HEAT TREATMENT OF STEELS

BY: Dr A.K. MOHAMED

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By the end of the presentation you will be able to answer the following questions:

- WHAT ARE THE TYPES OF METALS AND ALLOYS?
- WHAT IS "STEEL" AND WHAT IS "IRON-CARBON DIAGRAM"?
- WHAT ARE THE DIFFERENCES BETWEEN PERITECTIC, EUTECTIC AND EUTECTOID REACTIONS?
- HOW DO THE PROPERTIES OF THE STEEL CHANGE?
- WHAT ARE THE TYPES OF HEAT TREATMENT?
- WHAT ARE THE PROPERTIES TO BE ENHANCED FOR EACH HEAT TREATMENT?
- WHICH RANGES OF TEMPERATURE ARE USED FOR WHICH HEAT TREATMENT?
- WHAT IS "TTT" DIAGRAM?

Based on:

- "THEORY OF HEAT TREATMENT OF METALS" BY I.I. NOVIKOV, PUBLISHED IN 1987
- "PHYSICAL METALLURGY", 2014, VOL.2, CHAPTER 11

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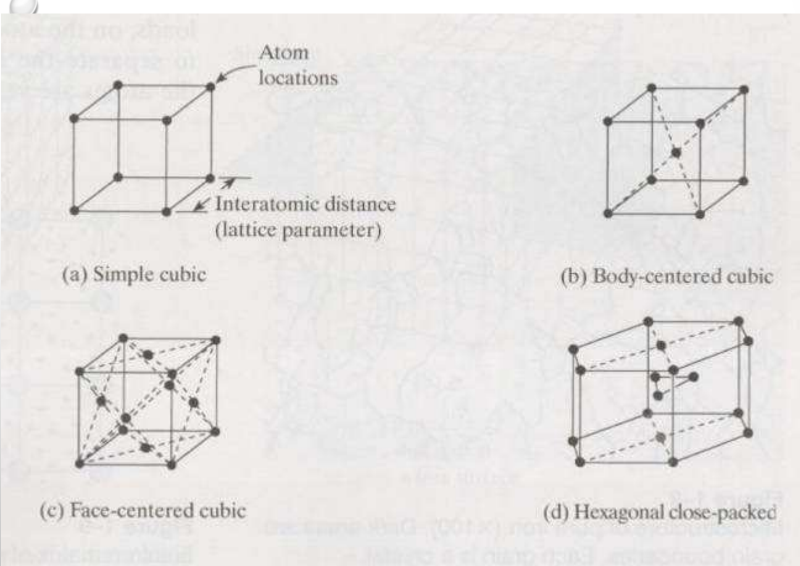

Crystalline structures (i.e. metals) atoms are arranged in unit cells – 4 common cells shown above

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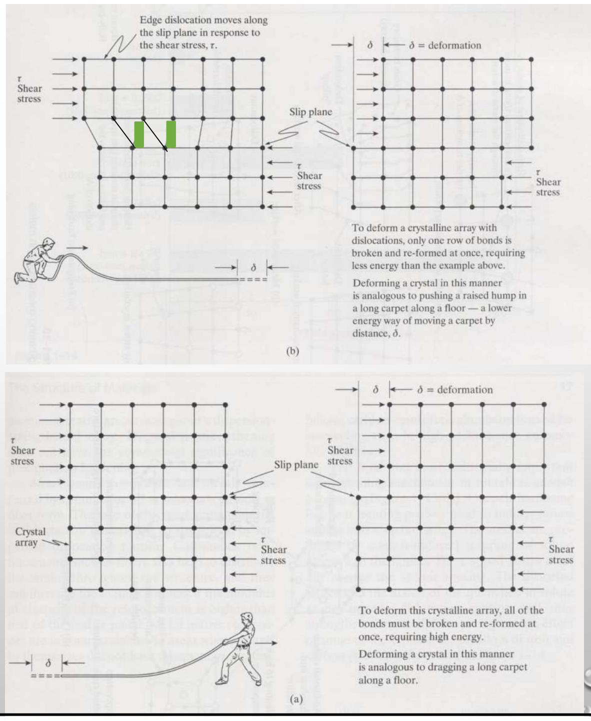
How do Metal Crystals Fail??

Answer: Slip due to dislocations



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THEORETICAL STRENGTH OF METAL

- STRENGTH, S_U SHOULD BE APPROXIMATELY E/10 IF BASED ON ATOMIC BOND.
- E/10 = 3,000 KSI FOR STEEL >>> ACTUAL S_U WHICH IS BETWEEN APPROXIMATELY 30 KSI TO 200 KSI
- WHY??????
- DEFECTS!!!

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TYPES OF DEFECTS:

- SURFACE DEFECTS
  - GRAIN BOUNDARIES
- POINT DEFECTS
  - VACANCY, SUBSTITUTIONAL (ATOM REPLACES HOST), INTERSTITIAL (ATOM SQUEEZES IN BETWEEN HOST), IMPURITY
- LINE DEFECTS
  - EDGE DISLOCATIONS, SCREW DISLOCATIONS

= good defect!

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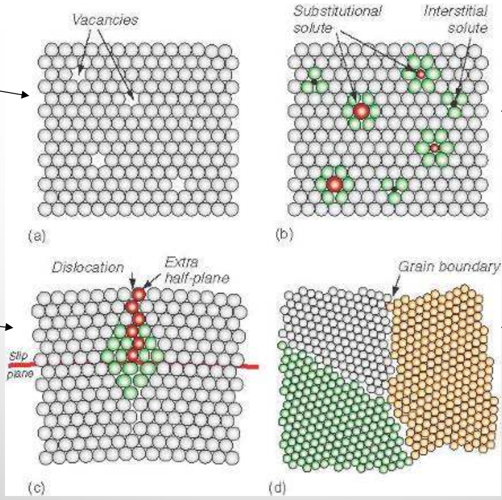
Little impact on strength



Alloying and heat treating

Greatest impact on strength and ductility!!

Course GB = weak,

Fine GB = strong and ductile

DEFECTS IN CRYSTALS. (A) VACANCIES–MISSING ATOMS. (B) FOREIGN (SOLUTE) ATOM ON INTERSTITIAL AND SUBSTITUTIONAL SITES.

(C) LINE DEFECT = A DISLOCATION–AN EXTRA HALF-PLANE OF ATOMS. (D) GRAIN BOUNDARIES.

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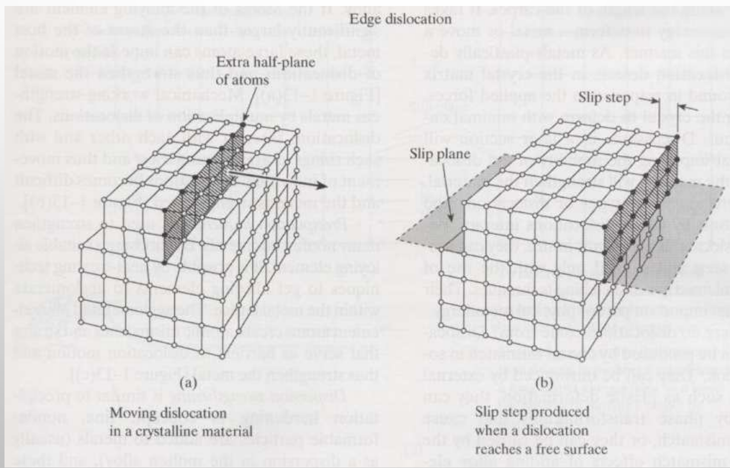
WHAT IS THE MOST SIGNIFICANT DEFECT?

