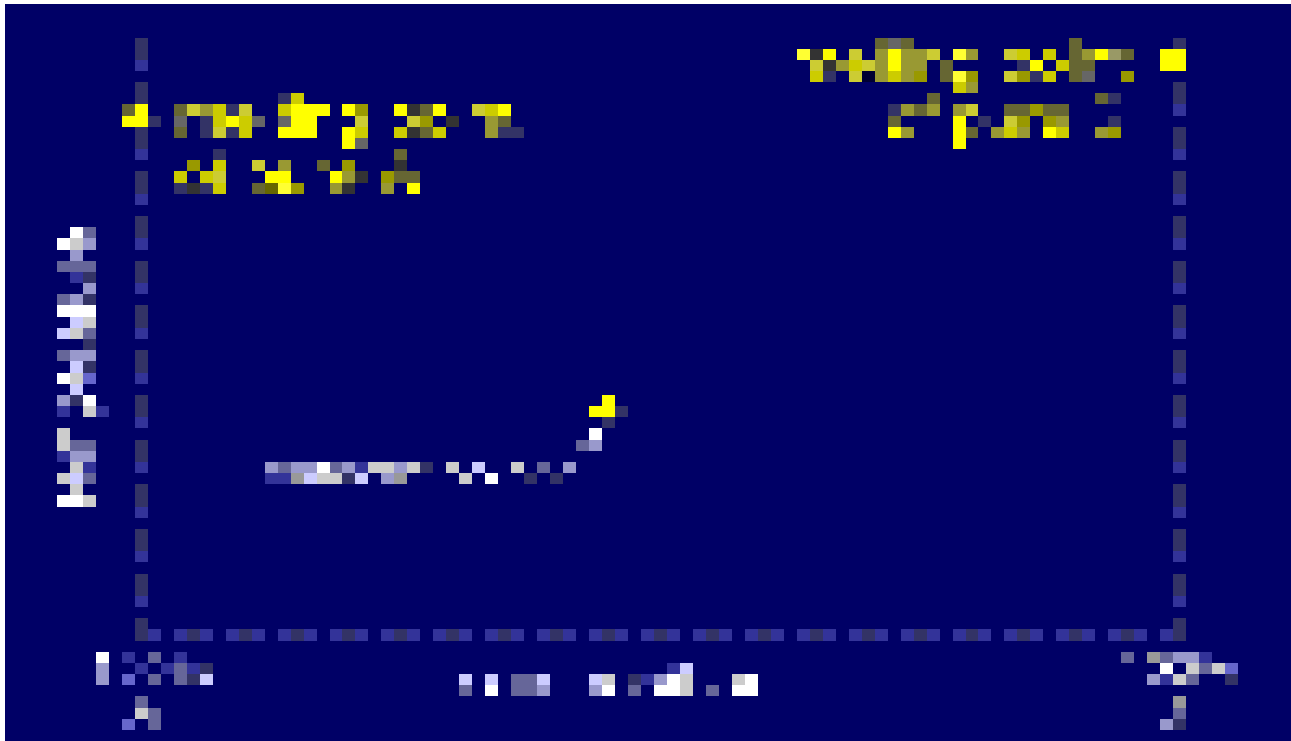


A binary phase diagram shows the phases formed in differing mixtures of *two elements* over a range of *temperatures*.



Compositions run from *100% Element A* on the left of the diagram, through all possible mixtures, to *100% Element B* on the right. The composition of an alloy is given in the form *A - x%B*. For example, *Cu - 20%Al* is 80% copper and 20% aluminium.


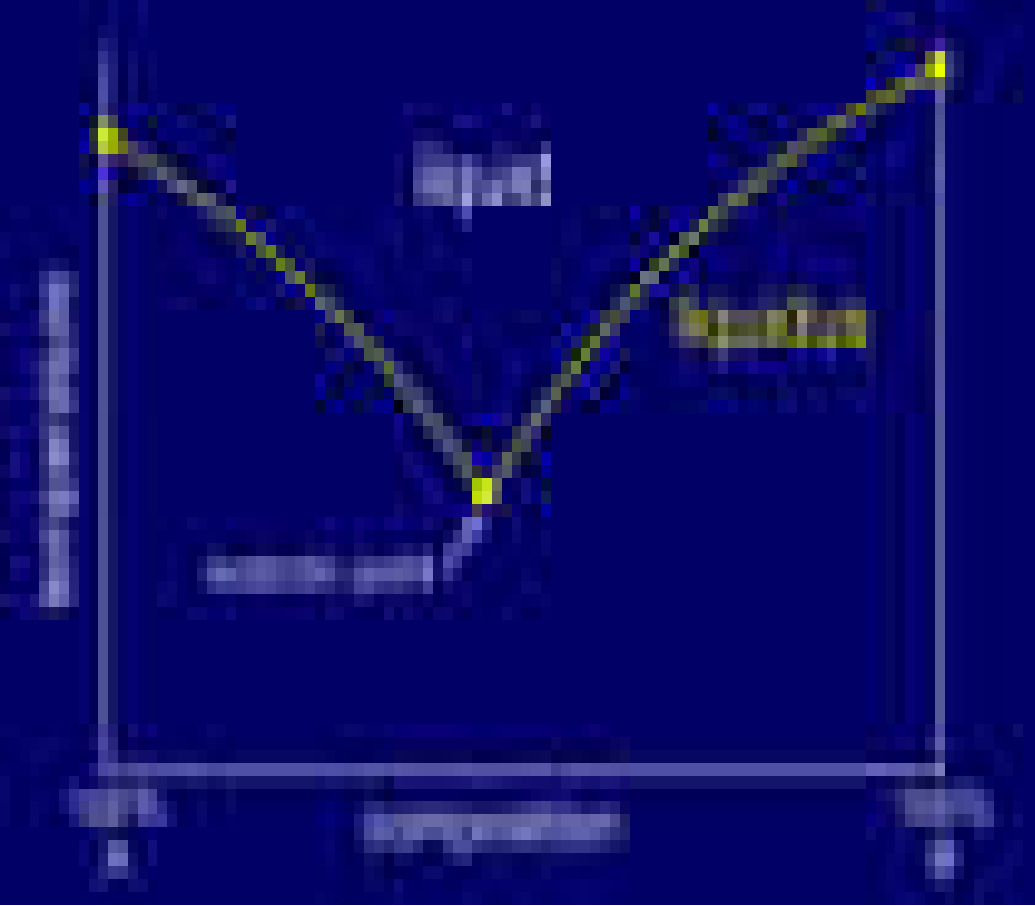




Alloys tend to solidify over a *temperature range*, rather than at a specific temperature like pure elements.

At each end of the phase diagram only one of the elements is present (100% A or 100% B) and therefore a specific melting point exists.

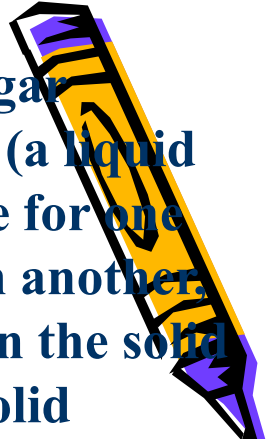
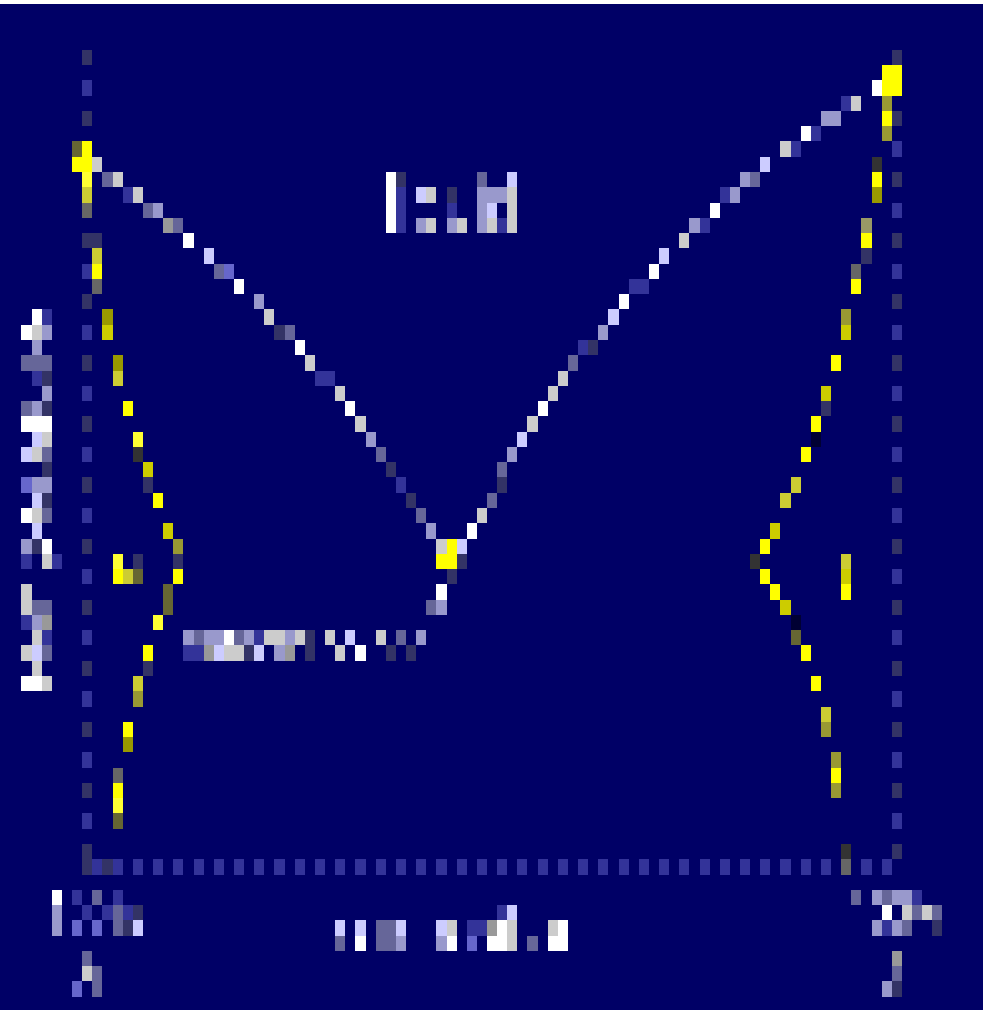




By cooling alloys from the liquid state and recording their cooling rates, the temperature at which they start to solidify can be determined and then plotted on the phase diagram. If enough experiments are performed over a range of compositions, a *start of solidification* curve can be plotted onto the phase diagram.

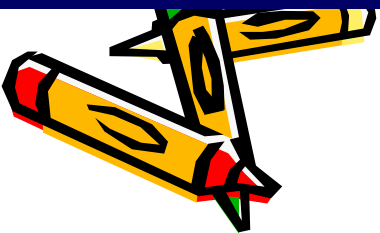
This curve will join the three single solidification points and is called the liquidus line.

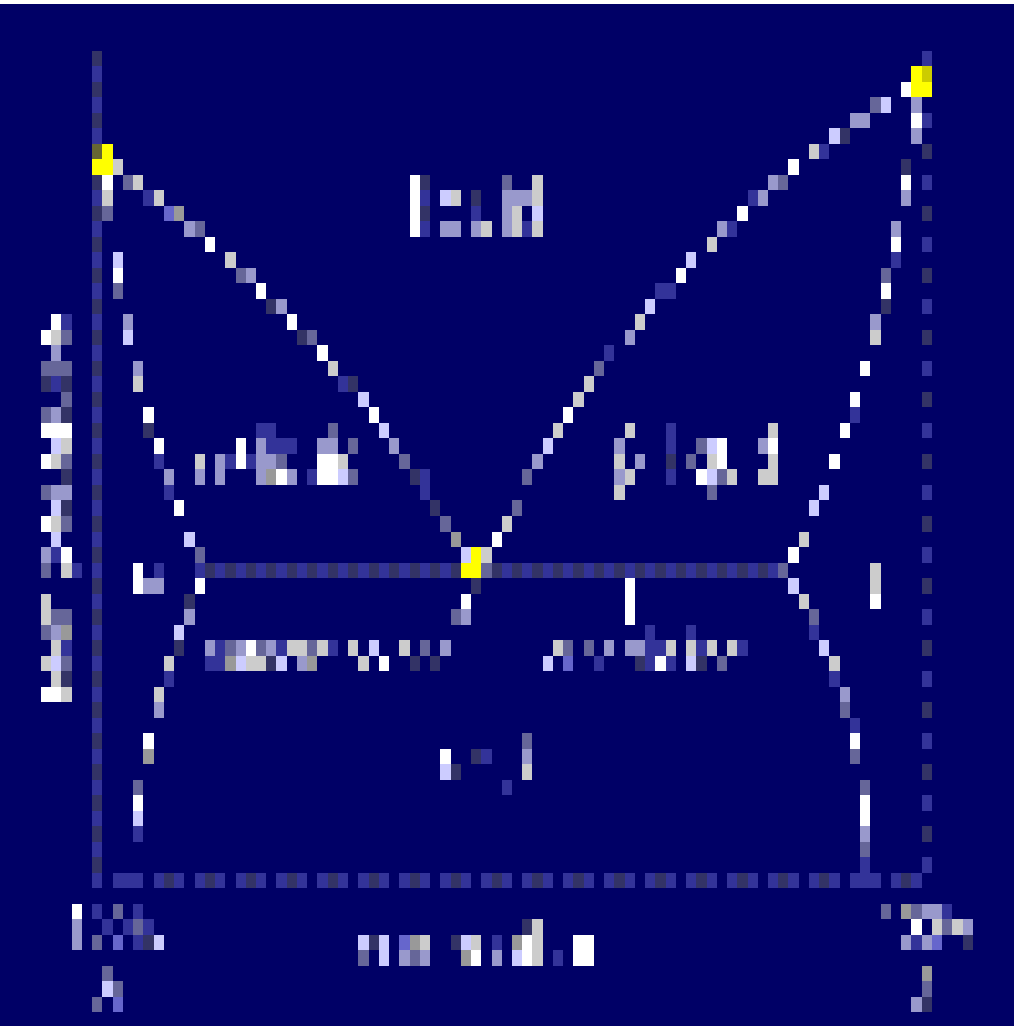




In the same way that sugar dissolves into hot tea (a liquid solution) it is possible for one element to dissolve in another, whilst both remain in the solid state. This is called solid solubility and is characteristically up to a *few percent by weight*.

The extent of the solid solubility region can be plotted onto the phase diagram and labelled appropriately. A solid solution of *B in A* (i.e. mostly A) is called alpha and a solid solution of *A in B* (i.e. mostly B) is called beta.

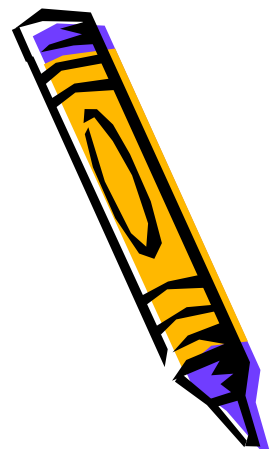
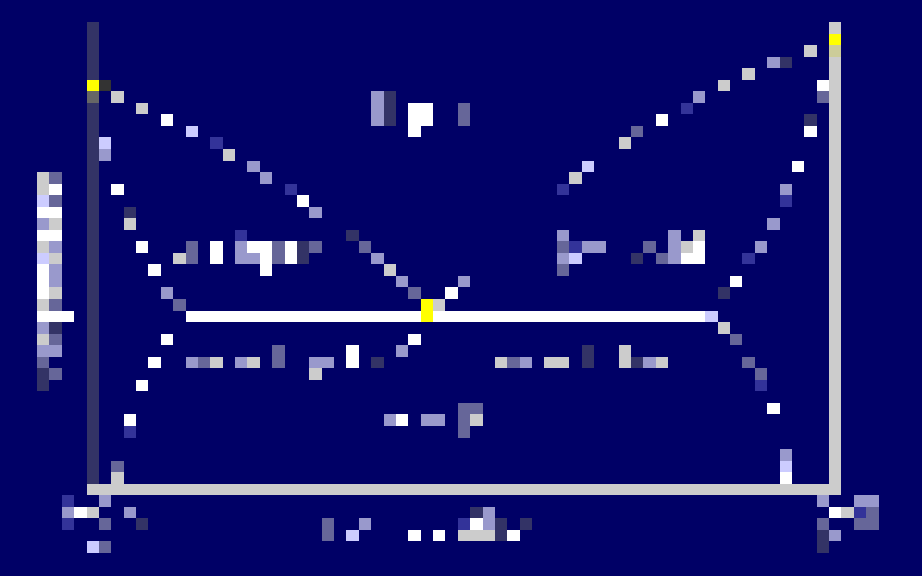




If an alloy's composition does not place it within the small solid solution regions at either side of the phase diagram, the alloy will become fully solid at the eutectic temperature, shown as the eutectic line on the phase diagram.

At alloy compositions and temperatures between the start of solidification and the point at which it becomes fully solid (the eutectic temperature) a *mushy* mix of either alpha or beta will exist as *solid lumps* with a liquid mixture of A and B.





A phase diagram is a temperature - composition map which indicates the phases present at a given temperature and composition.

It is determined experimentally by recording cooling rates over a range of compositions.

We will use these diagrams to understand and predict the alloy microstructure obtained at a given composition



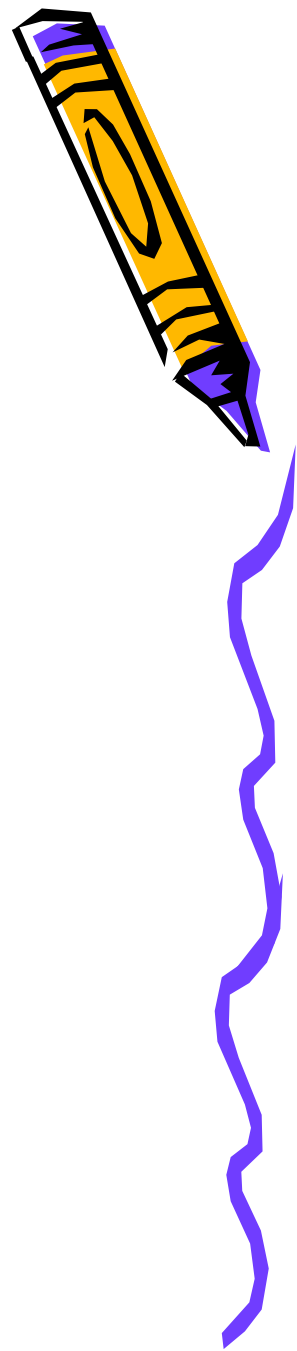
A simple phase diagram



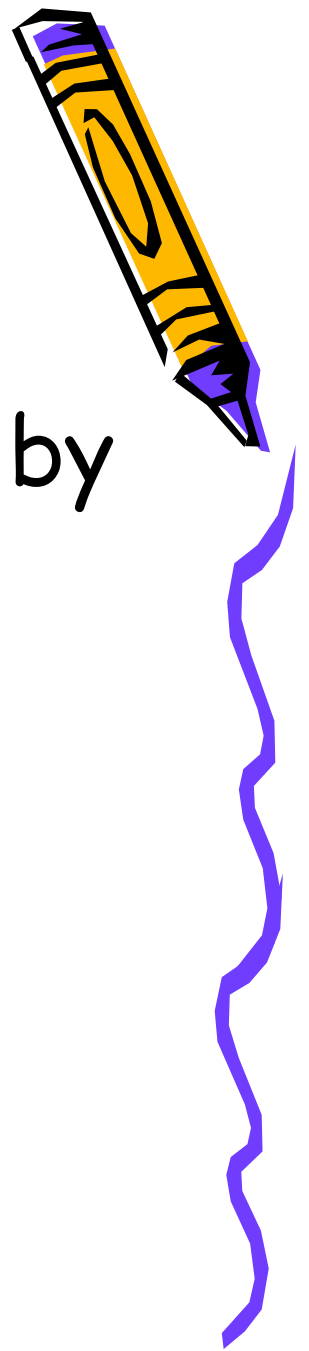
Very simple binary phase diagrams do not have a eutectic point. The liquid mixture will cool through a solidification region (temperature range) and become a solid solution of the two constituent elements.