Answer: The line defect (edge dislocation or screw dislocation)



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HOW TO STRENGTHEN METALS:

- KEY: PREVENT DISLOCATIONS FROM MOVING THROUGH CRYSTAL STRUCTURE!!!
- FINER GRAIN BOUNDARIES – CAN BE DONE BY RECRYSTALLIZING (AND COLD WORKING)
- INCREASE DISLOCATION DENSITY VIA *COLD WORKING* (STRAIN HARDENING)
- ADD ALLOYING ELEMENTS TO GIVE –*SOLID SOLUTION HARDENING.*
- ADD ALLOYING ELEMENTS TO GIVE PRECIPITATES OR DISPERSED PARTICLES – *PRECIPITATION HARDENING (AKA HEAT TREAT)*
- *DISPERSION HARDENING*– FINE PARTICLES (CARBON) IMPEDE DISLOCATION MOVEMENT.
  - REFERRED TO AS QUENCH HARDENING, AUSTENITIZING AND QUENCH OR SIMPLY “HEAT TREAT”.
  - GENERALLY 3 STEPS: HEAT TO AUSTENITE T, RAPID QUENCH, THEN TEMPER.

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Several cells form a crystal, if many crystals are growing in a melt at the same time, where they meet = grain boundry as shown below:

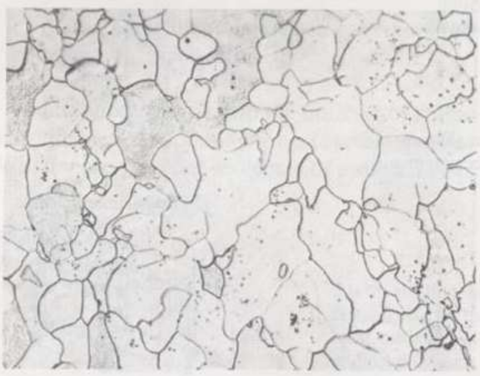

Figure 1–8
Microstructure of pure iron (×100). Dark areas are grain boundaries. Each grain is a crystal.

Mat’l constants

$$\sigma_y = \sigma_o + \frac{k_y}{\sqrt{d}}$$

Average grain diameter

Called Hall-Petch equation

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WORK HARDENING

Work hardening, or **strain hardening,** results in an increase in the strength of a material due to plastic deformation.

Plastic deformation = adding dislocations
– as dislocation density increases, they tend to "tie up" and don't move.

Ludwik's Equation:

Strain hardening index

$$\sigma = \sigma_y + K\epsilon_p^n$$

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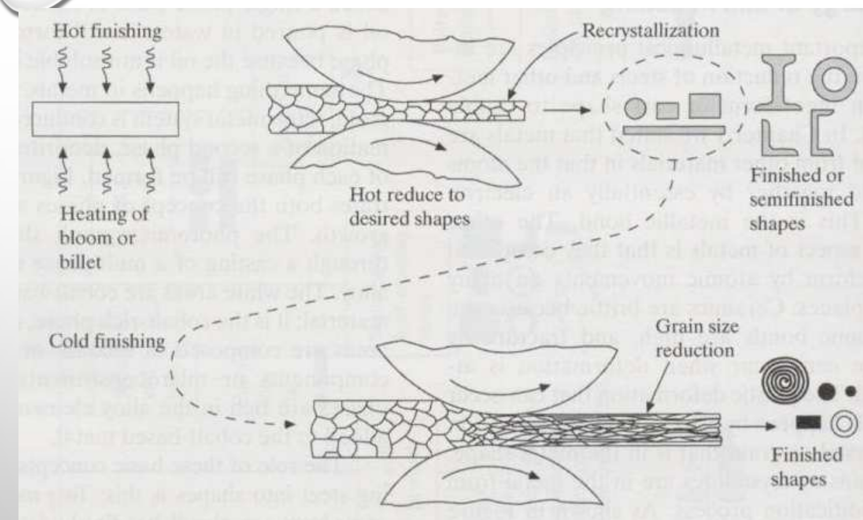

Hot finishing = 2 benefit
Cold finishing = 1 benefits

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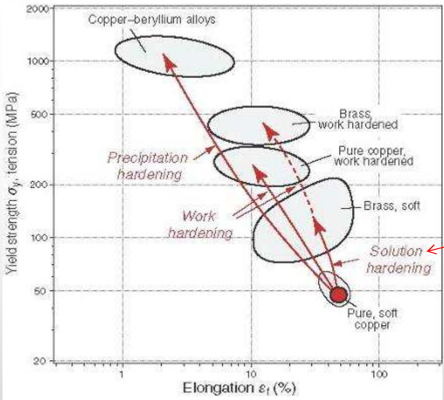

Add zinc to make brass

STRENGTHENING MECHANISMS AND THE CONSEQUENT DROP IN DUCTILITY, HERE SHOWN FOR COPPER ALLOYS.

THE MECHANISMS ARE FREQUENTLY COMBINED. THE GREATER THE STRENGTH,

THE LOWER THE DUCTILITY (THE ELONGATION TO FRACTURE, E_F).

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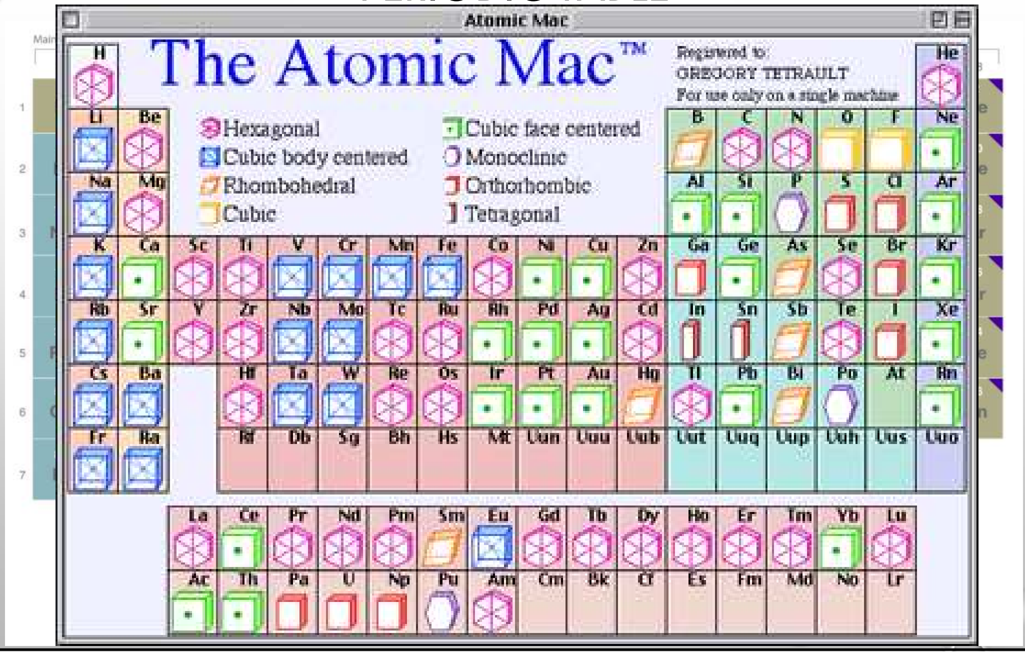
PERIODIC TABLE