Tie Lines and the Lever Rule



UNARY SYSTEMS



- Systems which can be defined by a single component are called **Unary Systems**

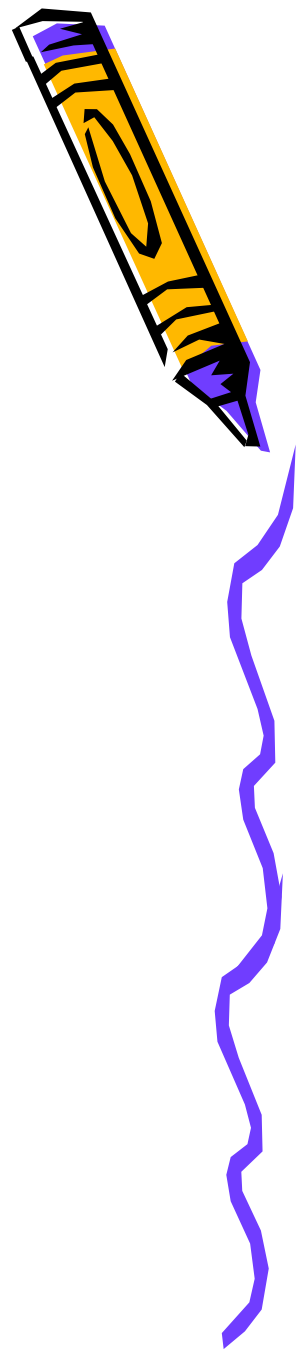


THE PHASE RULE

- For a system at equilibrium the phase rule relates:
- P = number of phases that can coexist, to
- C = number of components making up the phases, and
- F = degrees of freedom.
- Where these three variables are related in the equation
- $P + F = C + 2$



The degrees of freedom represent the environmental conditions which can be independantly varied without changing the number of phases in the system. Conditions include



Fundamental Definitions

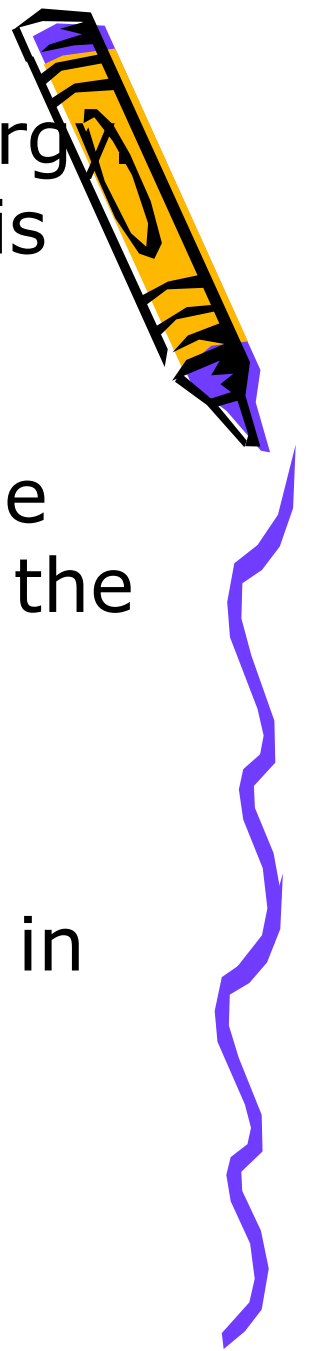


- **System:** Any particular portion of the universe in which we are interested.
- **Closed System:** A system isolated from the rest of the universe with respect to matter entering or leaving the system. Can however be heat (energy) transfer across boundaries of such a system.
- **Open System:** A system not isolated from the rest of the universe in which matter can move in and/or out of the system.
- **Component:** The smallest number of independent variable chemical constituents necessary to define any phase in the system.



- Phase: Any particular part of a system physically homogeneous in itself, but which can be separated mechanically from any other phase of the system.
- Homogeneous Reaction: Occurs within a single phase in a system.
- Heterogeneous Reaction: Occurs within more than one phase in a system.
- Equilibrium: The condition of minimum energy for the system such that the state of a reaction will not change with time provided P & T are kept constant.



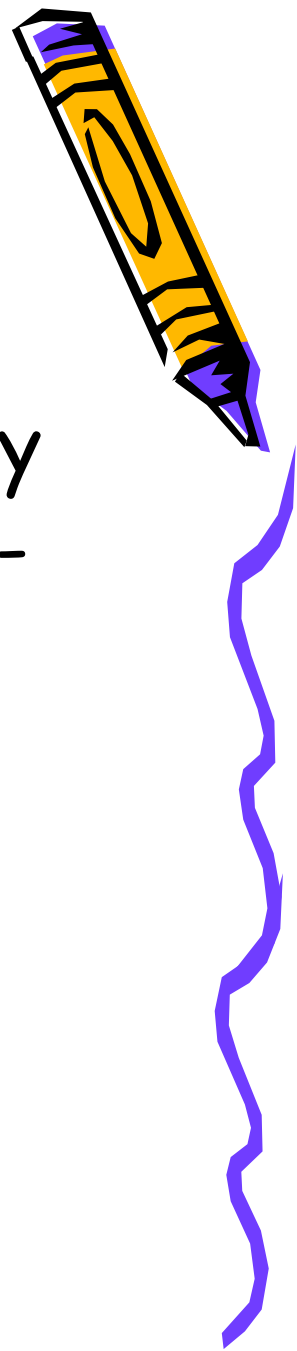


- Stability: The condition of minimum energy
- Instability: The condition where energy is not at a minimum.
- Metastability: The condition where the energy of the system exceeds that of one or more other possible configurations of the system.
- Degrees of Freedom (or Variance of a System): The number of independent variables which must be arbitrarily fixed in order to define a system completely. In petrology T, P and X (concentration) are most important.



Refernces

- Introduction to Physical Metallurgy by Sydney H. Avner, Tata McGraw-Hill Publishing company Limited.
- Engg. Materials and metallurgy by O.P. Khanna.



Definition of heat treatment

Heat treatment is an operation or combination of operations involving heating at a specific rate, soaking at a temperature for a period of time and cooling at some specified rate. The aim is to obtain a desired microstructure to achieve certain predetermined properties (physical, mechanical, magnetic or electrical).

Objectives of heat treatment (heat treatment processes)

The major objectives are

- to increase strength, hardness and wear resistance (**bulk hardening, surface hardening**)
- to increase ductility and softness (**tempering, recrystallization annealing**)
- to increase toughness (**tempering, recrystallization annealing**)
- to obtain fine grain size (**recrystallization annealing, full annealing, normalising**)
- to remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding (**stress relief annealing**)

- to improve machineability (**full annealing and normalising**)
- to improve cutting properties of tool steels (**hardening and tempering**)
- to improve surface properties (**surface hardening, corrosion resistance-stabilising treatment and high temperature resistance-precipitation hardening, surface treatment**)
- to improve electrical properties (**recrystallization, tempering, age hardening**)
- to improve magnetic properties (**hardening, phase transformation**)

Iron-Carbon System

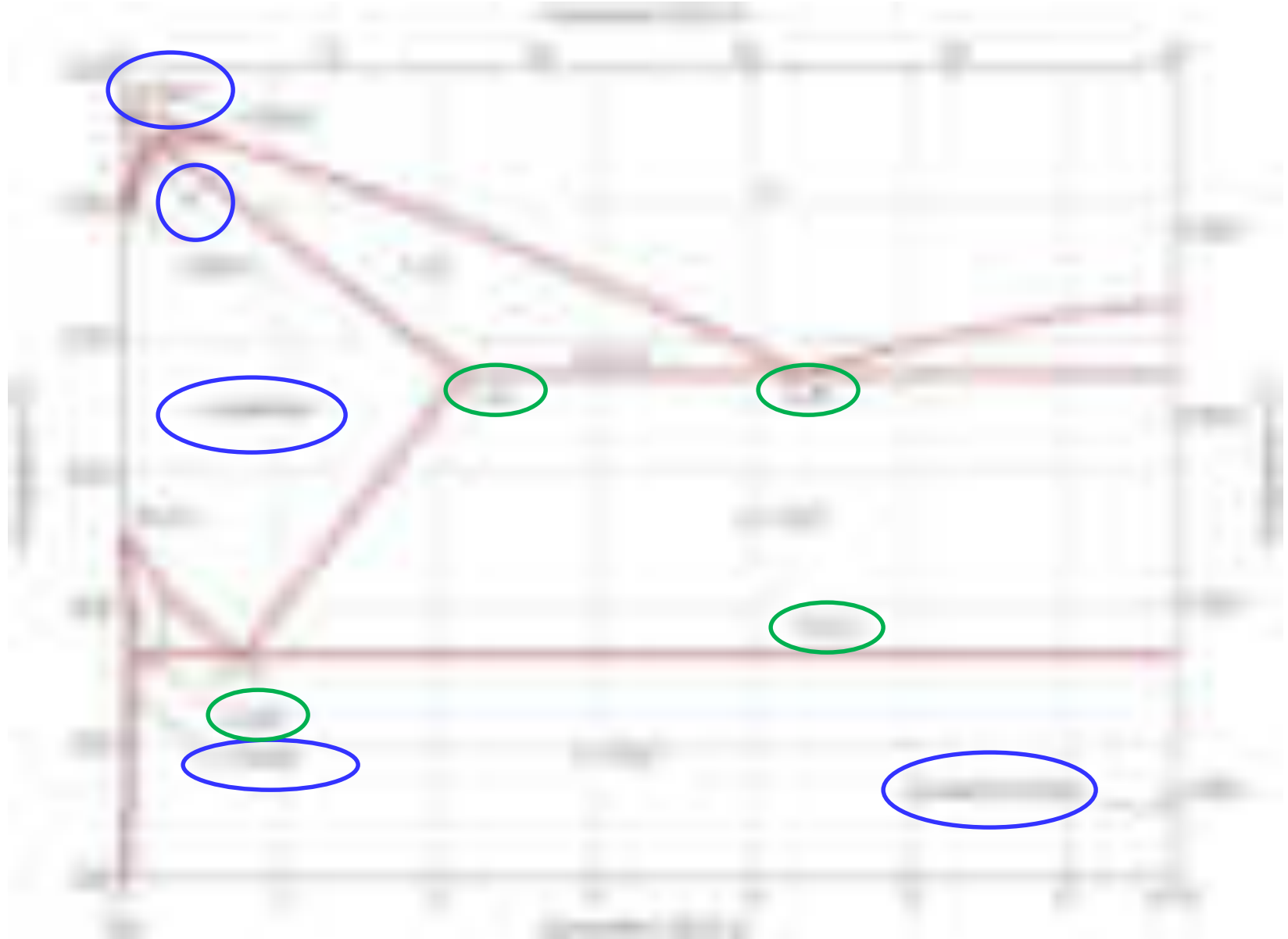
- **Pure iron** when heated experiences 2 changes in crystal structure before it melts.
- At room temperature the stable form, **ferrite (α iron)** has a **BCC** crystal structure.
- Ferrite experiences a polymorphic transformation to **FCC austenite (γ iron)** at $912\text{ }^{\circ}\text{C}$ ($1674\text{ }^{\circ}\text{F}$).
- At $1394\text{ }^{\circ}\text{C}$ ($2541\text{ }^{\circ}\text{F}$) austenite reverts back to BCC phase δ ferrite and melts at $1538\text{ }^{\circ}\text{C}$ ($2800\text{ }^{\circ}\text{F}$).
- Iron carbide (**cementite or Fe_3C**) an intermediate compound is formed at 6.7 wt% C.
- Typically, all steels and cast irons have carbon contents less than 6.7 wt% C.
- Carbon is an interstitial impurity in iron and forms a solid solution with the α , γ , δ phases.

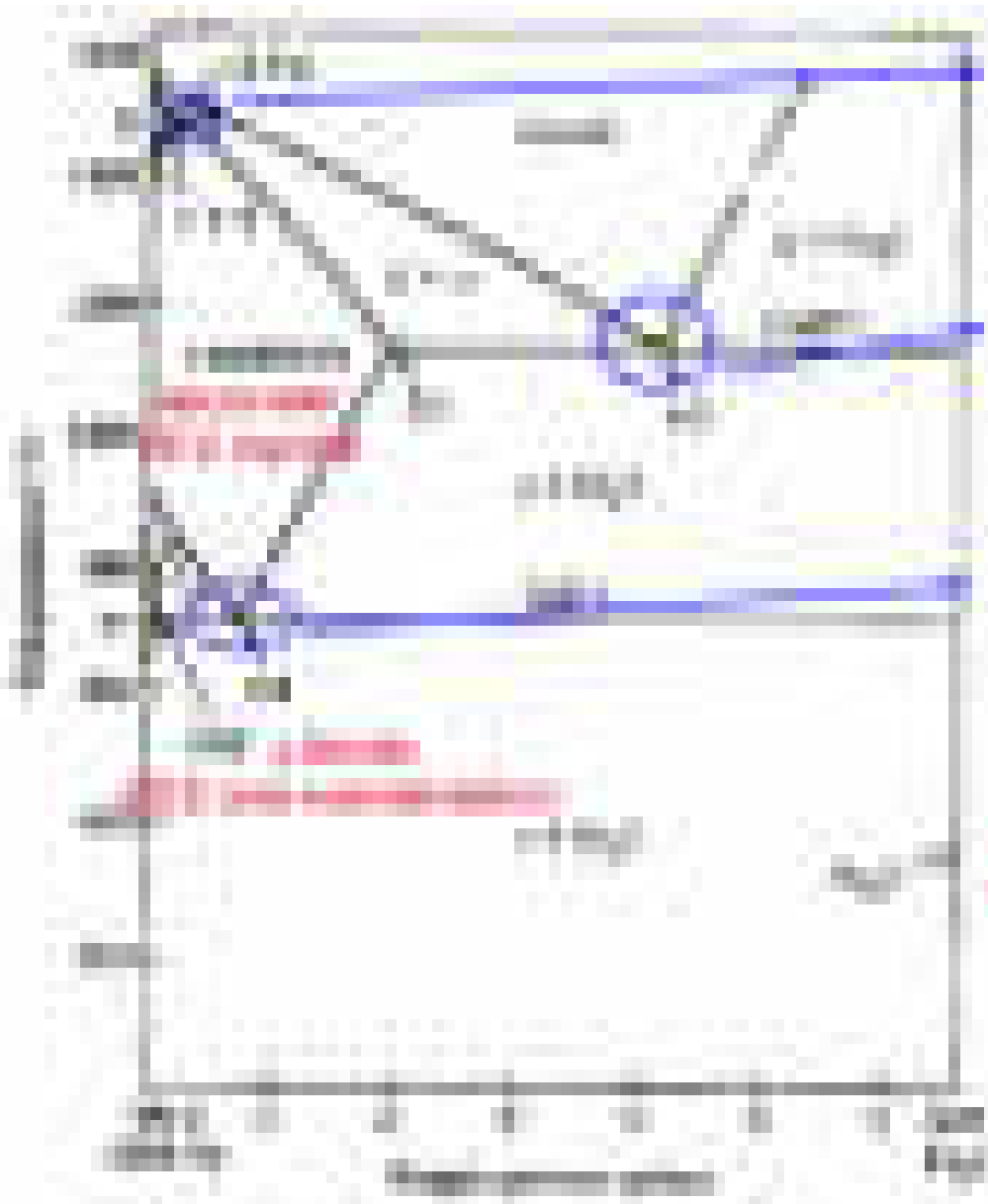






Iron-Carbon System





Boundary Condition (at $x=0$)

$\frac{\partial u}{\partial x} = 0$ (Neumann boundary)

Boundary Condition (at $x=4$)

$\frac{\partial u}{\partial x} = 0$ (Neumann boundary)

Boundary Condition (at $y=0$)

$\frac{\partial u}{\partial y} = 0$ (Neumann boundary)

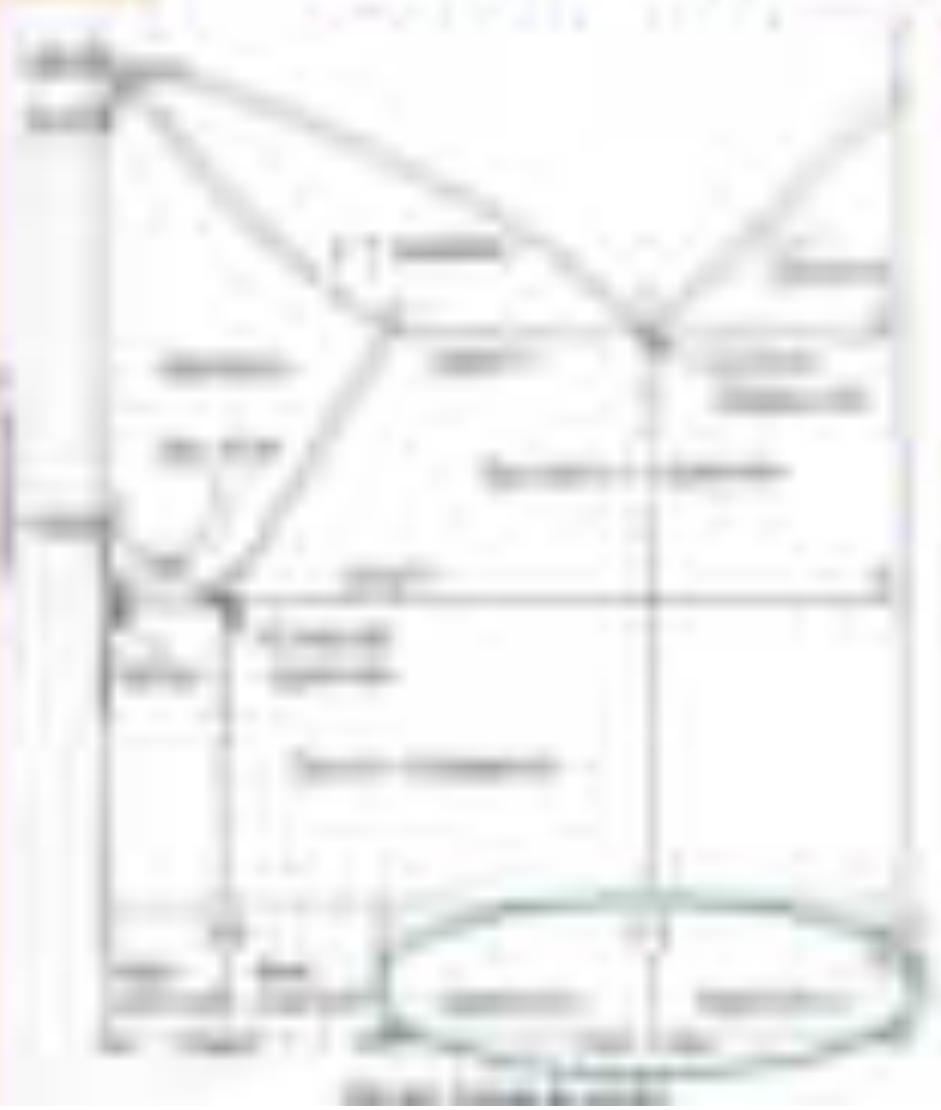
Red
Blue

Steel (All Carbon $\leq 2.0\%$)



- **Plain Carbon Steel**
(0.025% to 2.0% C)
- **Low alloy steel**
(0.025% to 1.0% C)
- **High alloy steel**
(0.025% to 2.0% C and 10% Ni)

Cast Iron (%Carbon > 2.0%)



- Hypoeutectic cast iron
 $2.0\% < \%C < 4.3\%$
- Hypereutectic cast iron
 $4.3\% < \%C < 6.67\%$

CRITICAL TEMPERATURE

- ❖ **Upper critical temperature (point) A_3** is the temperature, below which ferrite starts to form as a result of ejection from austenite in the hypoeutectoid alloys.
- ❖ **Upper critical temperature (point) A_{CM}** is the temperature, below which cementite starts to form as a result of ejection from austenite in the hypereutectoid alloys.
- ❖ **Lower critical temperature (point) A_1** is the temperature of the austenite-to-pearlite eutectoid transformation. Below this temperature austenite does not exist.
- ❖ **Magnetic transformation temperature A_2** is the temperature below which α -ferrite is ferromagnetic.