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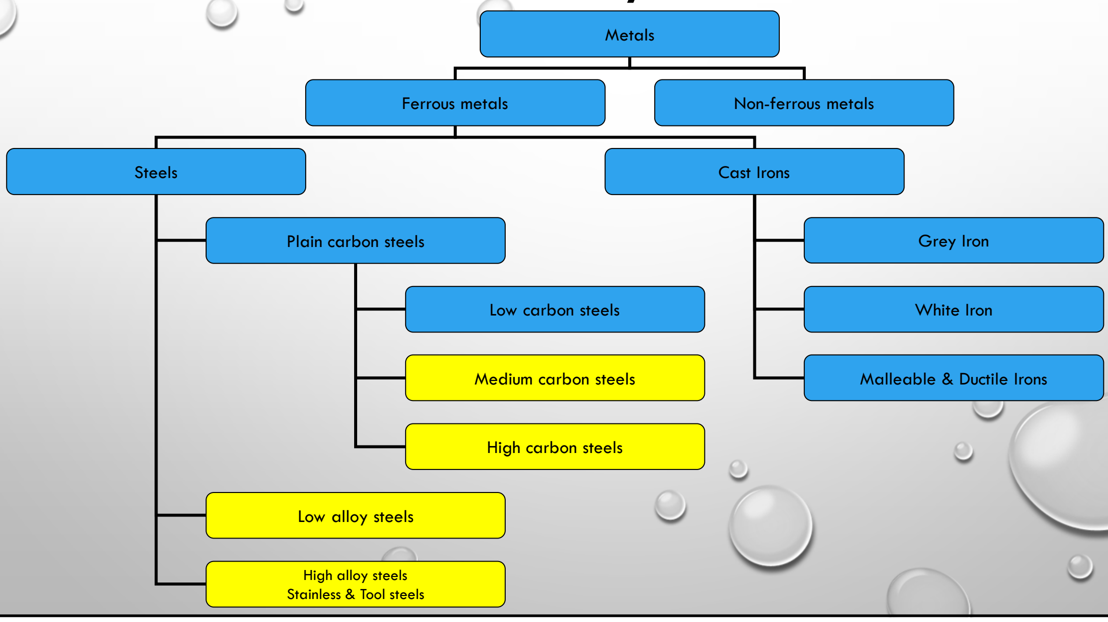
Metals and alloys classification



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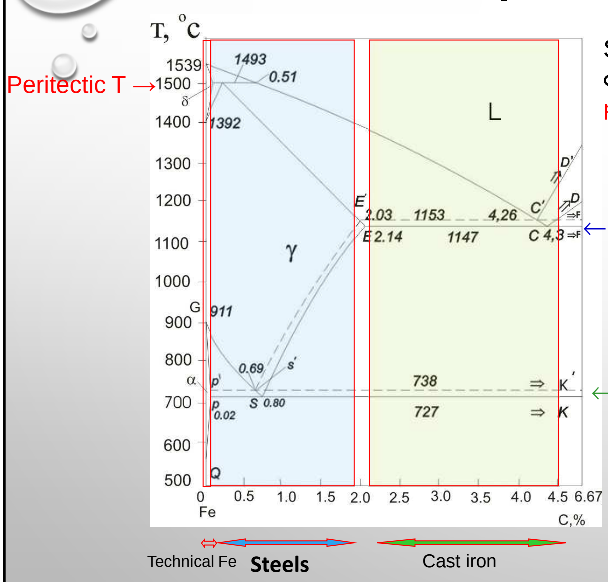
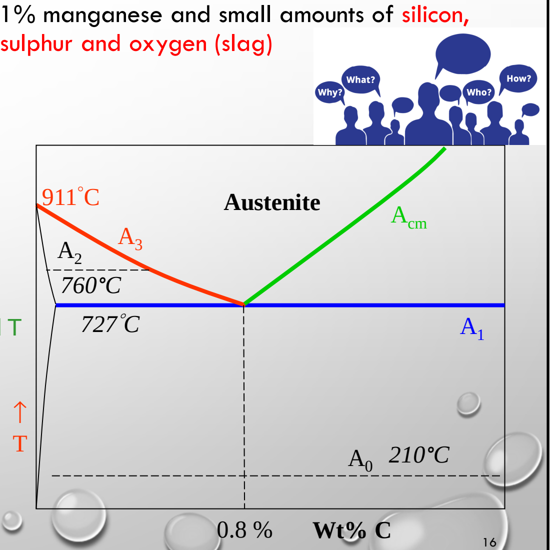
Iron-Carbon phase equilibrium diagram



Steel: is an alloy of iron and carbon containing less than ~2% carbon and 1% manganese and small amounts of silicon, phosphorus, sulphur and oxygen (slag)



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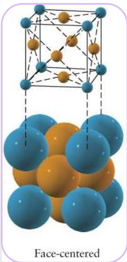
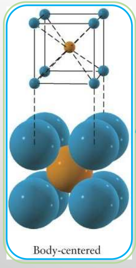
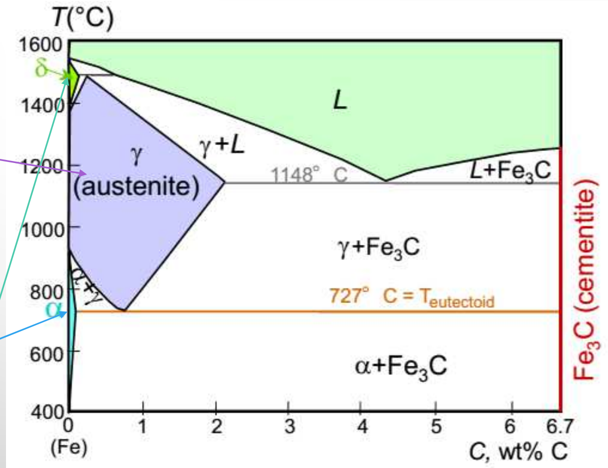
Iron-Carbon phase equilibrium diagram

N = 4,
0.74 atomic packing
$a = 2r\sqrt{2}$



N = 2,
0.68 atomic packing
$a = \frac{4r}{\sqrt{3}}$





Adabted from Fig. 10.28, Calister & Rethwisch 4e.

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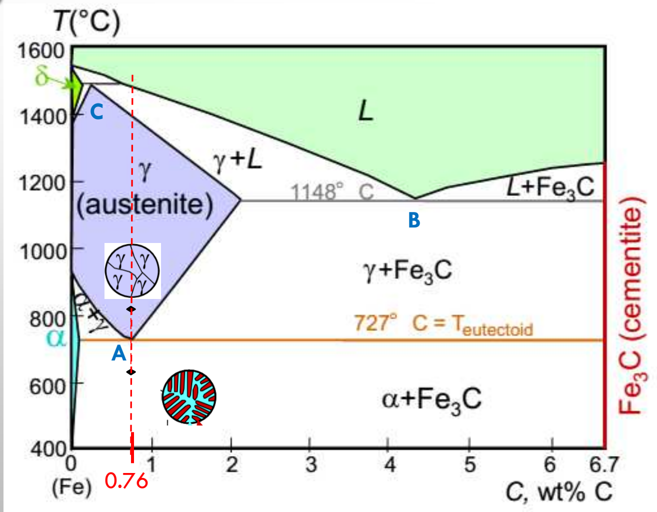
Iron-Carbon phase equilibrium diagram



Important reactions:

Eutectoid reaction (A):

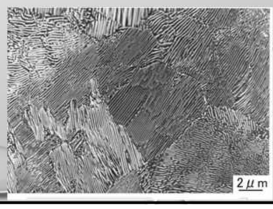
$\gamma \leftrightarrow \alpha + Fe_3C$

Eutectic reaction (B):

$L \leftrightarrow \gamma + Fe_3C$

Peritectic reaction (C):