Though carbon is present in relatively low concentrations, it significantly influences the mechanical properties of ferrite: (a) α ferrite, (b) austenite.

4 Solid Phases

- **1. Single phase**
 - **Single phase solid solution** - **substitutional** and **interstitial** - **same crystal structure**
 - **intermetallic compounds** - **different crystal structures**
- **2. Two phase solid**
 - **two different crystal structures**
 - **intermetallic compounds** - **different crystal structures**
 - **intermetallic compounds** - **same crystal structure**
- **3. Three phase**
 - **intermetallic compounds** - **different crystal structures**
 - **intermetallic compounds** - **same crystal structure**
- **4. Four phase**
 - **intermetallic compounds** - **different crystal structures**
 - **intermetallic compounds** - **same crystal structure**

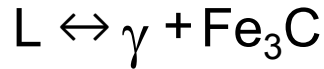
Iron carbide (Cementite or Fe_3C)

- Forms when the solubility limit of carbon in α ferrite is exceeded at temperatures below 727 °C.
- Mechanically, cementite is very hard and brittle.
- For ferrous alloys there are 3 basic types, based on carbon content:
 - ❑ Iron (ferrite phase): <0.008 wt% C room temp
 - ❑ Steel ($\alpha + \text{Fe}_3\text{C}$ phase): 0.008 to 2.14 wt% C
 - ❑ Cast iron: 2.14 to 6.70 wt% C

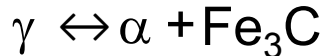
Iron-Carbon (Fe-C) Phase Diagram

- 2 important points

- **Eutectic (A):**

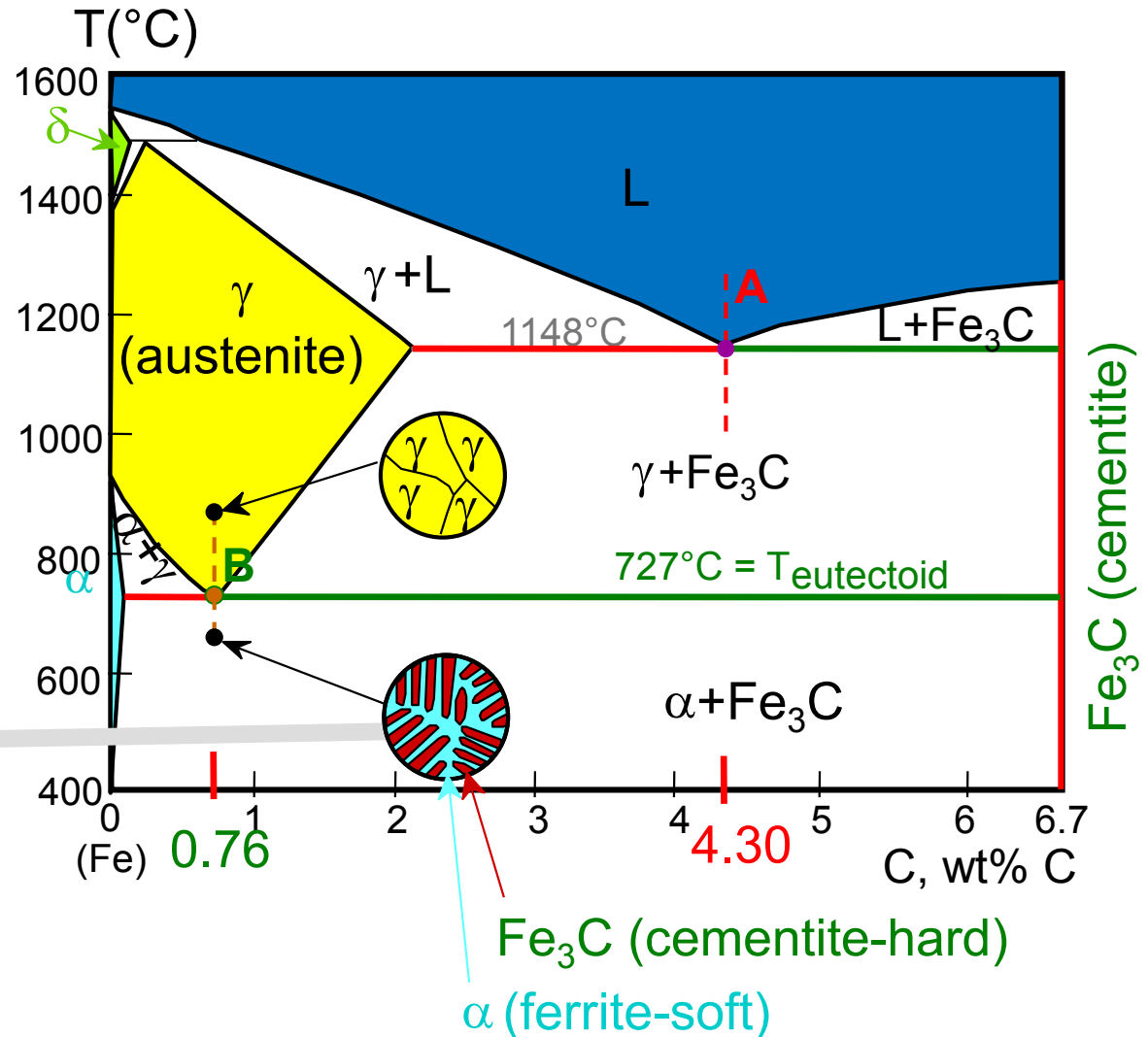


- **Eutectoid (B):**

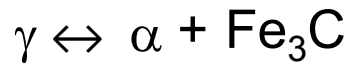


120 μm

Result: Pearlite = alternating layers of α and Fe₃C phases, not a separate phase.

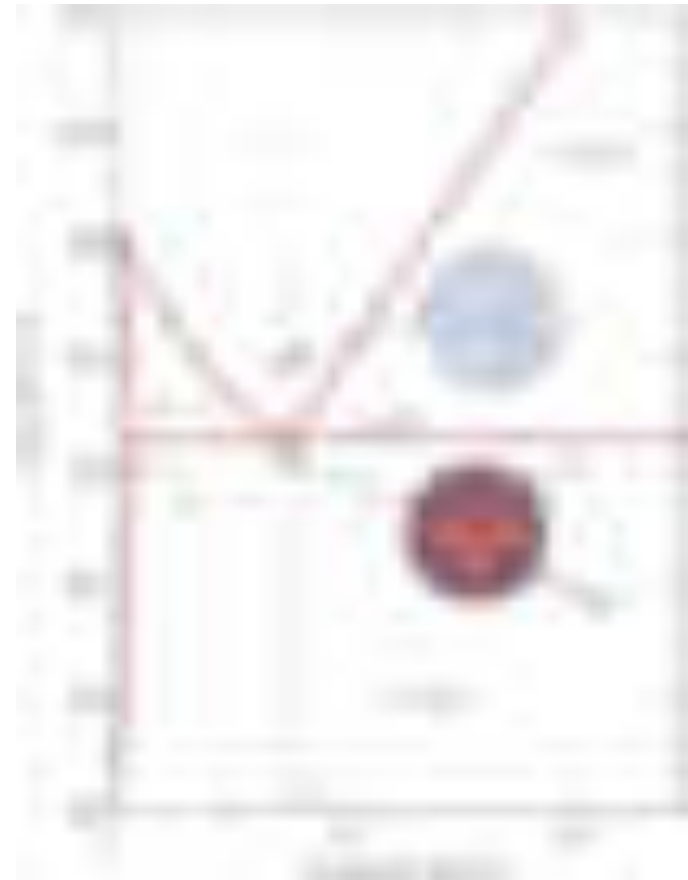


Eutectoid reaction:



Pearlite

1. Formation of pearlite
The eutectoid reaction in the Fe-Fe₃C system is a peritectic reaction. It occurs at 727°C and 0.8 wt% C. The reaction is: $\gamma \leftrightarrow \alpha + \text{Fe}_3\text{C}$. The product is pearlite, which is a lamellar structure of ferrite and cementite.



Redistribution of carbon by diffusion

Austenite – 0.76 wt% C

Ferrite - 0.022 wt% C

Cementite - 6.70 wt% C

Pearlite (Eutectoid mixture)



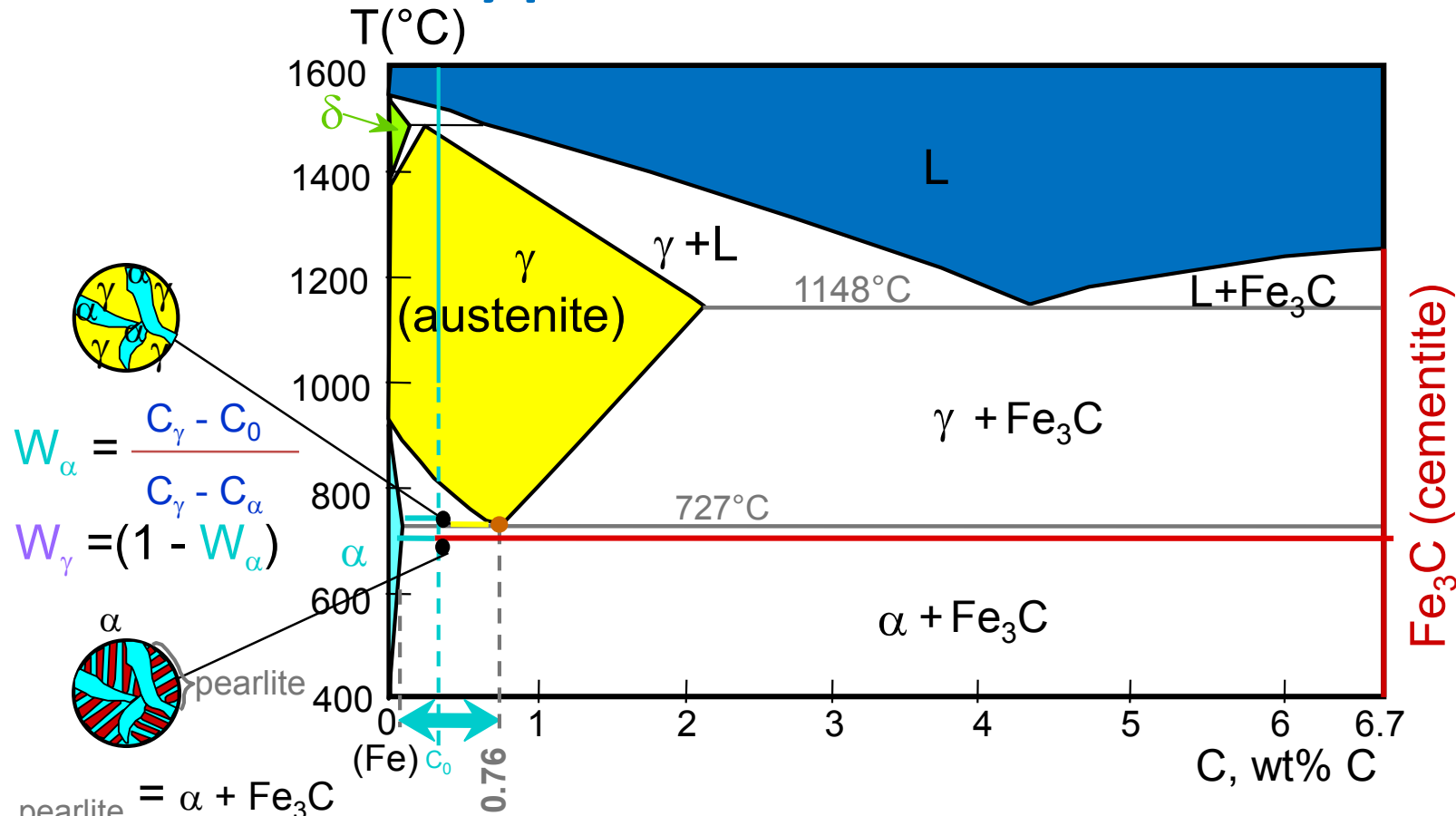
2500X



17000X

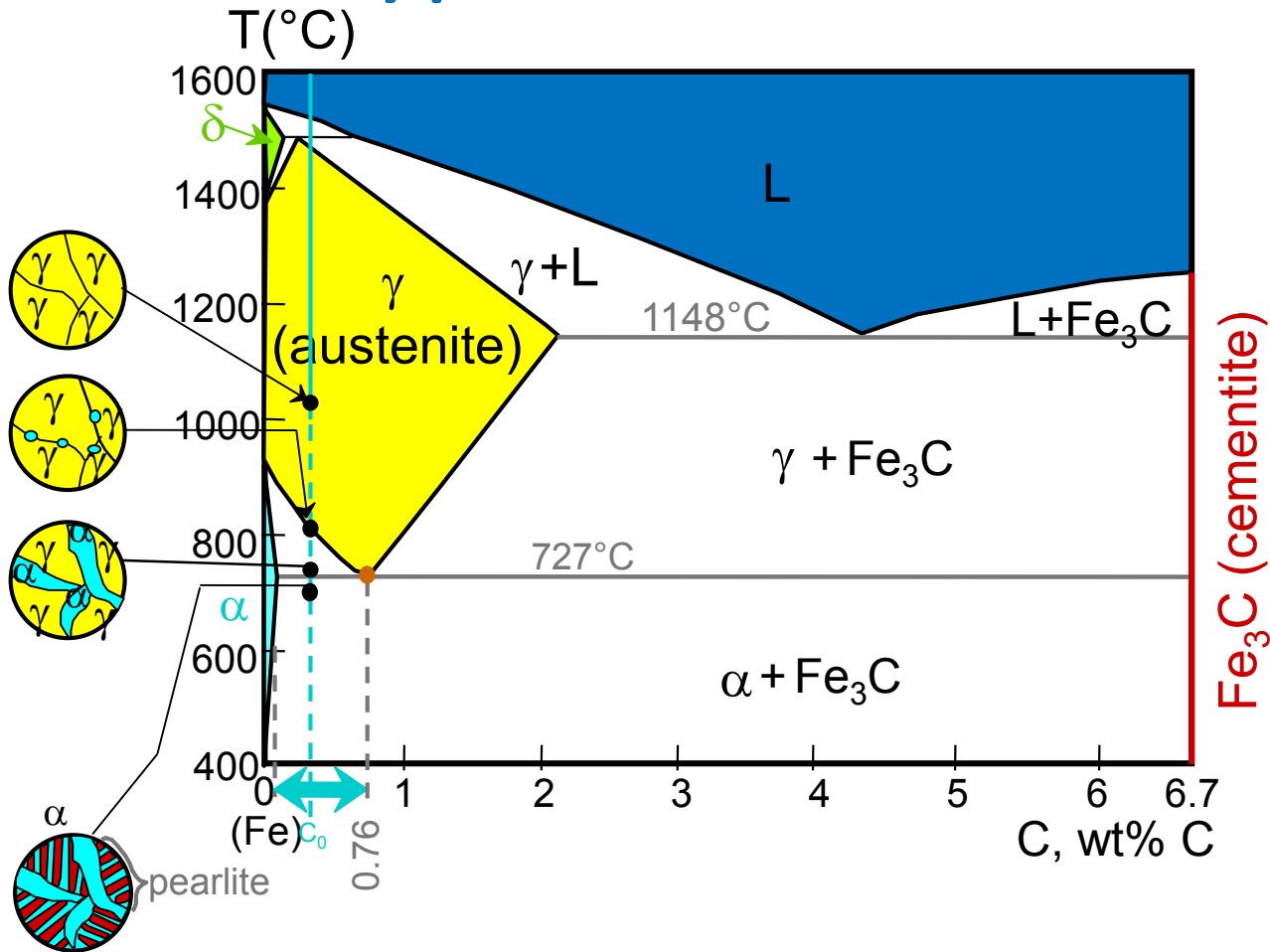
Microstructure of Pearlite

Hypoeutectoid Steel



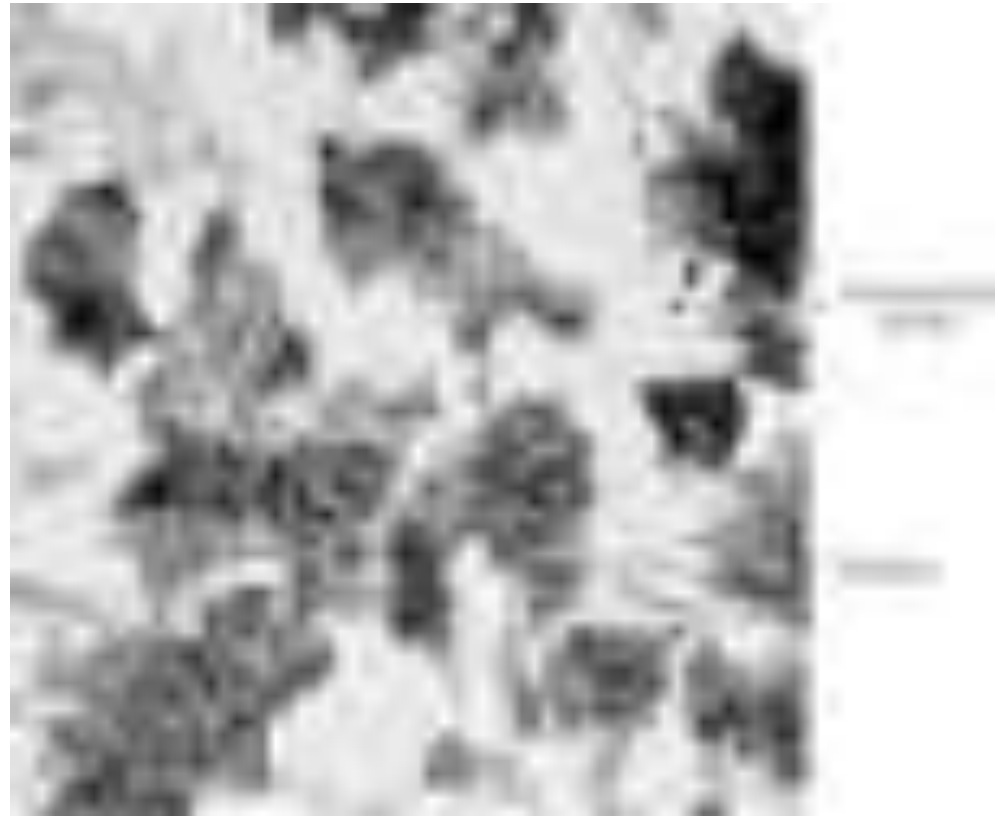
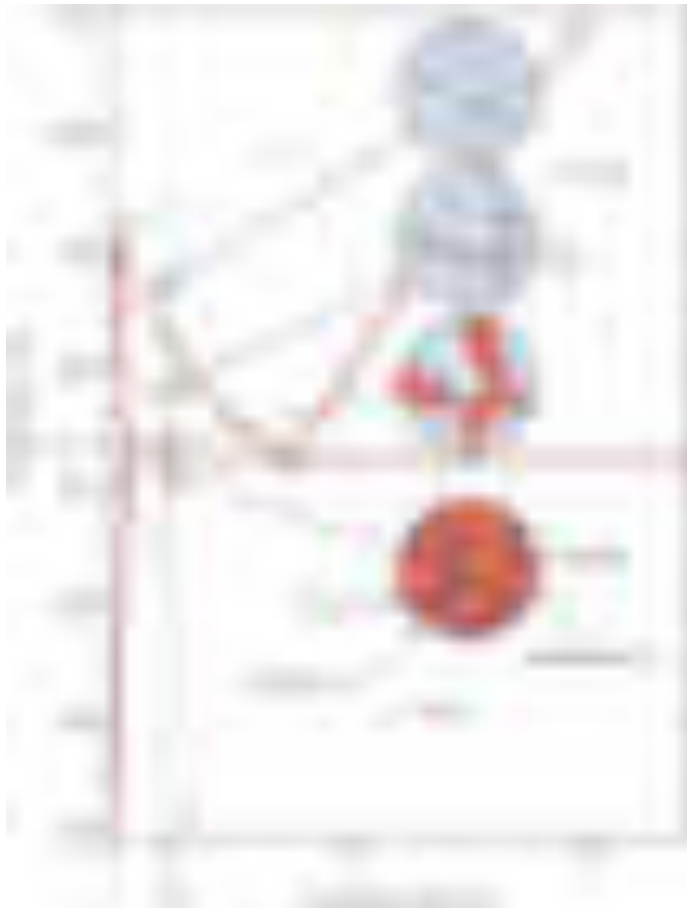
Microstructures for iron-iron carbide alloys that are below the eutectoid with compositions between 0.022 and 0.76 wt% Carbon are hypoeutectoid.

Hypoeutectoid Steel



Proeutectoid

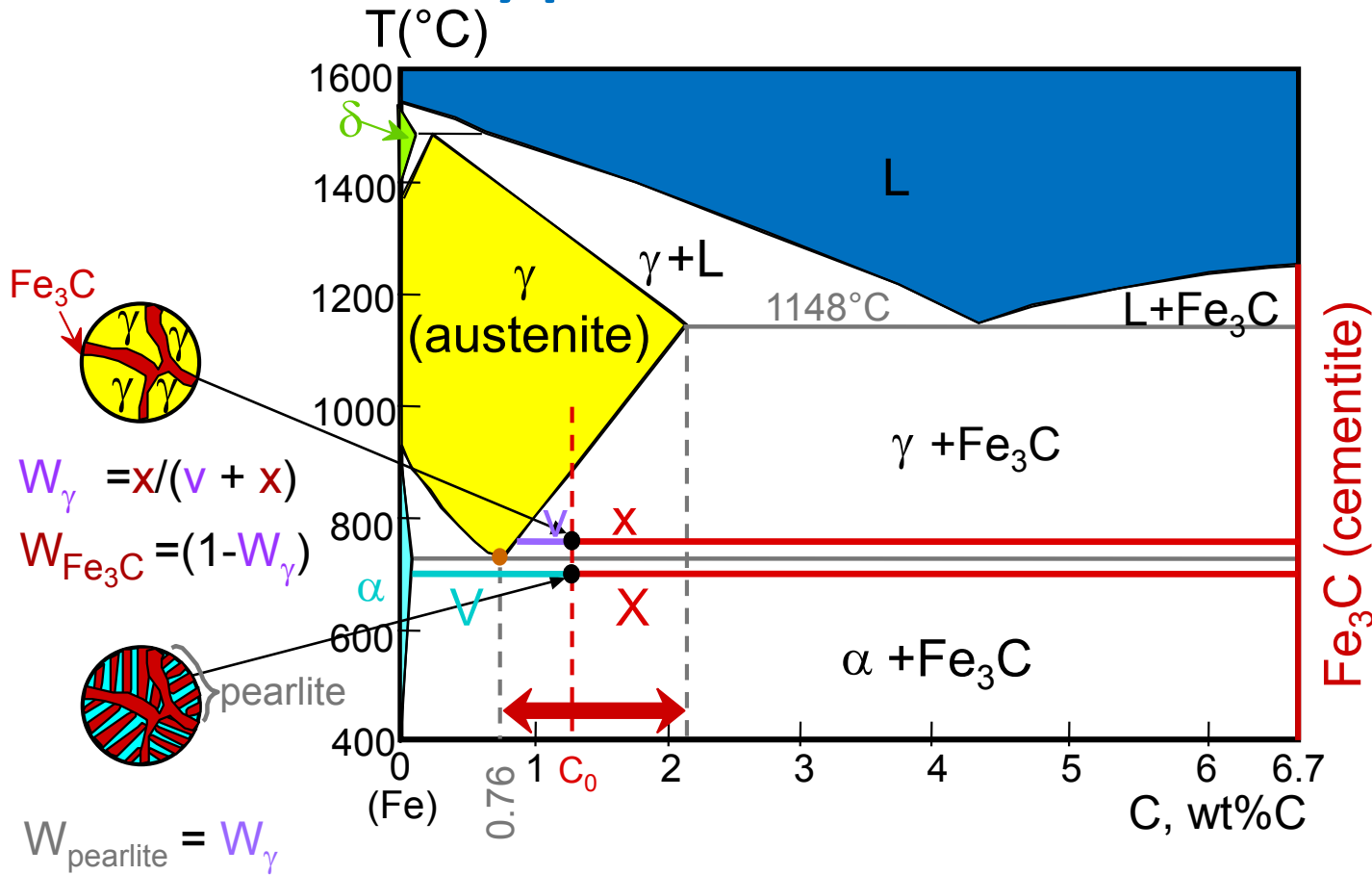
- Formed before the eutectoid
- Ferrite that is present in the pearlite is called eutectoid ferrite.
- The ferrite that is formed above the $T_{\text{eutectoid}}$ (727°C) is proeutectoid.



Fe-C phase diagram



Hyper

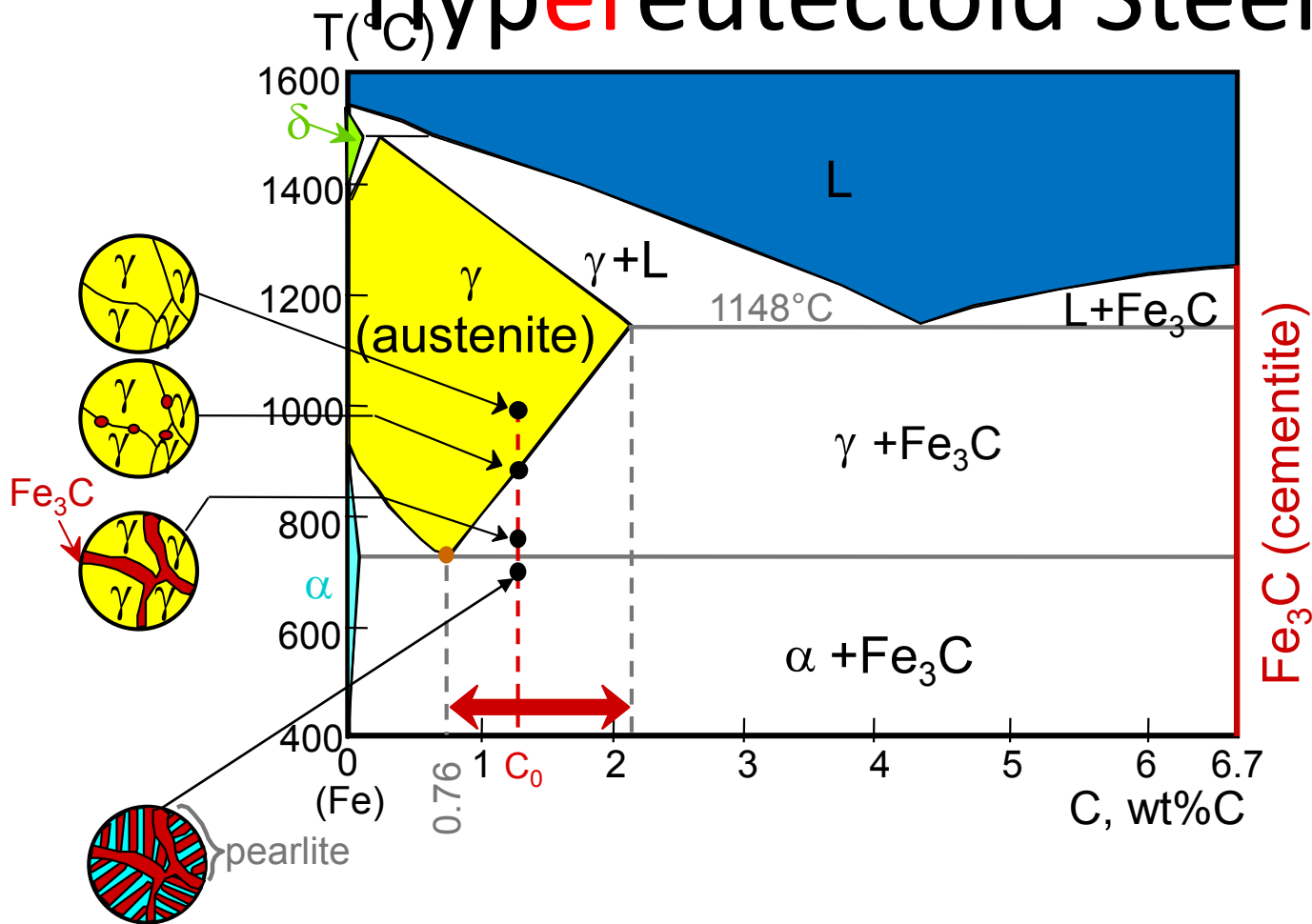


Microstructures for iron-iron carbide alloys that have compositions between **0.76 and 2.14 wt% carbon** are hyper

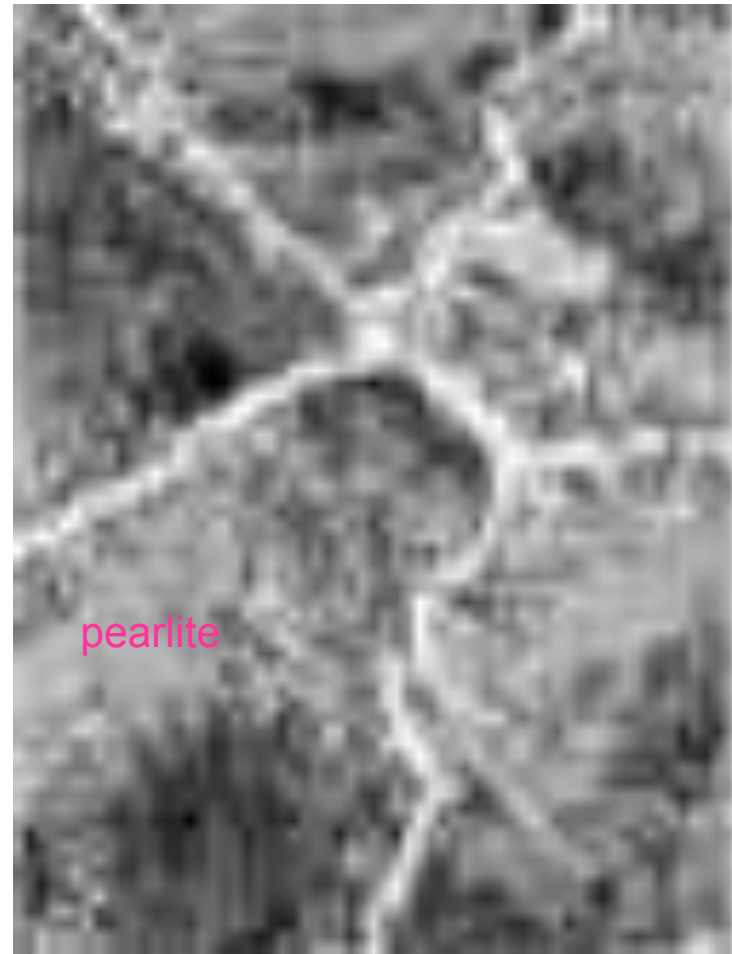
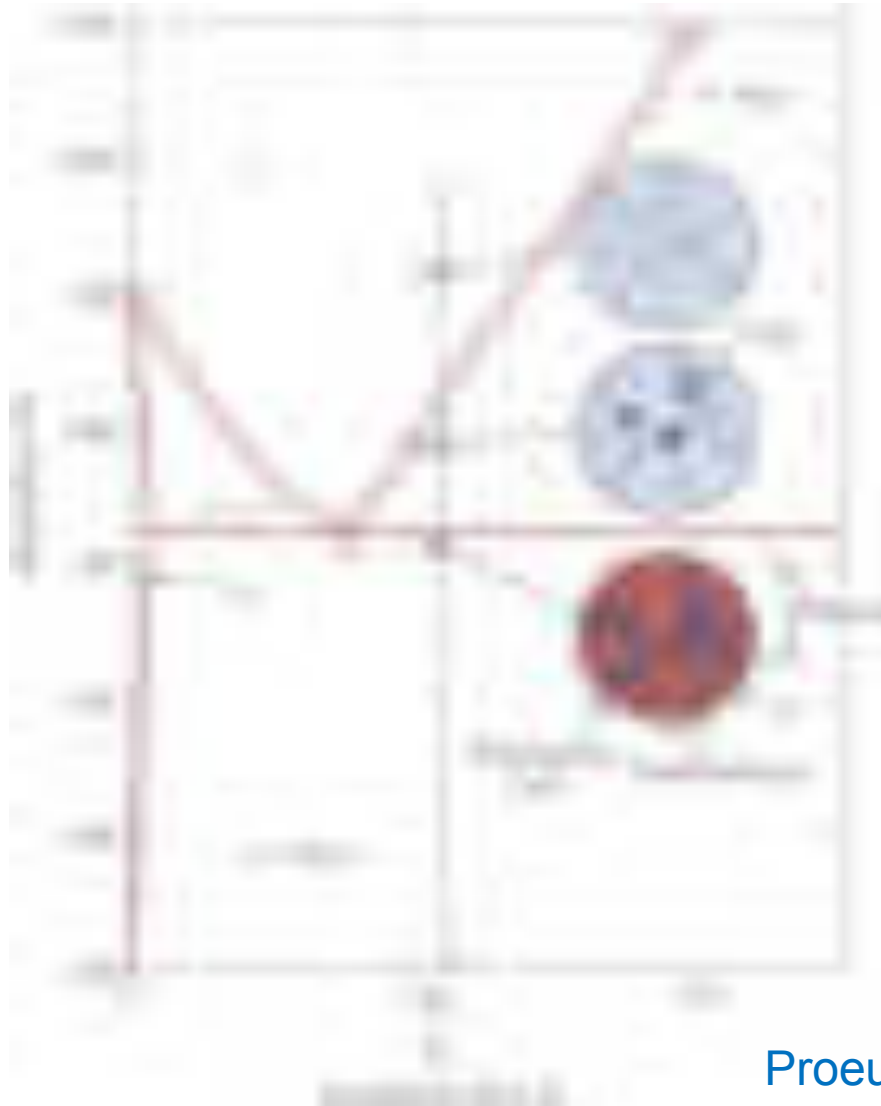
eutectoid (more than eutectoid).

Hyper

eutectoid Steel



Hyper-eutectoid Steel (1.2 wt% C)



Proeutectoid: formed above the $T_{\text{eutectoid}}$ (727°C)

Eutectic reaction

Liquid \leftrightarrow Solid₁ + Solid₂

Liquid (4.3wt%C) \leftrightarrow γ (2.11wt%C) + Fe₃C (6.67wt%C) at 1147°C

Liquid-100 wt% \rightarrow 51.97wt% γ + Fe₃C (48.11wt%)

The phase mixture of austenite and cementite formed at eutectic temperature is called ledeburite.



Fig.11: Microstructure of white cast iron containing massive cementite (white) and pearlite etched with 4% nital, 100x. After Mrs. Janina Radzikowska, Foundry Research Institute in Kraków, Poland

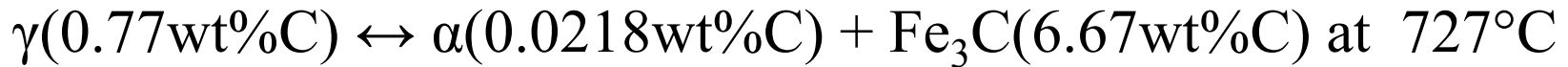


Fig. 12: High magnification view (400x) of the white cast iron specimen shown in Fig. 11, etched with 4% nital. After *Mrs. Janina Radzikowska, Foundry Research Institute in Kraków, Poland*



Fig. 13: High magnification view (400x) of the white cast iron specimen shown in Fig. 11, etched with alkaline sodium picrate. After *Mrs. Janina Radzikowska, Foundry Research Institute in Kraków, Poland*

Eutectoid reaction



Typical density

$$\alpha \text{ ferrite} = 7.87 \text{ gcm}^{-3}$$

$$\text{Fe}_3\text{C} = 7.7 \text{ gcm}^{-3}$$

volume ratio of α - ferrite:Fe₃C=7.9:1



Fig. 14: The process by which a colony of pearlite evolves in a hypoeutectoid steel.



Fig. 15 : The appearance of a pearlitic microstructure under optical microscope.



Fig. 16: A cabbage filled with water analogy of the three-dimensional structure of a single colony of pearlite, an interpenetrating bi-crystal of ferrite and cementite.



Fig. 17: Optical micrograph showing colonies of pearlite . Courtesy of *S. S. Babu*.

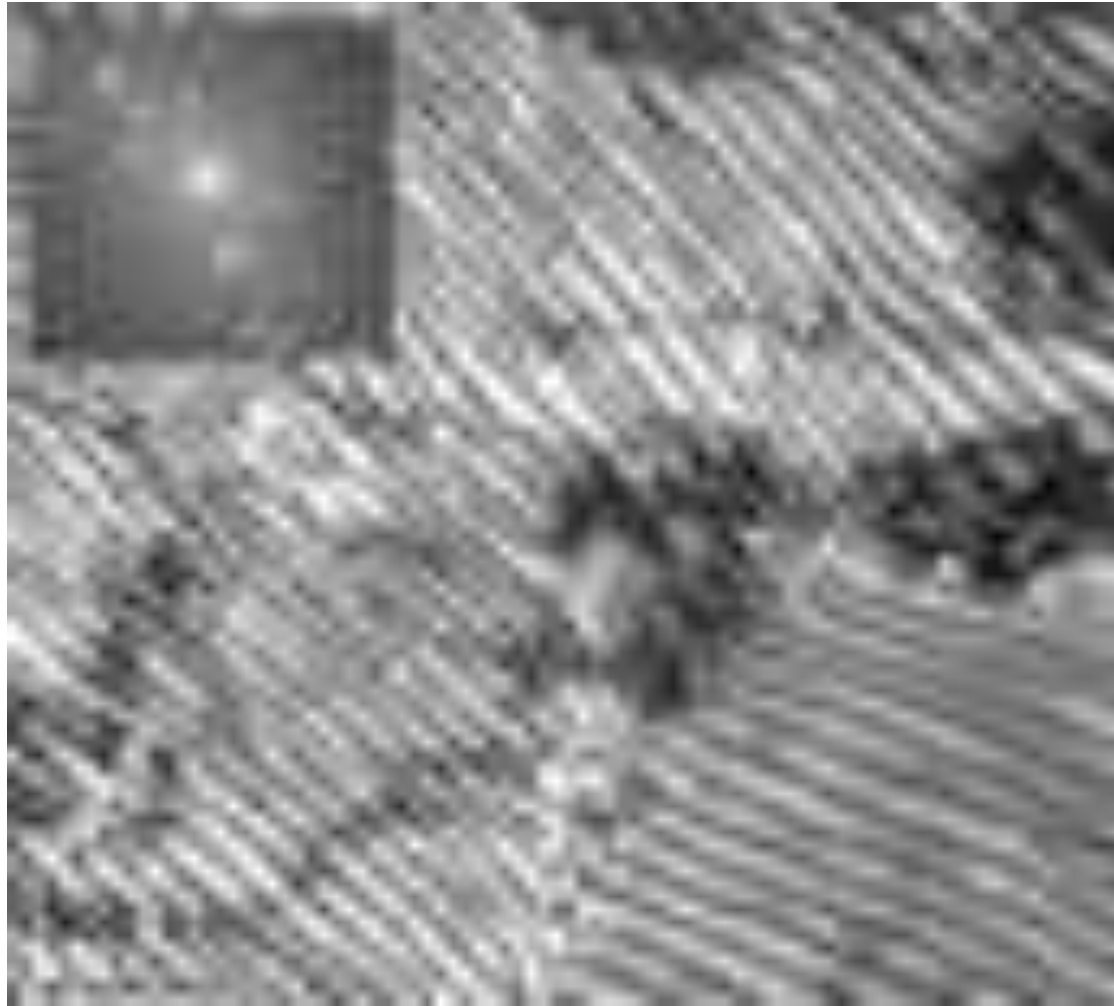


Fig. 18: Transmission electron micrograph of extremely fine pearlite.