$\delta + L \leftrightarrow \gamma$



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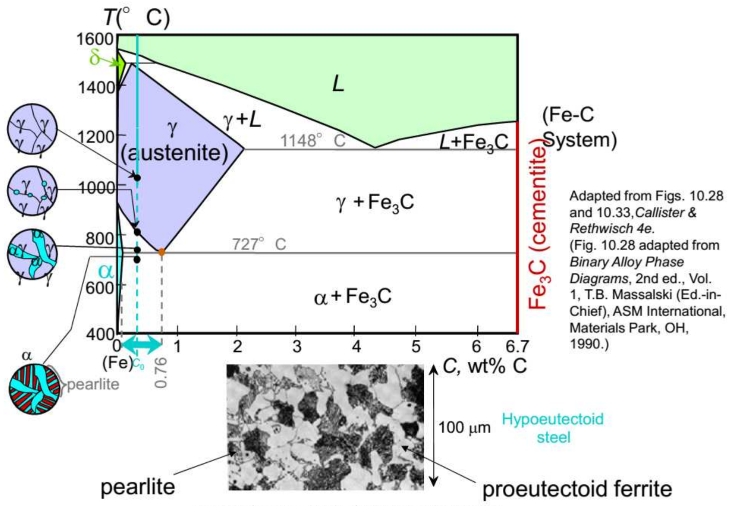
Iron-Carbon phase equilibrium diagram

Hypoeutectoid Steel

microstructure



Adapted from Fig. 10.34, *Callister & Rethwisch 4e.*

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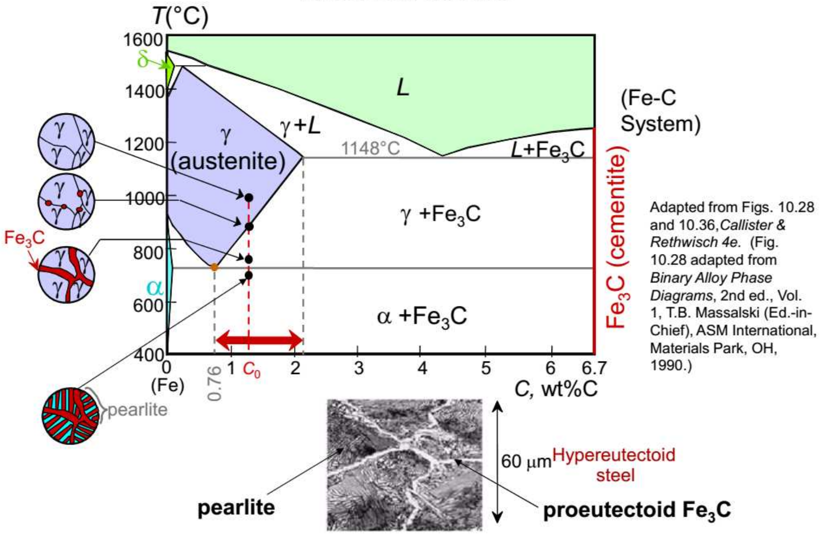
Iron-Carbon phase equilibrium diagram

Hypereutectoid Steel

microstructure



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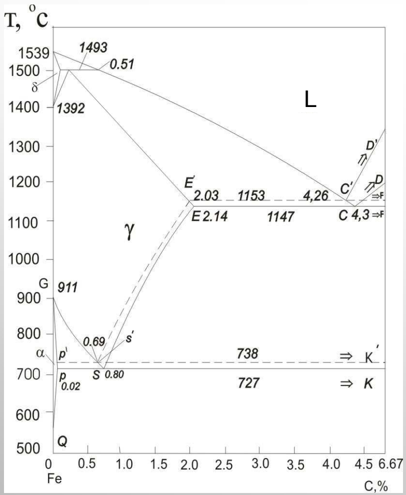
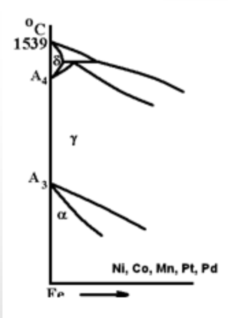
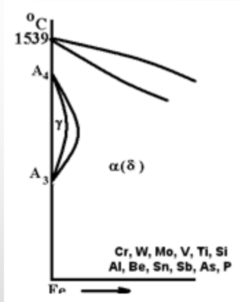
Iron-Carbon-Me phase equilibrium diagram







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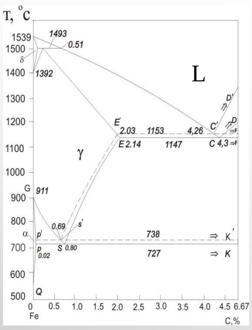
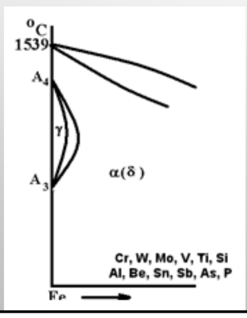
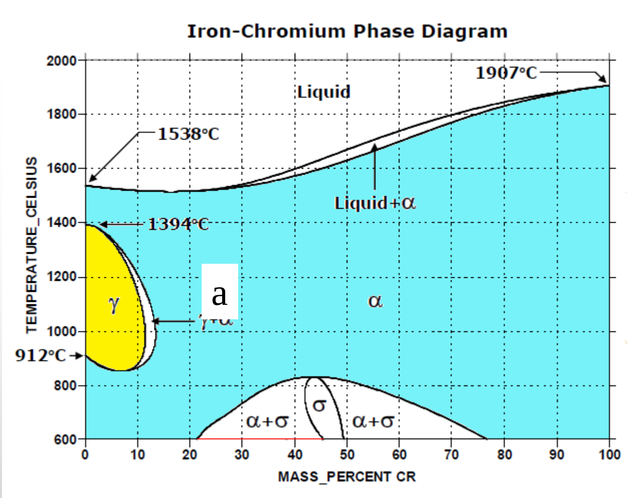
Fe-C vs Fe-Cr phase diagrams







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Definition of heat treatment

Heat treatment is an operation or combination of operations involving heating at a specific rate, holding 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).

The purpose of doing heat treatment

Increasing strength or hardness, increasing toughness, improving ductility and maximizing corrosion resistance

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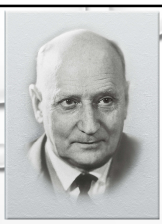

Prof. Andrey Anatolievich Bochvar
July 26, 1902 - September 18, 1984
Founder of non-ferrous metals Dept.