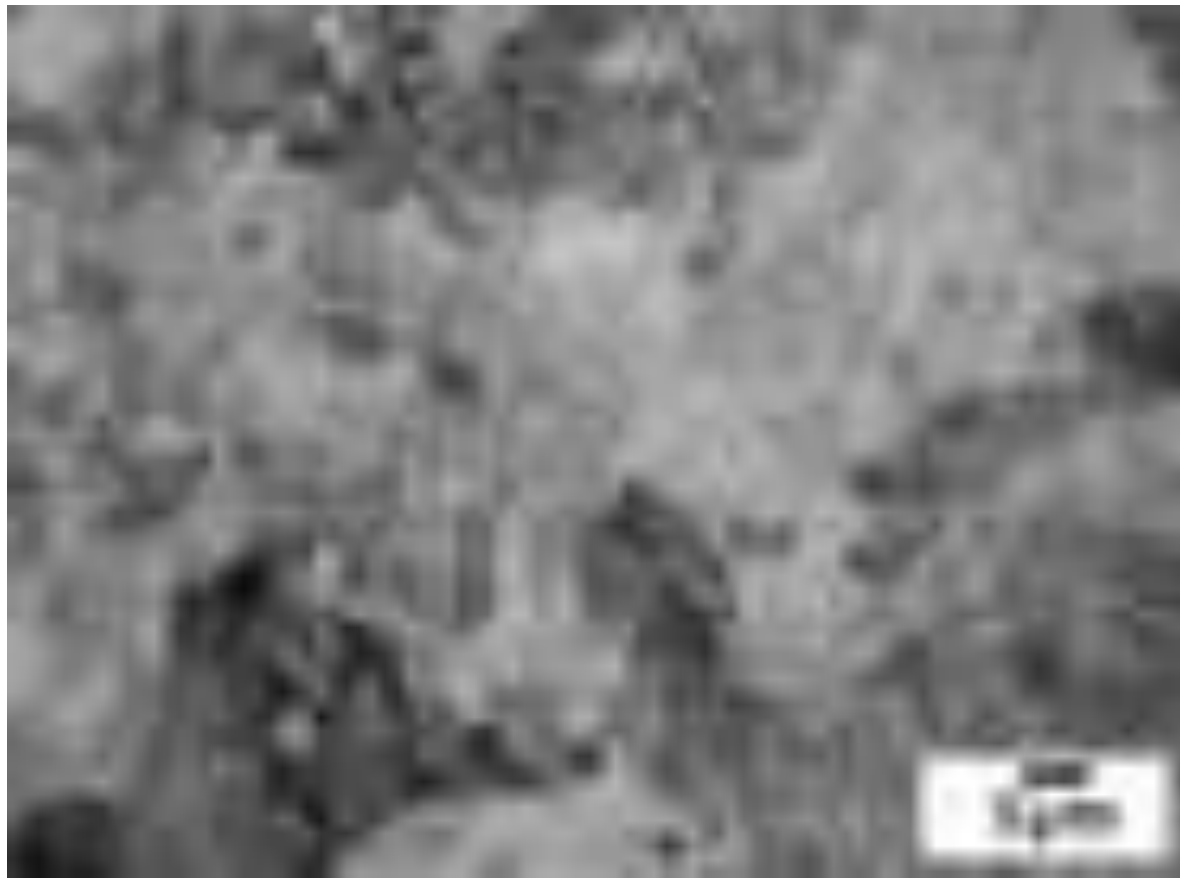


Fig.19: Optical micrograph of extremely fine pearlite from the same sample as used to create Fig. 18. The individual lamellae cannot now be resolved.

Limitations of equilibrium phase diagram

Stability of the phases under equilibrium condition only.

It does not give any information about other metastable phases.
i.e. bainite, martensite

No information about kinetics

No information about size

No information on properties.

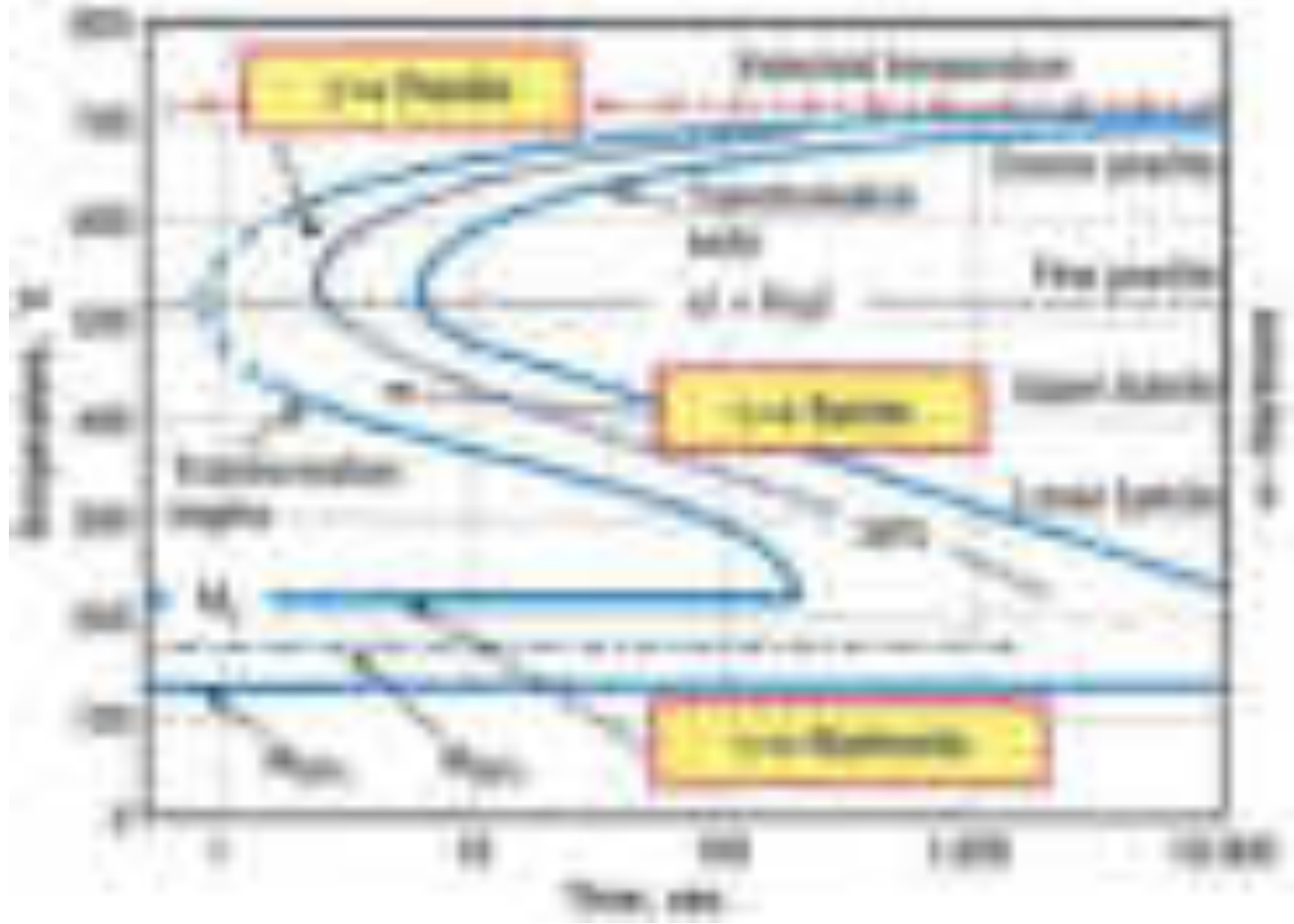
Time Temperature Transformation (TTT) Diagram

- TTT diagram stands for “time-temperature-transformation” diagram. It is also called isothermal transformation diagram
- TTT diagrams give the kinetics of isothermal transformations.

TTT DIAGRAM

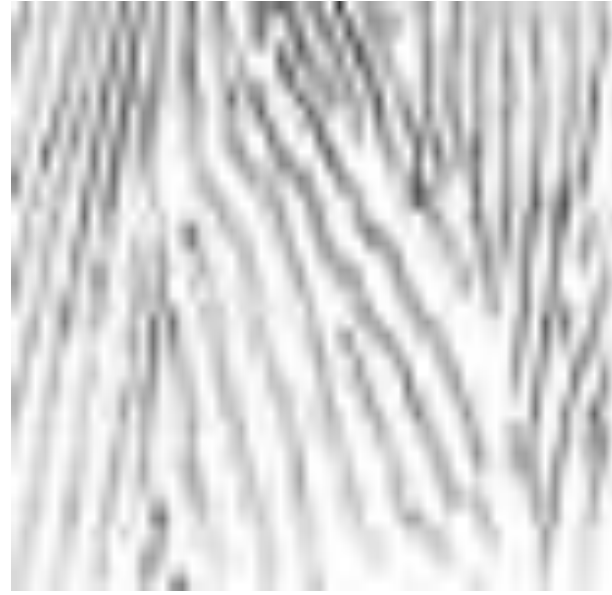
T (Time) T(Temperature) T(Transformation) diagram is a plot of temperature versus the logarithm of time for a steel alloy of definite composition. It is used to determine when transformations begin and end for an isothermal (constant temperature) heat treatment of a previously austenitized alloy. When austenite is cooled slowly to a temperature below LCT (Lower Critical Temperature), the structure that is formed is Pearlite. As the cooling rate increases, the pearlite transformation temperature gets lower. The microstructure of the material is significantly altered as the cooling rate increases. By heating and cooling a series of samples, the history of the austenite transformation may be recorded. TTT diagram indicates when a specific transformation starts and ends and it also shows what percentage of transformation of austenite at a particular temperature is achieved.

TTT DIAGRAM





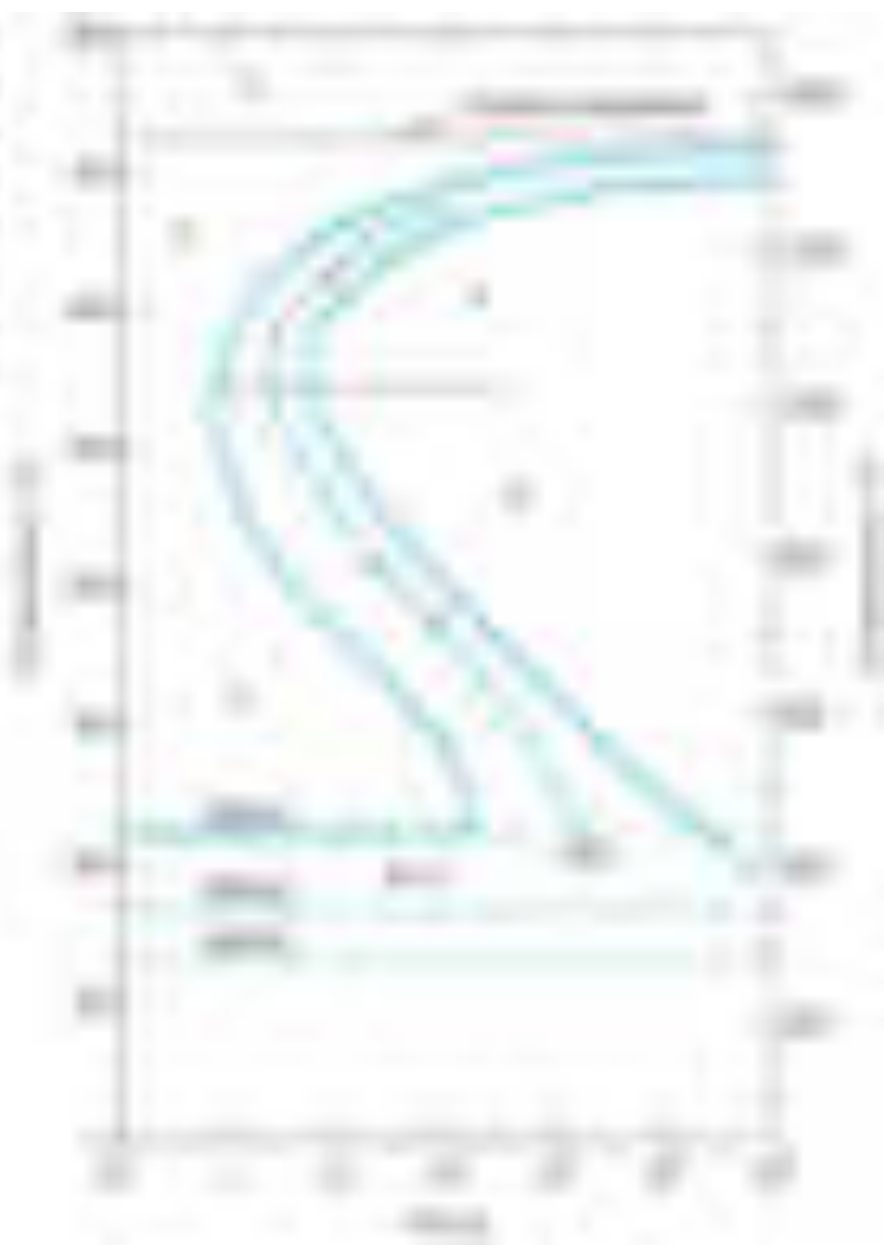
AUSTENITE



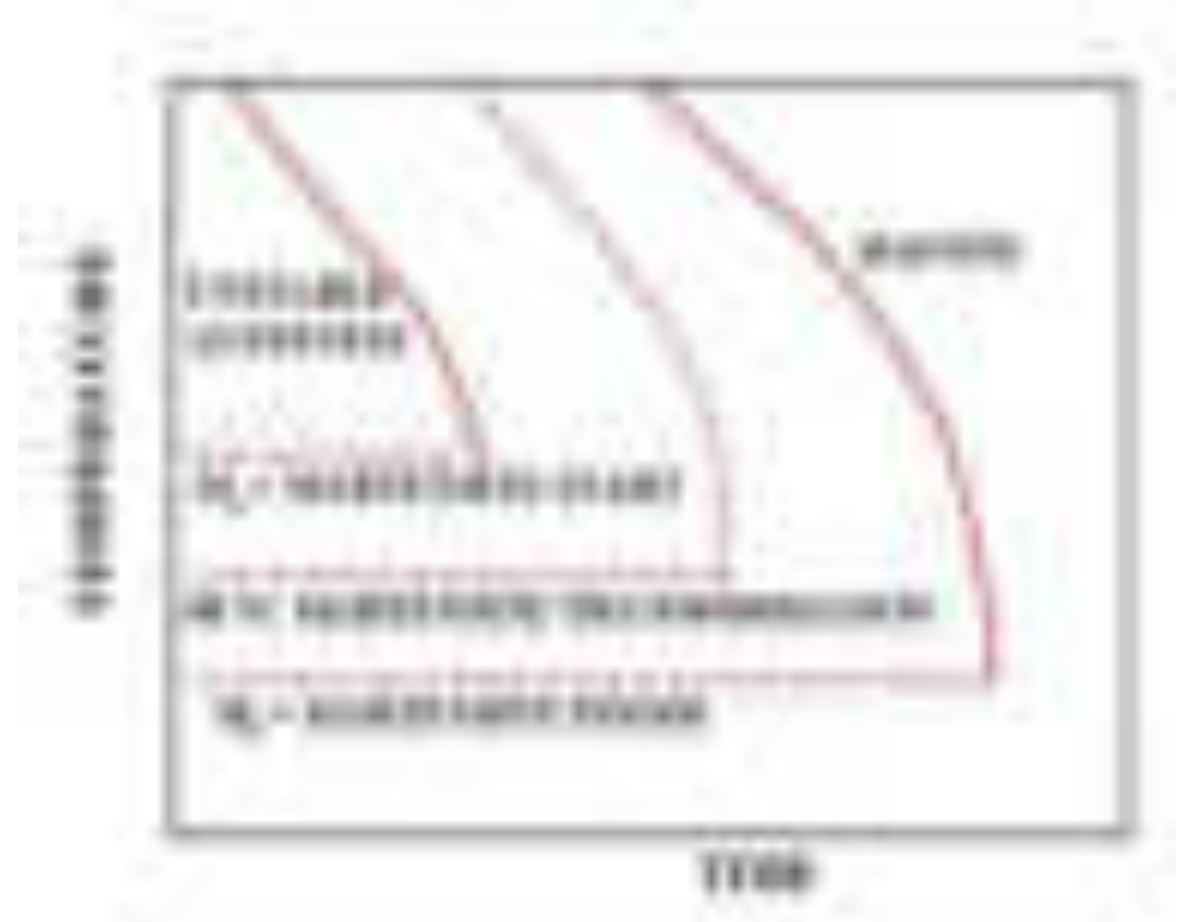
PEARLITE

Austenite is stable at temperatures above LCT but unstable below LCT. Left curve indicates the start of a transformation and right curve represents the finish of a transformation. The area between the two curves indicates the transformation of austenite to different types of crystal structures. (Austenite to pearlite, austenite to martensite, austenite to bainite transformation.) Isothermal Transform Diagram shows that γ to transformation (a) is rapid! at speed of sound; (b) the percentage of transformation depends on Temperature only:

Figure 10.10: Comparison of the performance of the different models. The plot shows the relative error of the solution for the different models as a function of the number of nodes. The relative error is defined as the absolute error divided by the maximum value of the solution. The plot shows that the performance of the models improves as the number of nodes increases, and that the performance of the models is similar for a given number of nodes.

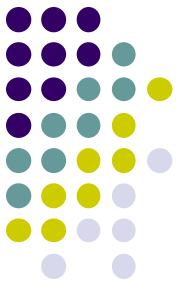


If a cooling rate is very high, the cooling curve will remain on the left hand side of the Transformation Start curve. In this case all Austenite will transform to Martensite. If there is no interruption in cooling the end product will be martensite.

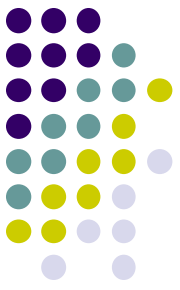


Lower half of TTT Diagram (Austenite-Martensite and Bainite Transformation Areas)

Definition of heat treatment



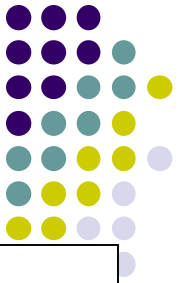
Heat treatment is an operation or combination of operations involving heating at a specific rate, soaking at a temperature for a period of time and cooling at some specified rate. The aim is to obtain a desired microstructure to achieve certain predetermined properties (physical, mechanical, magnetic or electrical).



Heat Treatment

- *Heat Treatment process is a series of operations involving the **heating and cooling** of metals in the solid state. Its purpose is to change a mechanical property or combination of mechanical properties so that the metal will be more useful, serviceable, and safe for definite purpose. By heat treating, a metal can be made harder, stronger, and more resistant to impact, heat treatment can also make a metal softer and more ductile. No one heat-treating operation can produce all of these characteristics. In fact, some properties are often improved at the expense of others. In being hardened, for example, a metal may become brittle.*

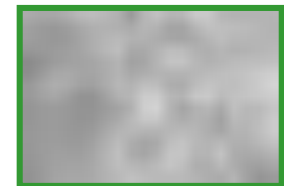
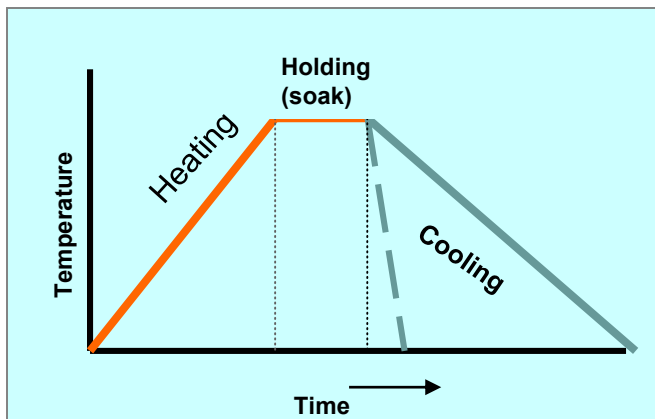
What is Heat Treating ?

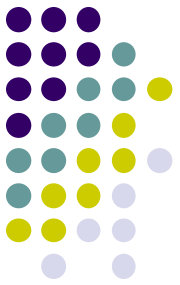


Controlled Heating And Cooling of Metal to Change Its Properties and Performance.

Through:

- Change in Microstructure
- Change in Chemistry or Composition

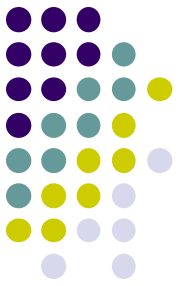




Why Use Heat Treating ?

In simple Terms....

- Soften a Part That Is Too Hard.
- Harden a Part That Is Not Hard Enough.
- Put Hard Skin on Parts That Are Soft.
- Make Good Magnets Out of Ordinary Material.
- Make Selective Property Changes Within Parts.

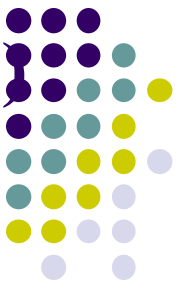


Who uses Heat Treating ?




- Aircraft Industry
- Automobile Manufacturing
- Defense Sector
- Forging
- Foundry
- Heavy Machinery Manufacturing
- Powder Metal Industries

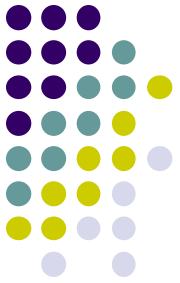
Objectives of heat treatment (heat treatment processes)



The major objectives are

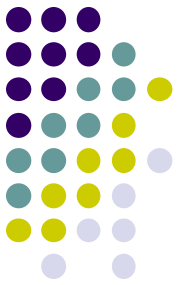
- to increase strength, hardness and wear resistance (**bulk hardening, surface hardening**)
- to increase ductility and softness (**tempering, recrystallization annealing**)
- to increase toughness (**tempering, recrystallization annealing**)
- to obtain fine grain size (**recrystallization annealing, full annealing, normalising**)
- to remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding (**stress relief annealing**)

- 
- to improve machineability (**full annealing and normalising**)
 - to improve cutting properties of tool steels (**hardening and tempering**)
 - to improve surface properties (**surface hardening, corrosion resistance-stabilising treatment and high temperature resistance-precipitation hardening, surface treatment**)
 - to improve electrical properties (**recrystallization, tempering, age hardening**)
 - to improve magnetic properties (**hardening, phase transformation**)



Heat Treating Processes

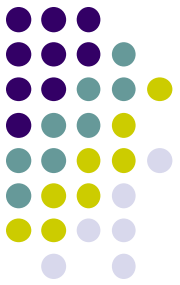




The types of Heat Treatment:

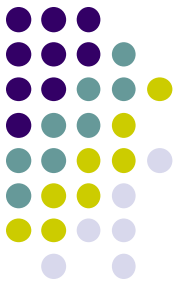
1. Softening.

2. Hardening.



1. Softening

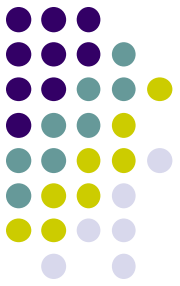
- *Done to reduce strength or hardness*
- *Remove residual stresses*
- *Improve toughness*
- *Restore ductility*
- *Refine grain size or change the electromagnetic properties of the steel.*



- *Restoring ductility or removing residual stresses is a necessary operation after a large amount of cold working have been performed, such as in a cold-rolling operation or wiredrawing.*
- *Annealing, normalizing and tempering* *are the some of principal ways by which metals are softened .*

Thermal processing of metals

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



Annealing Processes



- **Annealing**: a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then **slowly cooled**.
- **Three stages of annealing**
 1. Heating to the desired temperature
 2. Holding or “soaking” at that temperature
 3. Cooling, usually to room temperature

Purposes for Annealing



1. Relieve Internal Stresses

- **Internal stresses can build up in metal as a result of processing.**
 - **Stresses may be caused by previous processing operations such as welding, cold working, casting, forging, or machining.**
- **If internal stresses are allowed to remain in a metal, the part may eventually distort or crack.**
- **Annealing helps relieve internal stresses and reduce the chances for distortion and cracking.**

Purposes for Annealing (Cont'd)



2. Increasing Softness, Machinability, and Formability

- A softer and more ductile material is easier to machine in the machine shop.
- An annealed part will respond better to **forming operations**.

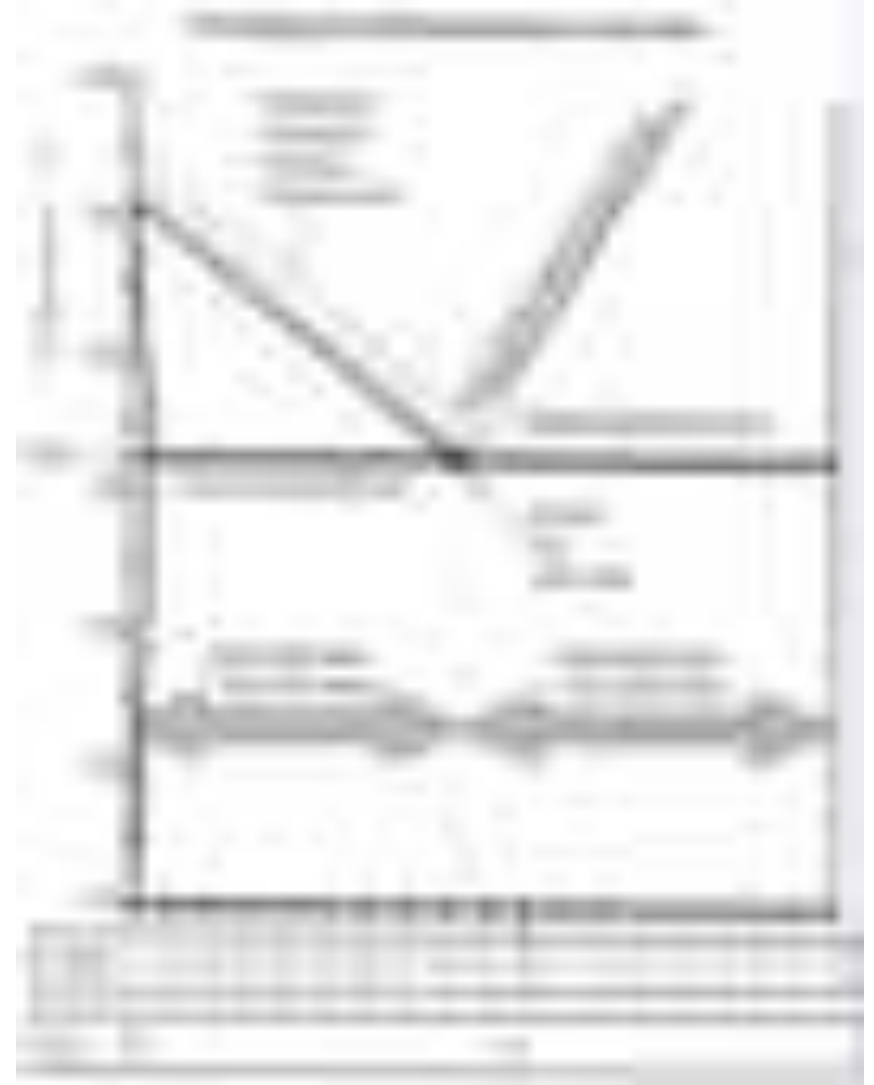
3. Refinement of Grain Structures

- After some types of metalworking (particularly cold working), the crystal structures are elongated.
- Annealing can change the shape of the grains back to the desired form.



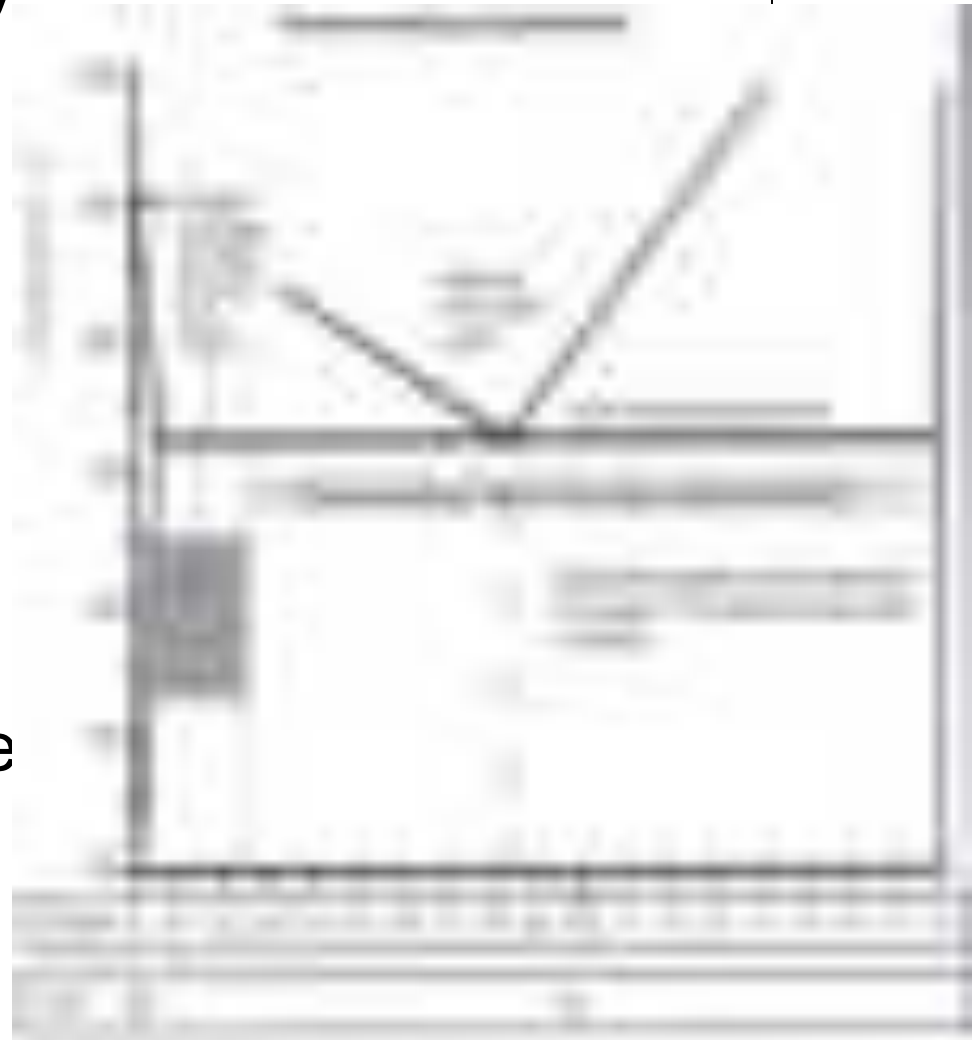
Annealing

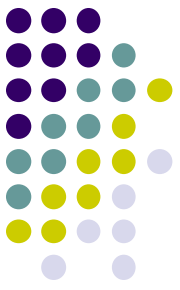
- Makes a metal as soft as possible
- Hypoeutectoid steels (less than 0.83% carbon) are heated above upper critical temp., soaked and cooled slowly.
- Hypereutectoid (above 0.83%) are heated above lower critical temp., soaked and allowed to cool slowly.



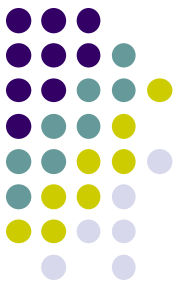


- **Process Annealing.** Low carbon steels may harden through cold working. They can be heated to around 100 degrees below lower critical temp., soaked and allowed to cool in air.
- **Spheroidising.** High carbon steels may be annealed just below the lower critical temp. to improve machinability.



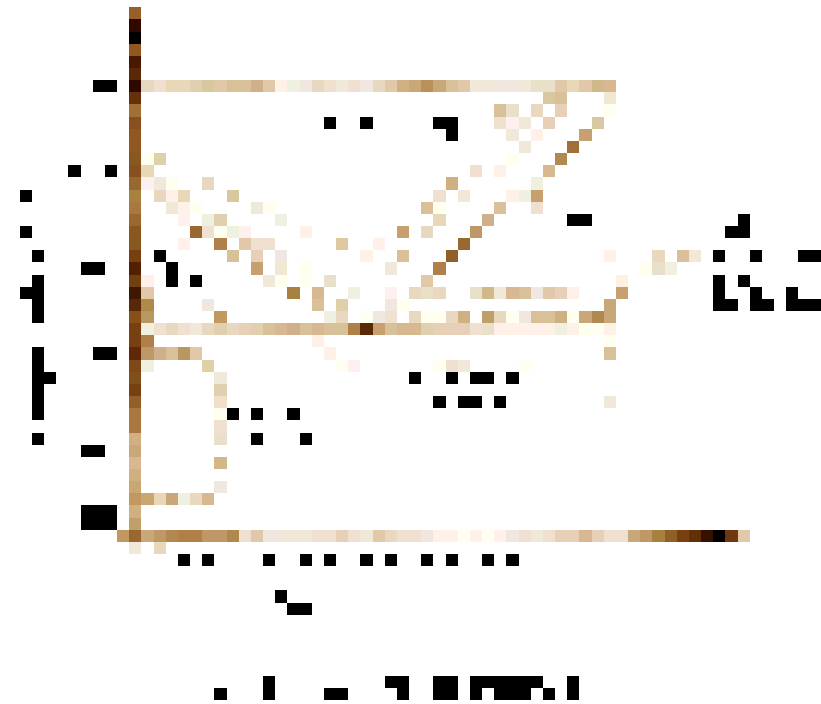


- **Normalising.** Internal stresses caused by rolling and rolling or forging are removed. Steels are heated above upper critical temp., soaked and cooled in air. The cooling rate is faster than annealing giving a smaller grain structure.
- **Stress relieving.** The component is reheated and held at temperature for a period of time and cooled slowly.



1. Stress-Relief Annealing

- It is an annealing process below the transformation temperature A_{c1} , with subsequent slow cooling, the aim of which is to reduce the **internal residual stresses** in a workpiece without intentionally changing its structure and mechanical properties

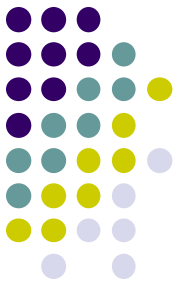




Causes of Residual Stresses

1. **Thermal factors** (e.g., thermal stresses caused by temperature gradients within the workpiece during heating or cooling)
2. **Mechanical factors** (e.g., cold-working)
3. **Metallurgical factors** (e.g., transformation of the microstructure)

How to Remove Residual Stresses?



- R.S. can be reduced only by a plastic deformation in the ***microstructure***.
- This requires that the ***yield strength*** of the material be lowered below the value of the **residual stresses**.
- The more the yield strength is lowered, the greater the plastic deformation and correspondingly the greater the possibility of reducing the residual stresses
- The **yield strength** and the **ultimate tensile strength** of the steel both decrease with increasing **temperature**

Stress-Relief Annealing Process



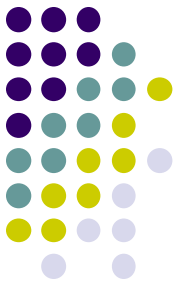
- For **plain carbon** and **low-alloy steels** the temperature to which the specimen is heated is usually between **450** and **650°C**, whereas for **hot-working tool steels** and **high-speed steels** it is between **600** and **750°C**
- This treatment will not cause any phase changes, but **recrystallization** may take place.
- Machining allowance sufficient to compensate for any warping resulting from stress relieving should be provided

Stress-Relief Annealing – R.S.

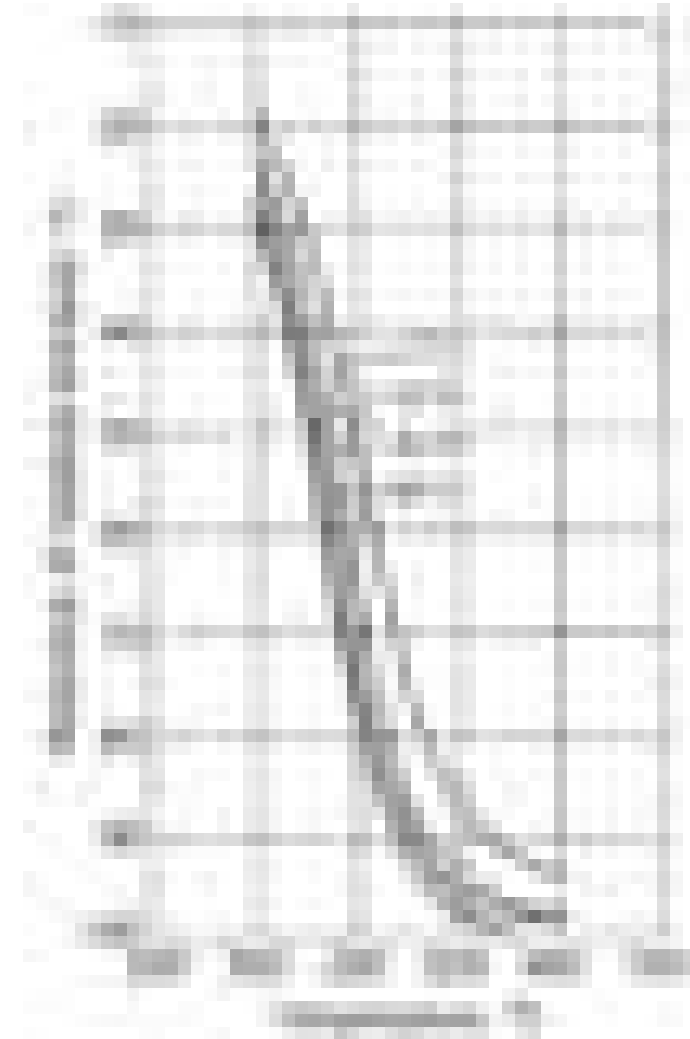


- In the heat treatment of metals, **quenching** or **rapid cooling** is the cause of the greatest residual stresses
- To activate plastic deformations, the local residual stresses must be above the **yield strength** of the material.
- Because of this fact, steels that have a high yield strength at elevated temperatures can withstand higher levels of residual stress than those that have a low yield strength at elevated temperatures
- Soaking time also has an influence on the effect of stress-relief annealing

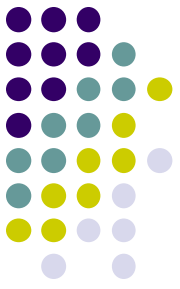
Relation between heating temperature and Reduction in Residual Stresses



- Higher temperatures and longer times of annealing may reduce residual stresses to lower levels

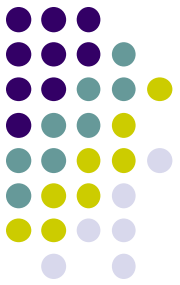


Stress Relief Annealing - Cooling



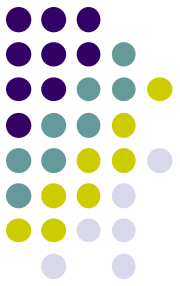
- The residual stress level after stress-relief annealing will be maintained only if the cool down from the annealing temperature is controlled and slow enough that no new internal stresses arise.
- New stresses that may be induced during cooling depend on the (1) **cooling rate**, (2) on the **cross-sectional size** of the workpiece, and (3) on the **composition of the steel**





- Stress relief annealing process consists of three steps. The first step is heating the cold worked steel to a temperature between 5000
- C and 5500
- The stress relief annealing partly relieves the internal stress in cold worked steels without loss of strength and hardness i.e. without change in the microstructure. It reduces the risk of distortion while machining, and increases corrosion resistance. Since only low carbon steels can be cold worked, the process is applicable to hypoeutectoid steels containing less than 0.4% carbon. This annealing process is also used on components to relieve internal stresses developed from rapid cooling and phase changes.
- C i.e. below its recrystallization temperature. The
- second step involves holding the steel component at this temperature for 1-2 hours. The final step is to cool the steel component to room temperature in air.