Heat treatment types

- Heat treatment (itself)
  - 1st order annealing
    - Homogenizing Annealing
    - Pre-recrystallizational softening
    - Pre-recrystallizational strengthening
    - Spheroidization Annealing
    - Stress-relief annealing
  - 2nd order annealing
  - I type quenching: With polymorphic transition; Martensitic transformation
  - II type quenching: Without polymorphic transition; Or solid solution treatment
  - Tempering
  - Ageing
- Thermo-mechanical
- Heat + chemical

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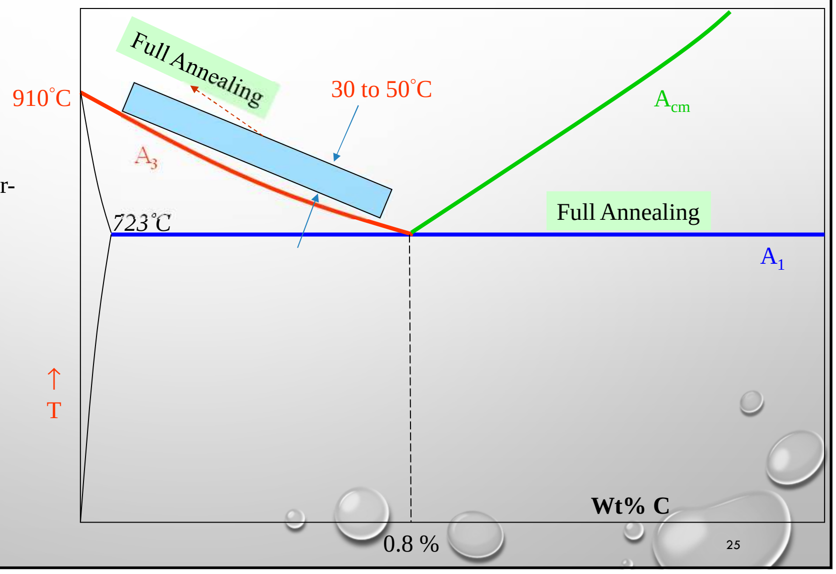
1st order annealing

Homogenizing Annealing

- Ranges of temperature where Annealing treatment are carried out for hypo- and hyper-eutectoid steels. Which followed by furnace cooling
- Hot worked steel and casting.



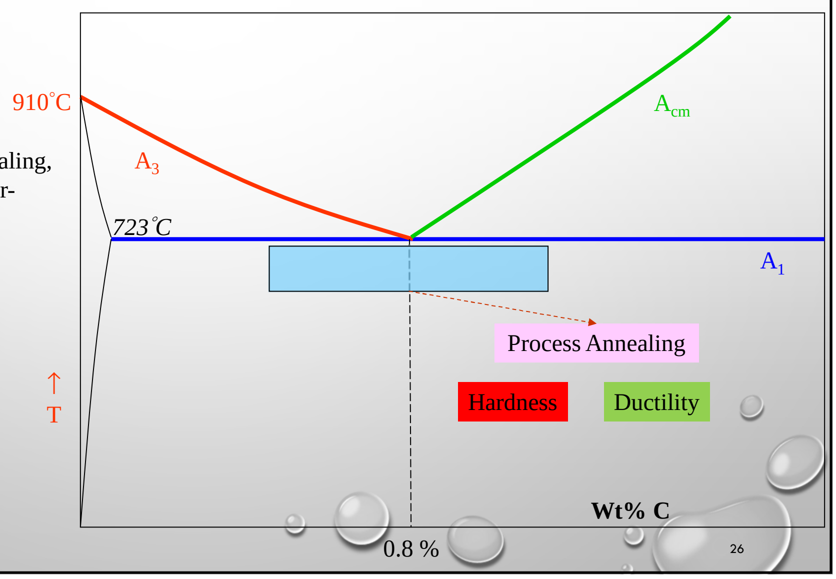
1st order annealing

Pre-recrystallizational softening

- Ranges of temperature where process annealing, treatment are carried out for hypo- and hyper-eutectoid steels.

Cold working:

Hardness ↑ Ductility ↓

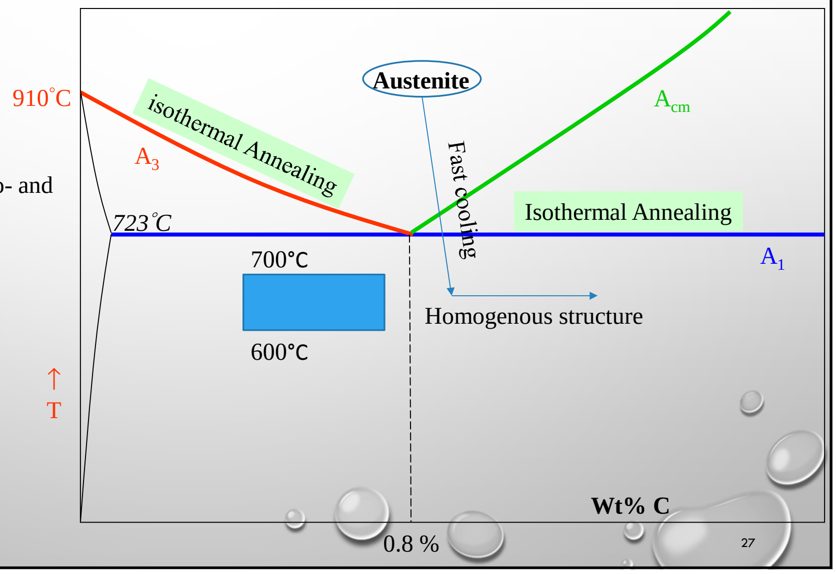


1st order annealing

Pre-recrystallizational strengthening

- Ranges of temperature where isothermal annealing, treatment are carried out for hypo- and hyper-eutectoid steels.

Applicable: low carbon and alloy steel



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1st order annealing

Spheroidization strengthening

1st method

- Ranges of temperature where process annealing, treatment are carried out for hypo- and hyper-eutectoid steels.
- The holding time is about 8h and cooled down slowly

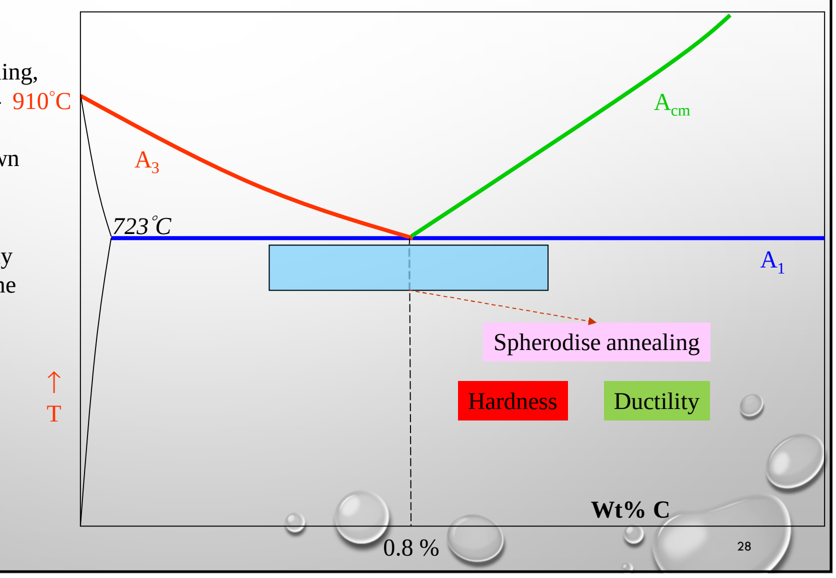
2nd method

- Heating and cooling the material alternatively between temperatures just above and below the lower critical temperature.