Full annealing (conventional annealing)

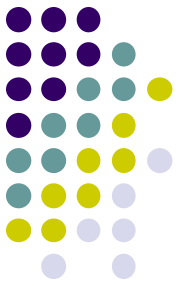


- Full annealing process consists of three steps. First step is heating the steel component to above
- A_3 (upper critical temperature for ferrite) temperature for hypoeutectoid steels and above A_1
- (lower critical temperature) temperature for hypereutectoid steels by 30-500
- C (Figures 4.7.1 and
- 4.7.2). In Figure 4.7.2, the terms α , γ and Fe_3C refer to ferrite, austenite and cementite phases.



The second step is holding the steel component at this temperature for a definite holding (soaking) period of at least 20 minutes per cm of the thick section to assure equalization of temperature throughout the cross-section of the component and complete austenization. Final step is to cool the hot steel component to room temperature slowly in the furnace, which is also called as furnace cooling. The full annealing is used to relieve the internal stresses induced due to cold working, welding, etc, to reduce hardness and increase ductility, to refine the grain structure, to make the material homogenous in respect of chemical composition, to increase uniformity of phase distribution, and to increase machinability.

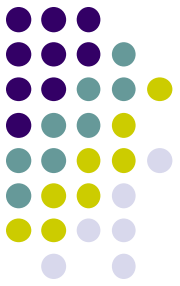
Spheroidise annealing



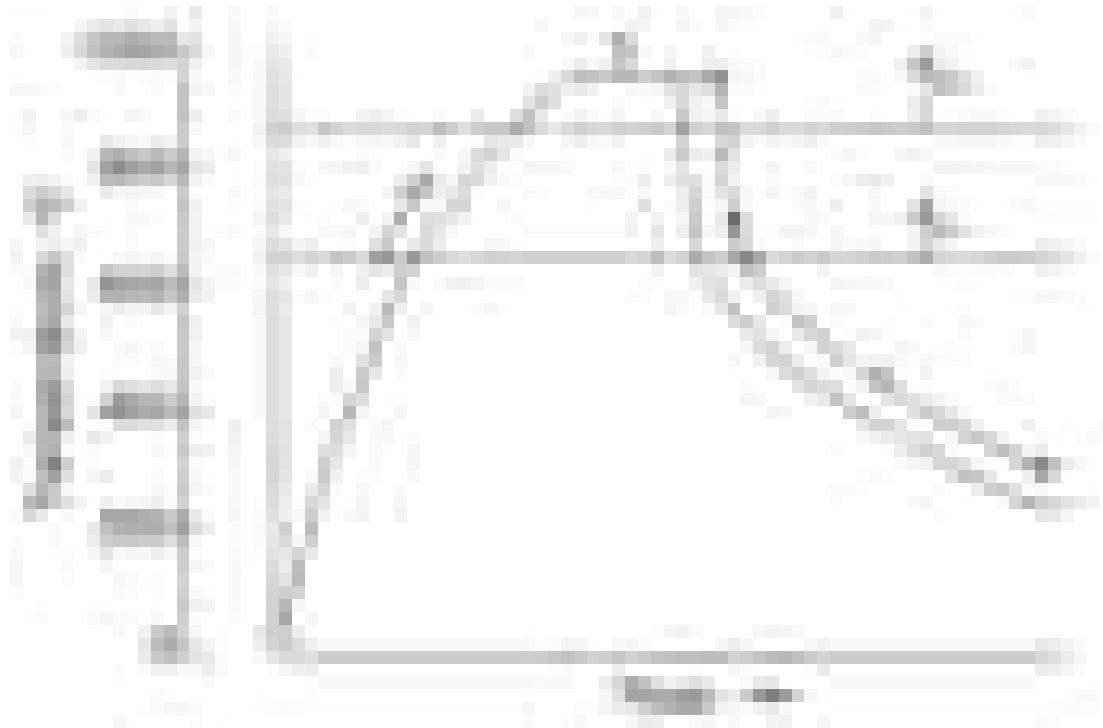
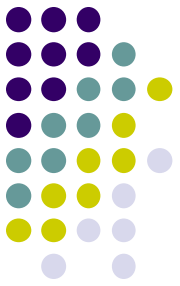
- Spheroidise annealing is one of the variant of the annealing process that produces typical
- microstructure consisting of the globules (spheroid) of cementite or carbides in the matrix of
- ferrite. The following methods are used for spheroidise annealing
- Holding at just below A
- Holding the steel component at just below the lower critical temperature (A_1
- 1
- Thermal cycling around A
-) transforms the
- pearlite to globular cementite particles. But this process is very slow and requires more time for
- obtaining spheroidised structure.
- In this method, the thermal cycling in the narrow temperature range around A
- 1
- 1 transforms
- cementite lamellae from pearlite to spheroidal. Figure 4.7.4 depicts a typical heat treatment cycle
- to produce spheroidised structure. During heating above A_1 , cementite or carbides try to dissolve
- and during cooling they try to re-form. This repeated action spheroidises the carbide particles.
- Spheroidised structures are softer than the fully annealed structures and have excellent
- machinability. This heat treatment is utilized to high carbon and air hardened alloy steels to
- soften them and to increase machinability, and to reduce the decarburization while hardening of
- thin sections such as safety razor blades and needles.

2. Normalizing

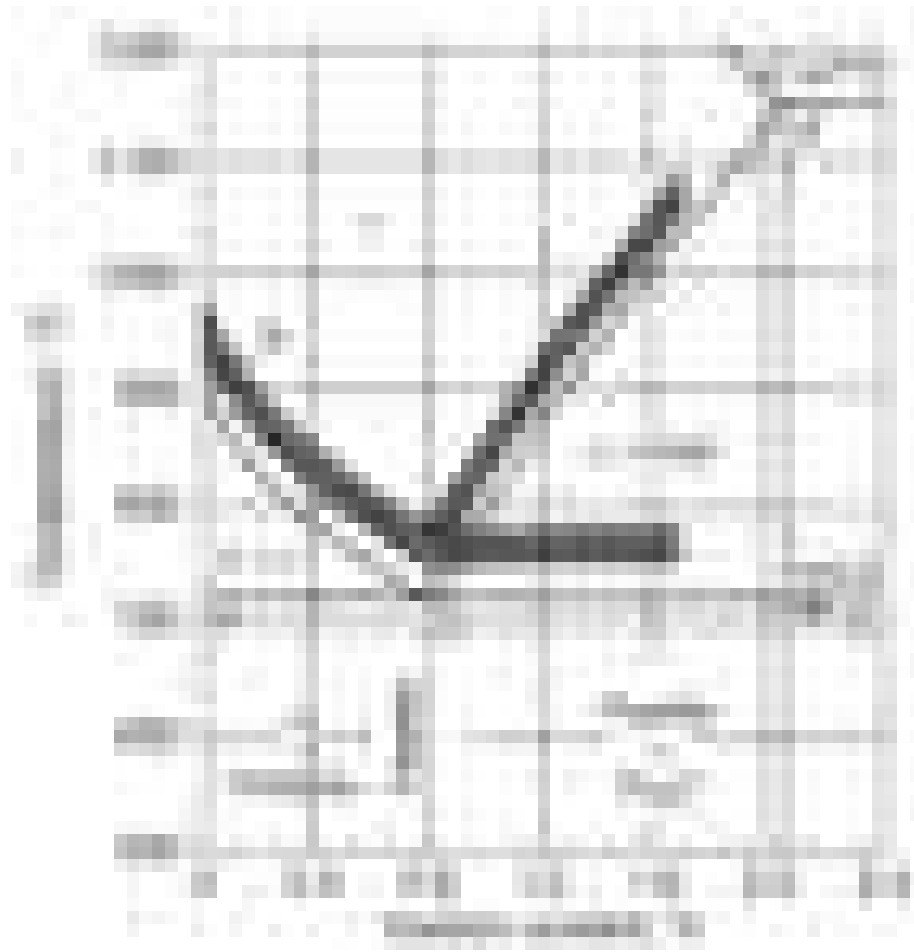
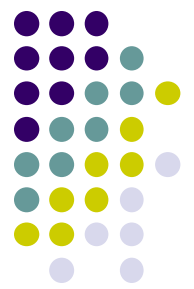
- A heat treatment process consisting of austenitizing at temperatures of **30–80°C** above the **A_{C3}** transformation temperature followed by slow cooling (usually in air)
- The aim of which is to obtain a fine-grained, uniformly distributed, **ferrite–pearlite** structure
- Normalizing is applied mainly to unalloyed and low-alloy hypoeutectoid steels
- For hypereutectoid steels the austenitizing temperature is **30–80°C** above the **A_{C1}** or **A_{Cm}** transformation temperature



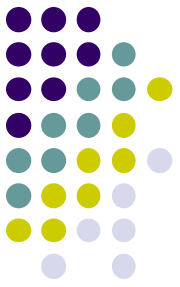
Normalizing – Heating and Cooling



Normalizing – Austenitizing Temperature Range



Effect of Normalizing on Grain Size

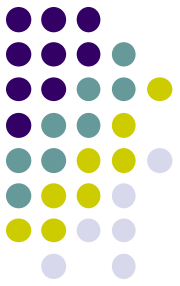


- Normalizing **refines** the grain of a steel that has become **coarse-grained** as a result of heating to a high temperature,

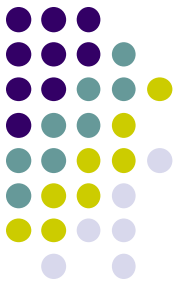


Carbon steel of 0.5% C (a) As rolled or

Normalizing

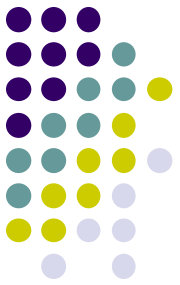


- Normalizing process consists of three steps. The first step involves heating the steel component
- above the A_3 temperature for hypoeutectoid steels and above A_{cm} (upper critical temperature for
- cementite) temperature for hypereutectoid steels by 300
- C to 500
- C (Figure 4.7.5). The second step
- involves holding the steel component long enough at this temperature for homogeneous
- austenization. The final step involves cooling the hot steel component to room temperature in
- still air. Due to air cooling, normalized components show slightly different structure and
- properties than annealed components. The same are explained in Table 4.7.1.



Hardening

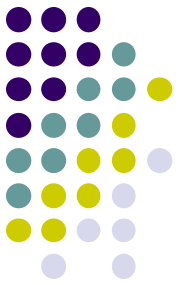
- Medium and High carbon steels (0.4 – 1.2%) can be heated until red hot and then quenched in water producing a very hard and brittle metal. At 723 degrees, the BCC ferrite changes into Austenite with a FCC structure.



Hardening 0.6% carbon steel

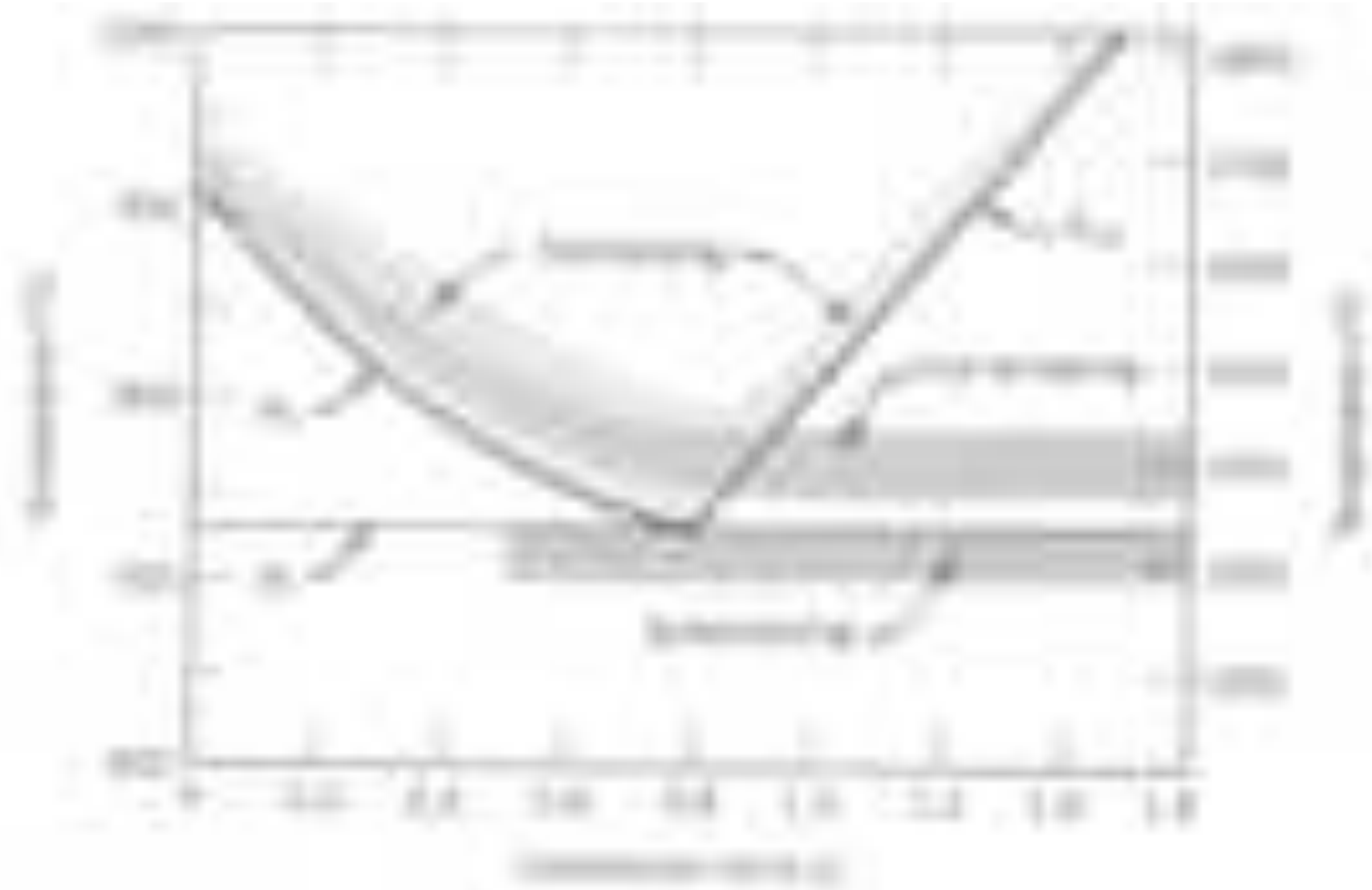
- The metal is heated to over 780 degrees, which allows the carbon to dissolve into the FCC Austenite.
- Quenching the metal quickly in water prevents the structure from changing back into BCC.
- A different structure, Body Centre Tectragonal (BCT) is formed. It is called Martensite and is extremely hard and brittle with a needle-like microstructure.



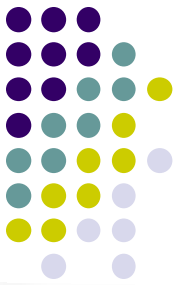


Tempering

- To remove some of the brittleness from hardened steels, tempering is used. The metal is heated to the range of 220-300 degrees and cooled.
- Tempering colours are an indicator of temperature on polished metals. Colours range from yellow to brown to violet and blue.

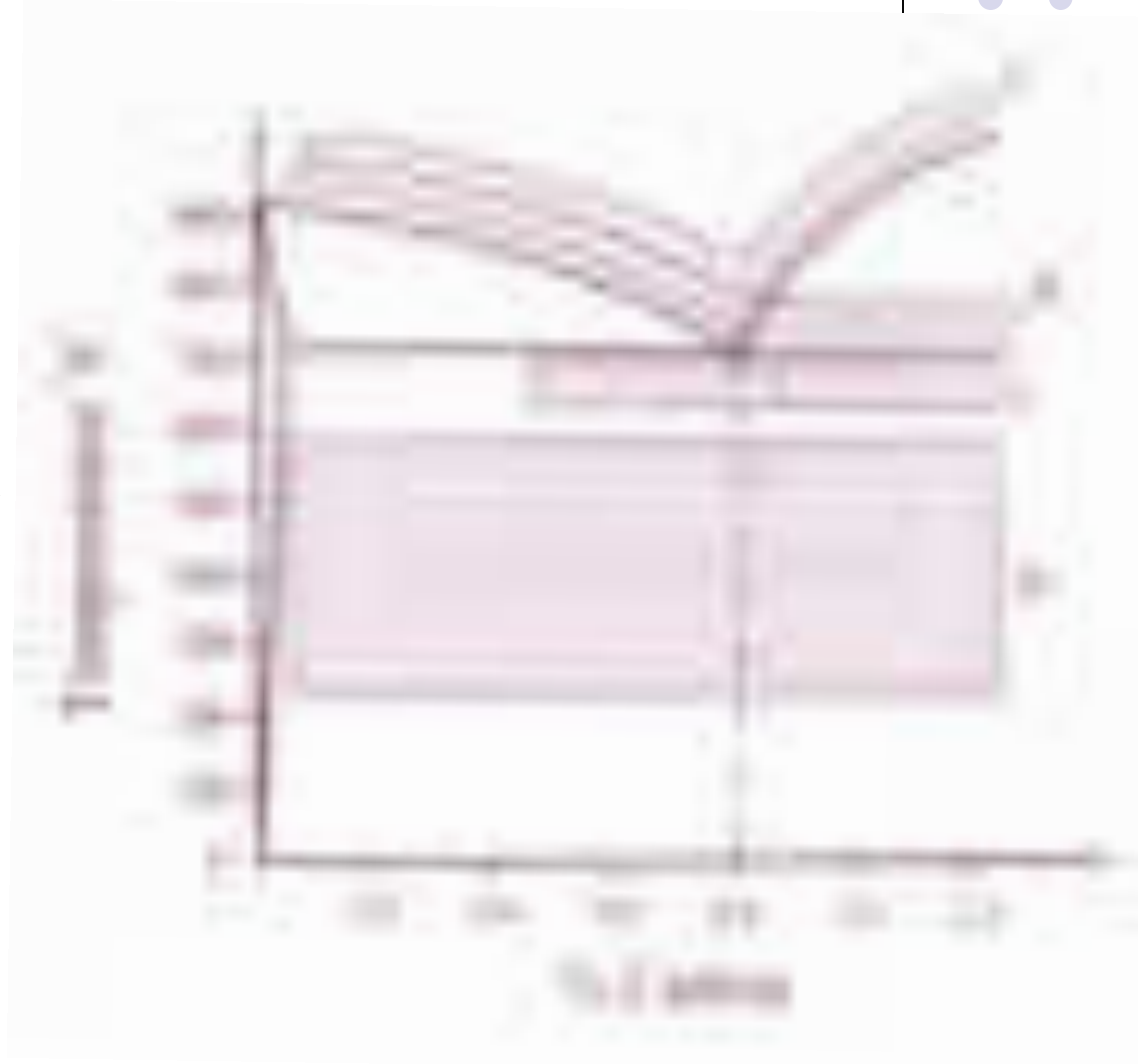


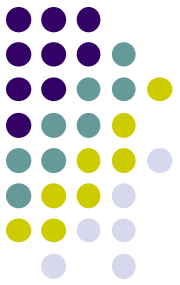
The miscibility gap in the phase diagram is the co-existence of the two phases, indicating that a single composition range for phase coexistence exists.