High carbon and alloy steel

Machinability

Internal structure



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1st order annealing

Stress-relief Annealing

Brittleness at isolated locations ↑
Sudden breaks

This process involves heating the casting or structure to about 650°C. The temperature is maintained constantly for a few hours and allowed to cool down slowly

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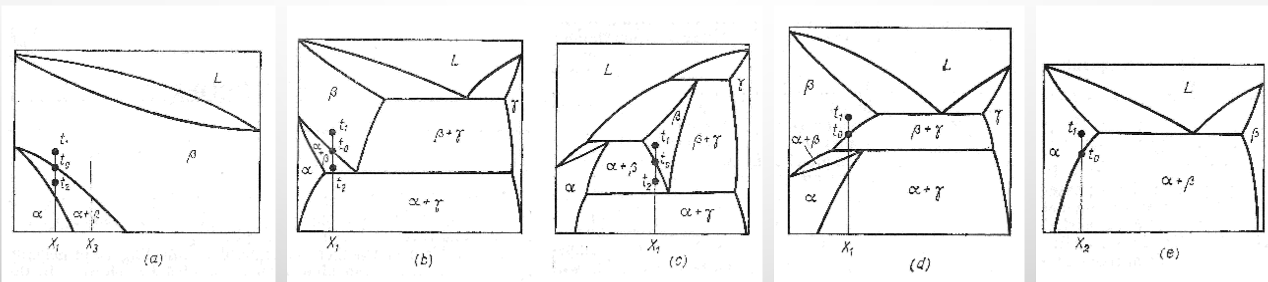
2nd order annealing

Alloy undergoes qualitative or quantitative changes in the phase composition during heating and reverse changes during cooling. Second-order annealing is principally applicable to all metals and alloys whose phase composition in the solid state varies qualitatively or quantitatively with temperature.



polymorphic transformations | eutectoid transformations | peritectoid transformations | dissolution of one phase in another

Systems with various solid-state phase transformations

Principal parameters
1- Temperature of heating
2- Time of holding
3- Cooling rate

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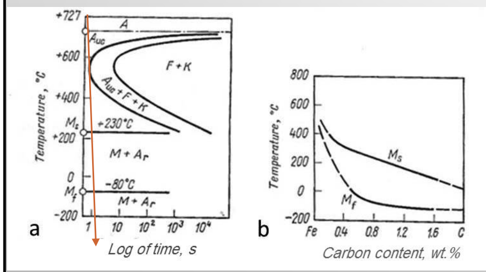
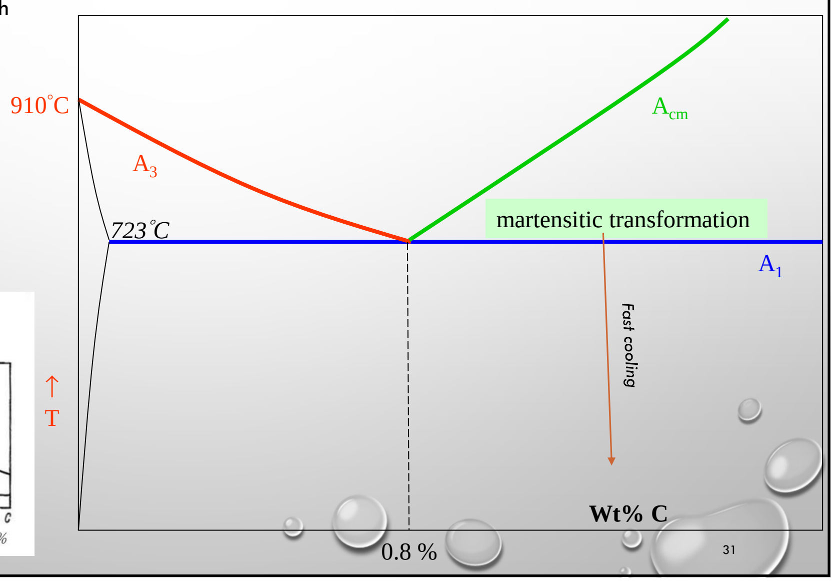
I type quenching QUENCHING WITH POLYMORPHIC CHANGE

- Applicable to all metals and alloys in which the crystal lattice is rearranged on cooling
- Quick cooling by quenching causes martensitic transformation and produces a new phase which is called *martensite*
- *Martensitic quenching or hardening to martensite.*
- *martensitic transformation is diffusionless*
- high-carbon steels, martensite is formed at sub-zero temperatures





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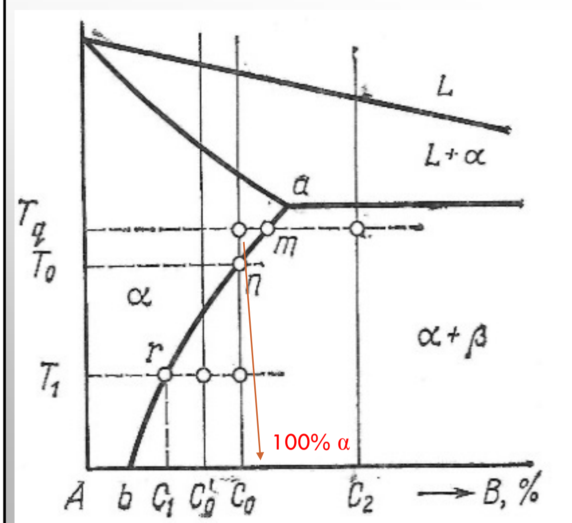
II type quenching QUENCHING WITHOUT POLYMORPHIC CHANGE



Applicable to all alloys in which one of the phases is fully or partially soluble in another

Quenching without polymorphic change results in the formation of supersaturated solution

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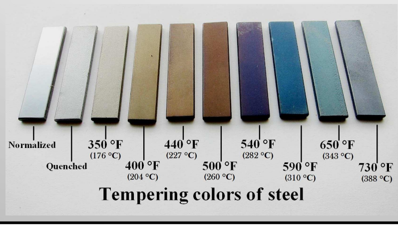
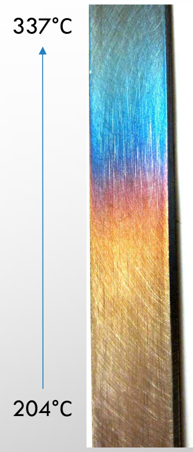
Tempering

Is a process of heat treating, which is used to increase the toughness of iron-based alloys. Tempering is usually performed after quenching, to reduce some of the excess hardness, and is done by heating the metal to some temperature below the critical point for a certain period of time, then allowing it to cool in still air.

- Between 66 and 148 ℃ ⟷ internal stresses, decrease in brittleness
- 148 to 205 ℃ ⟷ internal stresses, reduction in hardness
- 260 to 340 ℃ ⟷ decrease in ductility and an increase in brittleness "tempered martensite embrittlement" tool steel
- 370 to 540 ℃ ⟷ toughness is desired at the expense of strength
- 540 to 600 ℃ ⟷ Excellent toughness



Tempering colors of steel



Differentially tempered steel

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Tempering

Tempering is used with martensite-quenched alloys
during tempering of steel is decomposition of the martensite with precipitation of carbides
(a) A strong supersaturation of the solid solution - martensite;
(b) An increased density of crystal lattice defects - dislocations, low- and high-angle boundaries, twin interlayers; and
(c) The presence of an appreciable amount of retained austenite in many steels

The nature of structural changes in tempering depends on
1- The temperature and time of tempering
2- the content of carbon in the steel

Tempering types:
1- Low tempering 100-180°C
2- average tempering 350-450°C
3- High tempering 450-650°C

Segregation of carbon in martensite
↓
Precipitation of carbides from martensite
↓
Cementite particle coarsening and spheroidization

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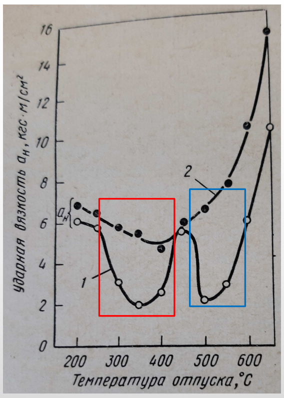
Tempering

Embrittlement:

Non-reversible

Reversible



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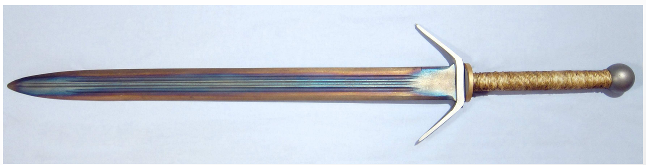
Tempering

Differential tempering

Differential tempering is a method of providing different amounts of temper to different parts of the steel. The method is often used in bladesmithing, for making knives and swords, to provide a very hard edge while softening the spine or center of the blade.



Differential tempering consists of applying heat to only a portion of the blade, usually the spine, or the center of double-edged blades. For single-edged blades, the heat, often in the form of a flame or a red-hot bar, is applied to the spine of the blade only. The blade is then carefully watched as the tempering colors form and slowly creep toward the edge. The heat is then removed before the light-straw color reaches the edge.

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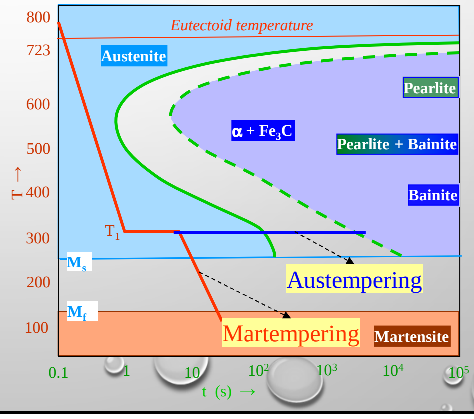
MARTEMPERING & AUSTEMPERING

- These processes have been developed to avoid residual stresses generated during quenching.
- In both these processes Austenized steel is quenched above M_s (say to a temperature T_1) for homogenization of temperature across the sample.
- In Martempering the steel is then quenched, and the entire sample transforms simultaneously to martensite. This is followed by tempering.
- In Austempering instead of quenching the sample, it is held at T_1 for it to transform to bainite.



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Aging

Precipitation hardening

Is a process used to increase strength by producing precipitates of the alloying material within the metal structure. Solution treatment is the heating of an alloy to a suitable temperature, holding it at that temperature long enough to cause one or more constituents to enter into a solid solution and then cooling it rapidly enough to hold these constituents in solution.

Eng. Alfred Wilm
1906

Merica, Waltenberg and Scott
1919

Aging types:

Artificial Aging

The treatment of a metal alloy at elevated temperatures so as to accelerate the changes in the properties of an alloy as a result of the casting and forging process. Generally, the chemical properties of newly cast and forged metals naturally change and settle very slowly at room temperature.

Natural Aging

Aging that occurs at room temperature is referred as natural aging.

Benefits of Aging:

- Not only helps to enhance high strength of alloys but helps them to acquire other valuable properties such as high coercivity
- Restore the equilibrium in the metal and to eliminate any unstable conditions brought upon by a prior operation
- Reduce the resilience and ductility of alloys

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Ageing

Two explanation of the process:

1- Disperse particles act as 'pins' and 'wedge' the slip planes

2- Formation of small element "copper"-rich zones in the supersaturated solution, "which were later called Guinier-Preston zones".

The main shapes of precipitates:

1- Fine-lamellar (usually disc-shaped)

2- Equiaxed (usually spherical or cubic) and acicular

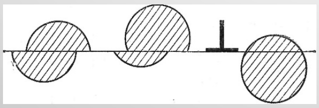
} surface energy and elastic strain energy

The mechanisms of this hardening:

(a) Impediment of dislocations by the elastic stress field around precipitates in the matrix;

(b) 'chemical' hardening owing to precipitates being sheared by dislocations; and

(c) Hardening through dislocations circumventing precipitated particles.



Shear of precipitates by a gliding edge dislocation (scheme)

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Thermo-mechanical treatment

Combines mechanical or plastic deformation process like compression or forging, rolling etc

Application of thermomechanical treatment

Steel billets 130mm² ("pencil ingots") are heated to approximately 1200°C to 1250°C in a reheat furnace. Then, they are progressively rolled to reduce the billets to the final size and shape of reinforcing bar. After the last rolling stand, the billet moves through a quench box. The quenching converts the billet's surface layer to martensite and causes it to shrink. The shrinkage pressurizes the core, helping to form the correct crystal structures.

Major purposes of thermomechanical treatment

1- Higher yield strength
2- Improved toughness
3- Good cold forming particularly by bending
4- Lower cost which are possible by using hot-rolled rather than heat treated sections
5- achieving desired properties with fewer amounts of alloying elements

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Thermo-mechanical treatment

Low temperature Thermo-mechanical Treatment (LTHT)

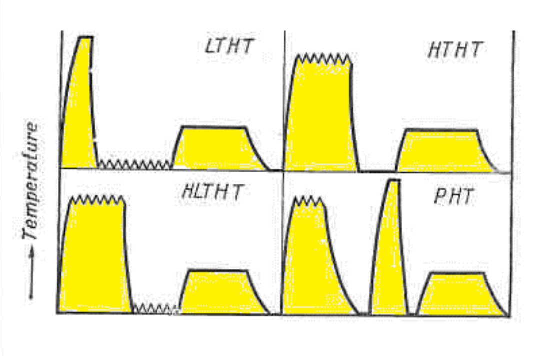
Higher values of ultimate strength and yield strength, but lowers ductility

High-Low temperature Thermo-mechanical Treatment (HLTHT)

High temperature Thermo-mechanical Treatment (HTHT)

Form a supersaturated solid solution with non-recrystallized structure upon hot deformation and quenching

Preliminary Thermo-mechanical Treatment (PHT)



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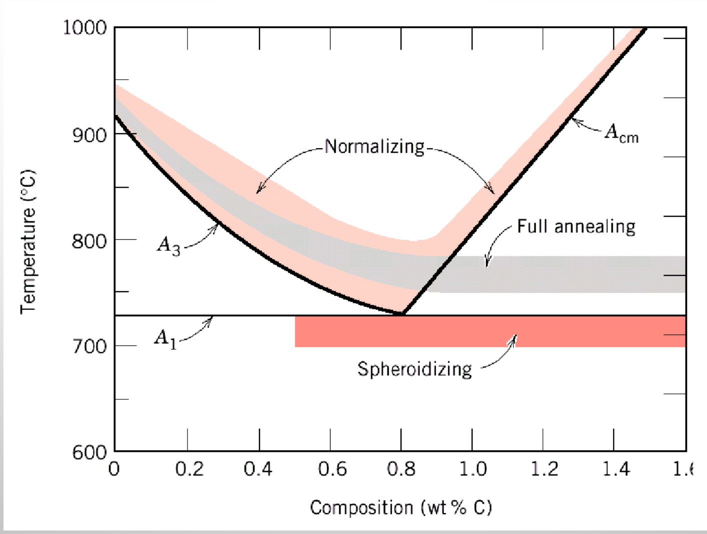
Normalization Vs Full Annealing



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Normalizing

Steels that have been plastically deformed by, for example, a rolling operation, consist of grains of pearlite (and most likely a proeutectoid phase), which are irregularly shaped and relatively large, but vary substantially in size. An annealing heat treatment called **normalizing** is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution; fine-grained pearlitic steels are tougher than coarse-grained ones. Normalizing is accomplished by heating at least 50°C above the upper critical temperature—that is, above for compositions less than the eutectoid (0.8 wt% C), and above for compositions greater than the eutectoid. After sufficient time has been allowed for the alloy to completely transform to austenite—a procedure termed **austenitizing**—the treatment is terminated by cooling in air.

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Full Annealing

A heat treatment known as **full annealing** is often utilized in low- and medium carbon steels that will be machined or will experience extensive plastic deformation during a forming operation. In general, the alloy is treated by heating to a temperature of about 50°C above the A_3 line (to form austenite) for compositions less than the eutectoid, or, for compositions in excess of the eutectoid, 50°C above the *A*1 line (to form austenite and Fe_3C phases). The alloy is then furnace cooled; that is, the heat-treating furnace is turned off and both furnace and steel cool to room temperature at the same rate, which takes several hours.