Heat Treatments

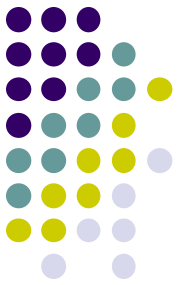
- A – Normalising
- B – Annealing or Hardening
- C – Spheroidising or Process Annealing
- D - Tempering





Quenching media

- Brine (water and salt solution)
- Water
- Oil
- Air
- Turn off furnace



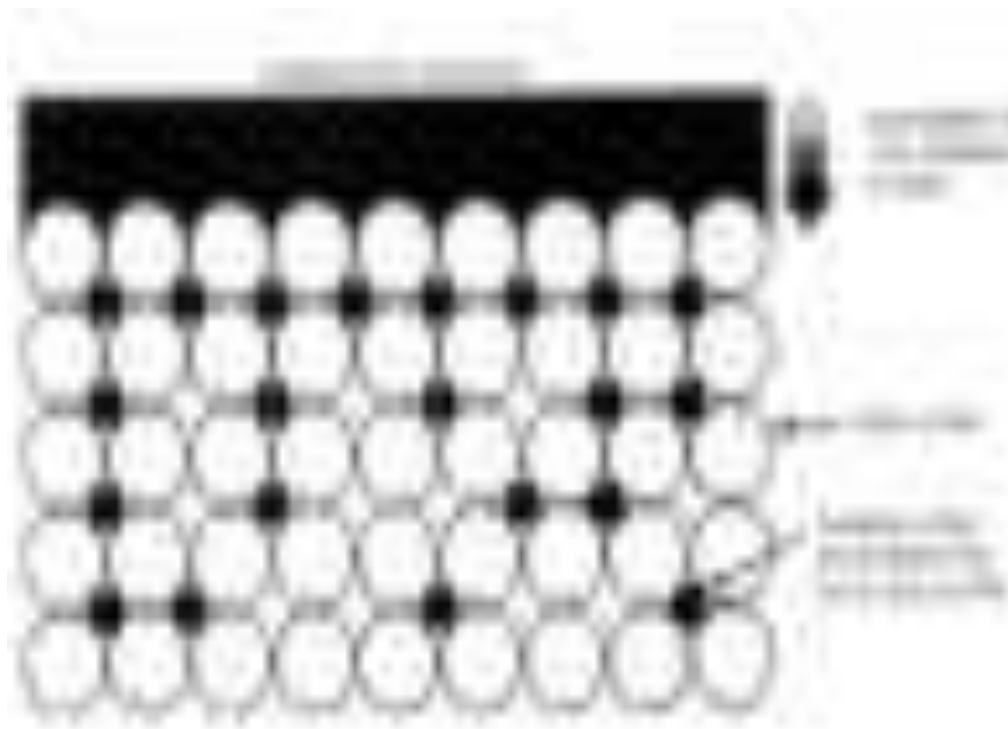
Case hardening

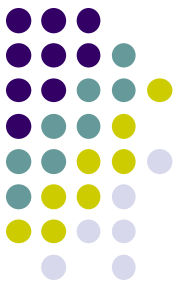
- Low carbon steels cannot be hardened by heating due to the small amounts of carbon present.
- Case hardening seeks to give a hard outer skin over a softer core on the metal.
- The addition of carbon to the outer skin is known as carburising.



Pack carburising

- The component is packed surrounded by a carbon-rich compound and placed in the furnace at 900 degrees.
- Over a period of time carbon will diffuse into the surface of the metal.
- The longer left in the furnace, the greater the depth of hard carbon skin. Grain refining is necessary in order to prevent cracking.



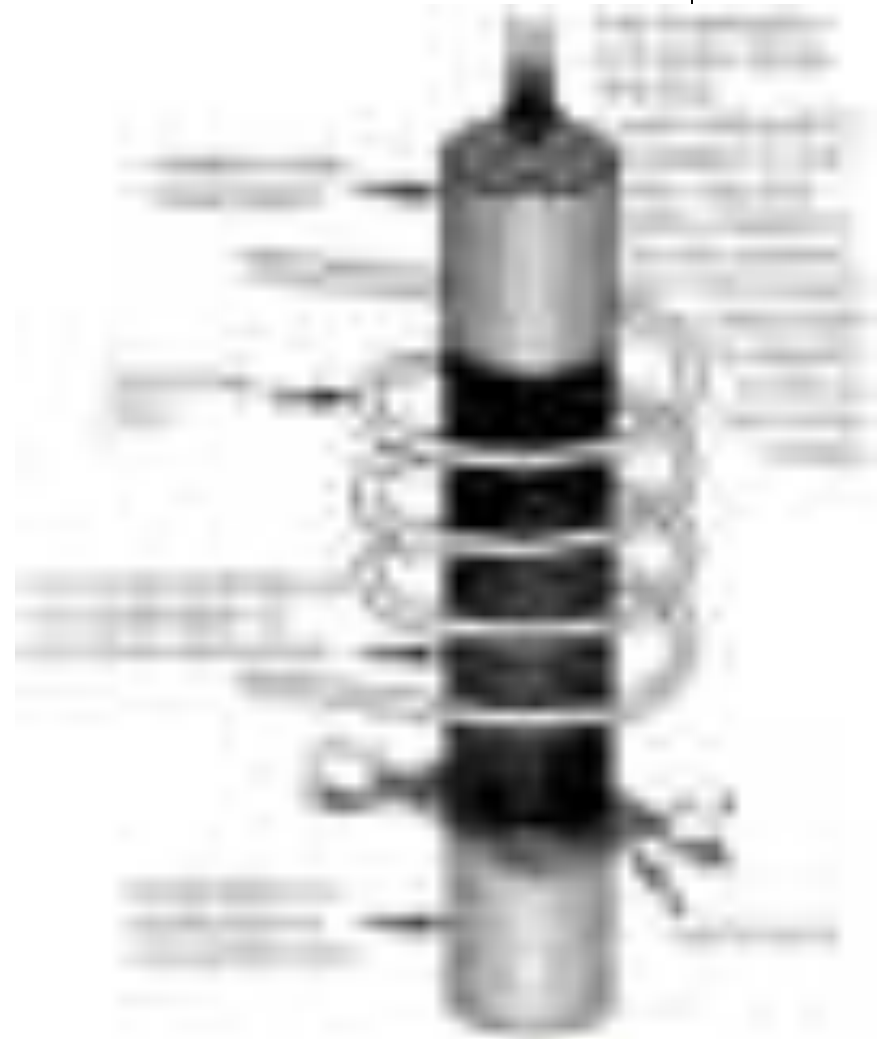


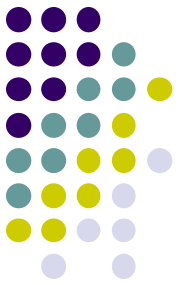
- **Salt bath carburising.** A molten salt bath (sodium cyanide, sodium carbonate and sodium chloride) has the object immersed at 900 degrees for an hour giving a thin carbon case when quenched.
- **Gas carburising.** The object is placed in a sealed furnace with carbon monoxide allowing for fine control of the process.
- **Nitriding.** Nitrides are formed on a metal surface in a furnace with ammonia gas circulating at 500 degrees over a long period of time (100 hours). It is used for finished components.



Induction hardening

- Induced eddy currents heat the surface of the steel very quickly and is quickly followed by jets of water to quench the component.
- A hard outer layer is created with a soft core. The slideways on a lathe are induction hardened.



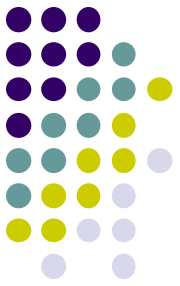


Flame hardening

- Gas flames raise the temperature of the outer surface above the upper critical temp. The core will heat by conduction.
- Water jets quench the component.

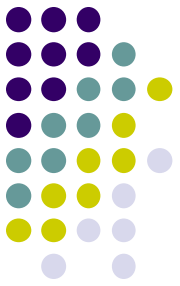


Age hardening



- Hardening over a period of time
- Also known as precipitation hardening
- Occurs in duraluminium which is an aluminium alloy that contains 4% copper. This makes this alloy very useful as it is light yet reasonably hard and strong, it is used in the space industry.
- The metal is heated and soaked (solution treatment) then cooled and left.

Pyrometry



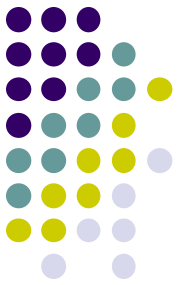
The measurement and control of temperature in a furnace is called pyrometry.



Seger cones

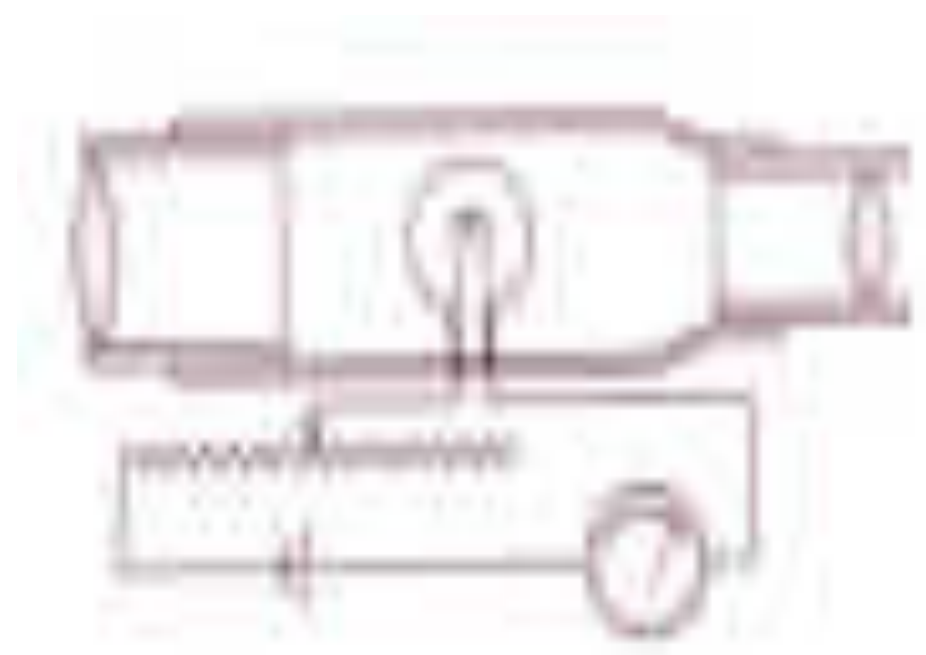
- A traditional method of gauging furnace temperature.
- Cones with known melting temperatures are placed in the furnace, temperature is identified as cones collapse.





Optical pyrometer

- Also known as 'disappearing filament'.
- The light intensity of a lamp, which can be adjusted, is compared to the light from a furnace.
- Temperature is measured when the filament seems to disappear in the glow from the furnace.



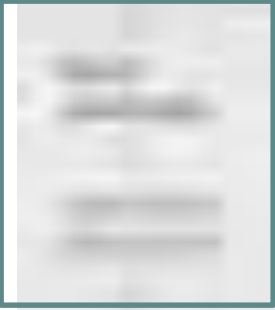


Thermo-electric pyrometer

- A thermocouple uses the principle that a small current flows if two dissimilar metals are joined in a loop with different temperatures at the junctions.
- A galvanometer at the cold junction detects a change in current at the hot junction in the furnace



Heat
treating
for
strength!



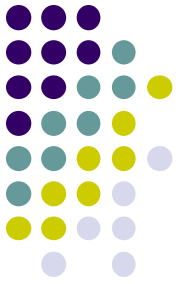
10.4 Direct Hardening –

Austenitizing and quench:

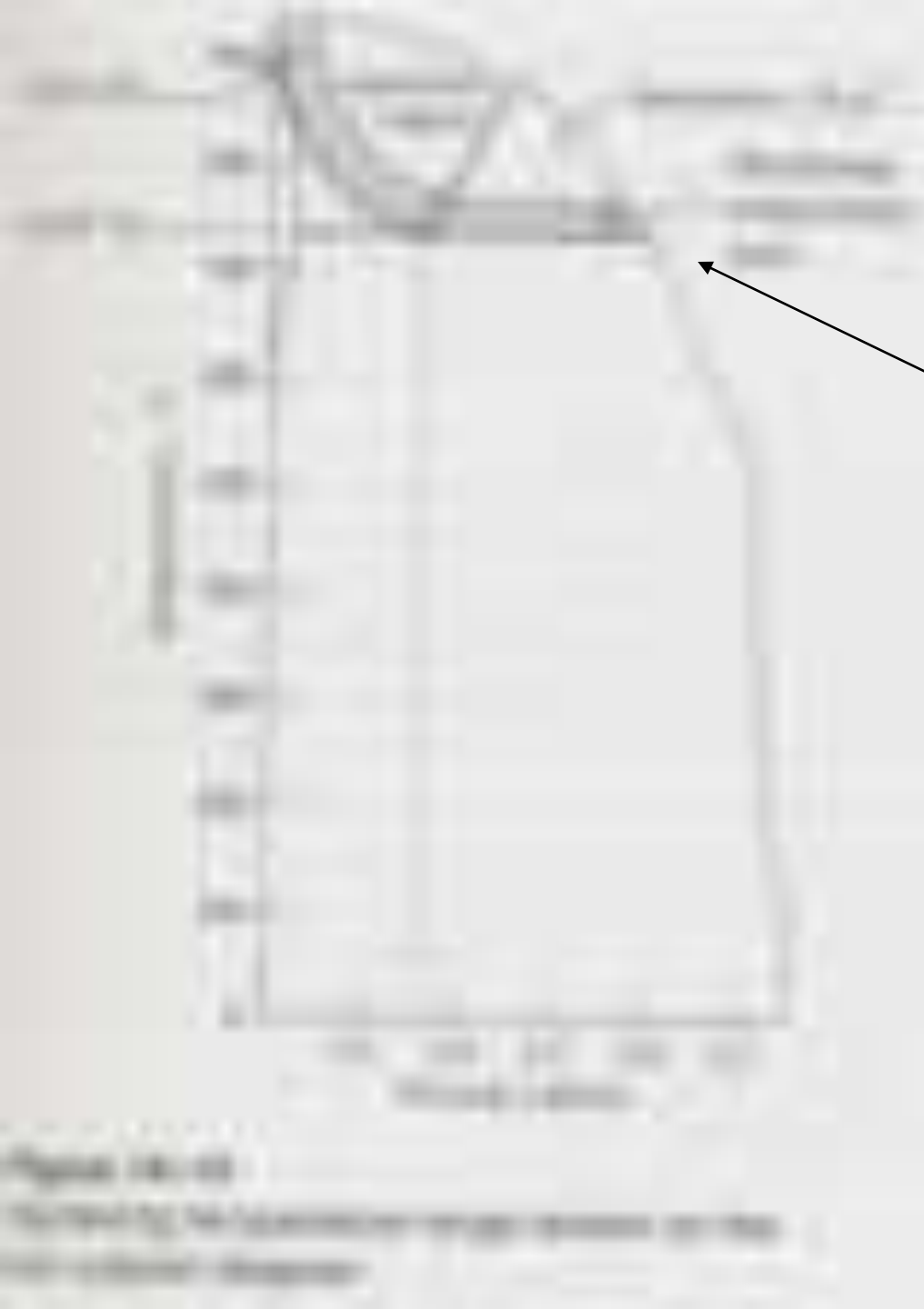


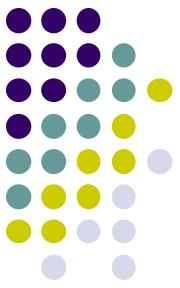
- Austenitizing – again taking a steel with .6% carbon or greater and heating to the austenite region.
- Rapid quench to trap the carbon in the crystal structure – called martensite (BCT)
- Quench requirements determined from isothermal transformation diagram (IT diagram).
- Get “Through” Hardness!!!

Austenitizing:

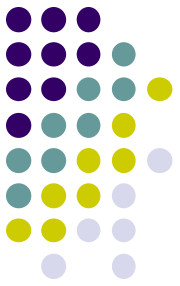


Heat to austenite range.
Want to be close to
transformation
temperature to get fine
grain structure.

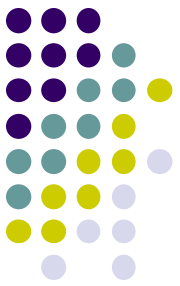




For this particular steel want to cool from about 1400 F to <400 F in about 1 second!



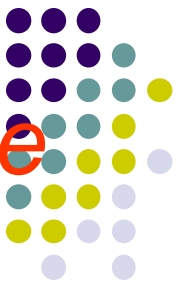
For this particular steel want to cool from about 1400 F to <400 F in about 1 second!



Quenching:

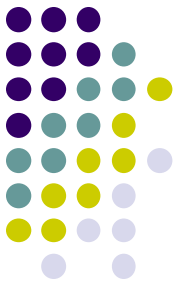
- Depending on how fast steel must be quenched (from IT diagram), the heat treater will determine type of quenching required:
 - Water (most severe)
 - Oil
 - Molten Salt
 - Gas/ Air (least severe)
 - Many phases in between!!! Ex: add water/polymer to water reduces quench time! Adding 10% sodium hydroxide or salt will have twice the cooling rate!

13.4 Direct Hardening - *Selective Hardening*



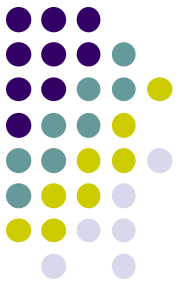
- Same requirements as austenitizing:
 - Must have sufficient carbon levels ($>0.4\%$)
 - Heat to austenite region and quench
- Why do?
 - When only desire a select region to be hardened: Knives, gears, etc.
 - Object too big to heat in furnace! Large casting w/ wear surface
- Types:
 - Flame hardening, induction hardening, laser beam hardening

Flame Hardening:





Induction Hardening



Diffusion Hardening (aka Case Hardening):



- Why do?
 - Carbon content too low to through harden with previous processes.
 - Desire hardness only in select area
 - More controlled versus flame hardening and induction hardening.
 - Can get VERY hard local areas (i.e. HRC of 60 or greater)
 - Interstitial diffusion when tiny solute atoms diffuse into spaces of host atoms
 - Substitutional diffusion when diffusion atoms too big to occupy interstitial sites – then must occupy vacancies