The microstructural product of this anneal is coarse pearlite (in addition to any proeutectoid phase) that is relatively soft and ductile. The full-anneal cooling procedure is time consuming; however, a microstructure having small grains and a uniform grain structure results.

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Annealed	Normalised
• Less hardness, tensile strength and toughness.	• Slightly more hardness, tensile strength and toughness.
• Pearlite is coarse and usually gets resolved by the optical microscope.	• Pearlite is fine and usually appears unresolved with optical microscope.
• Grain size distribution is more uniform.	• Grain size distribution is slightly less uniform.
• Internal stresses are least.	• Internal stresses are slightly more.

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Heat + chemical Case hardening or diffusion treatment

Requirements:
High temp (> 900 F)
Host metal must have low concentration of the diffusing species
Must be atomic suitability between diffusing species and host metal

Most Common Types:
Carburizing
Nitriding
Carbonitriding
Cyaniding

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Carburizing **(Diffusion Hardening):**

- Pack carburizing most common:
  - Part surrounded by charcoal treated with activating chemical – then heated to austenite temperature.
  - Charcoal forms CO_2 gas which reacts with excess carbon in charcoal to form CO.
  - CO reacts with low-carbon steel surface to form atomic carbon
  - The atomic carbon diffuses into the surface
  - Must then be quenched to get hardness!

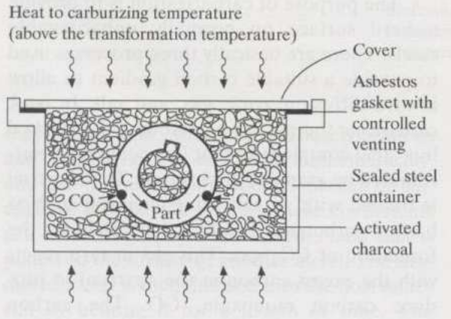

Figure 10–21
Pack carburizing

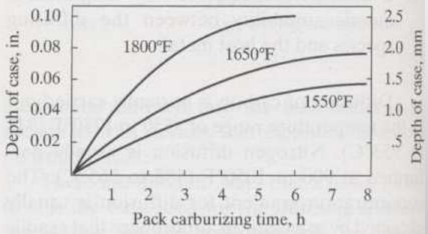

Figure 10–22
Effect of carburizing temperature on case depth
Source: G. M. Enos and W. E. Fontaine. *Elements of Heat Treatment*. New York: John Wiley & Sons, Inc., 1963.

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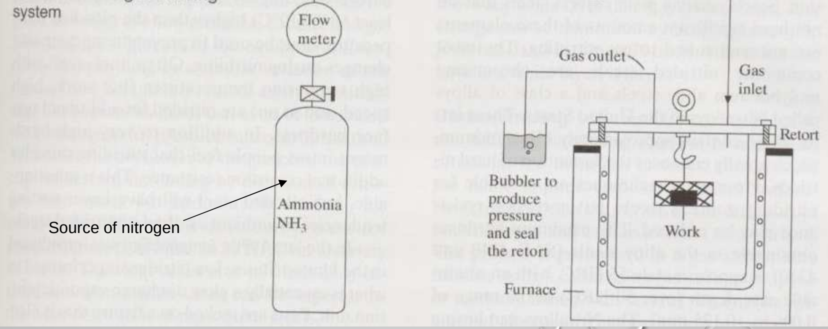
Nitriding **(Diffusion Hardening):**

- Nitrogen diffused into surface being treated. Nitrogen reacts with steel to form very hard iron and alloy nitrogen compounds.
- Process does not require quenching – big advantage.
- The case can include a white layer which can be brittle – disadvantage
- More expensive than carburizing

Figure 10–24
Schematic of a gas nitriding system



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Reduction process: $2NH_3 \rightarrow 2N + 3H_2$

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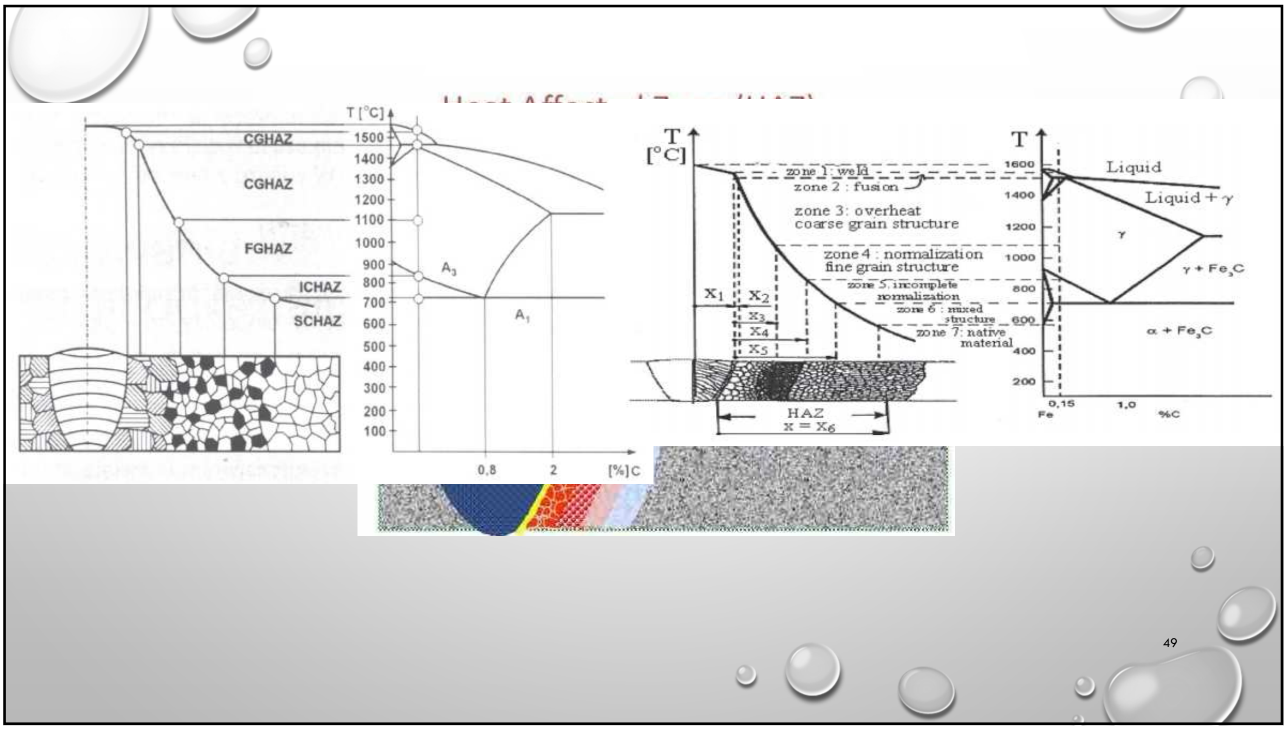
CGHAZ
CGHAZ
FGHAZ
ICHAZ
SCHAZ
T [°C]
A3
A1
0,8
2
[%]C
T
[°C]
zone 1: weld
zone 2 : fusion
zone 3: overheat
coarse grain structure
zone 4 : normalization
fine grain structure
zone 5: incomplete
normalization
zone 6 : mixed
structure
zone 7: native
material
HAZ
Liquid
Liquid + γ
γ
γ + Fe3C
α + Fe3C
%C

49