Introduction to Engineering Metallurgy

- Extractive metallurgy: Extraction to get the metals from the raws, and then the refining.

*will use the already refined metals.

A Course

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Chapter One

Structure of Metals and Alloys

- **Introduction**

- Physical metallurgy is concerned with exploring and utilizing the relationships between the structures of metals and alloys and their engineering properties.

- Engineers are may be interested in several types of properties such as;

- Physical properties
- Chemical properties → [corrosion resistance].
- Electrical properties
- Mechanical properties

*Mechanical metallurgy.

- In this course emphasis would be given to mechanical properties, which include:

- Strength
- Hardness
- Ductility
- Toughness and
- Percent elongation and
- Corrosion behavior.

- The properties of an engineering alloy would normally determine its "***performance***" under certain working conditions including:

- 1. Loading (type of load, magnitude of load, etc.) and
  - → Static / Dynamic
- 2. Working environment (such as working temperature, corrosiveness, etc.)

- The main factor that normally determines these properties is the ***structure*** of the metal or alloy (at different structural levels, as will be seen later)

- In addition, the structure of a certain metal or alloy is normally a result of both the ***chemical composition and the processing route*** it has been through; both mechanical (such as forming, rolling, forging, etc.) and thermal (such as welding, heat treatment, etc.).

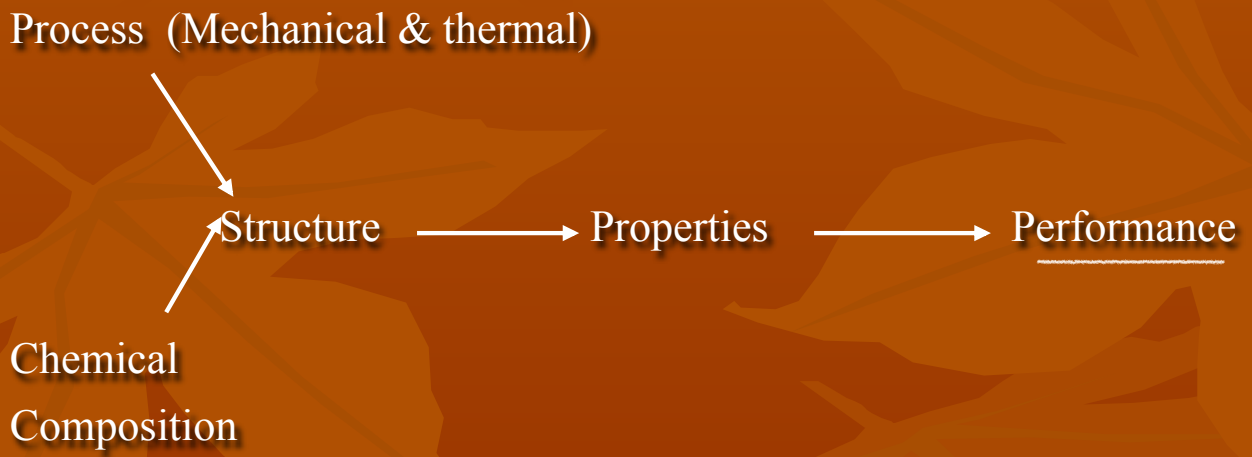
Composition: Gradeianess inside the alloy.

processing route: 1. mechanical
2. thermal.] ⇒ or Both [thermomechanical processing].

* mechanical (Cold working).
* thermal (Hot working).

hot deformation.

Area of interest of physical metallurgy



Levels of structure

- Structure can be defined as the

"***Arrangement of internal building units***".

- In general there are four levels of structure as follows:
  1. Sub-atomic
  2. Atomic
  3. Microscopic level
  4. Macroscopic Level.

Structure : Atom
Building unit : -electrons
-neutrons.

- ***Sub-atomic level***: this level represents the arrangement of electrons, neutrons and protons within individual atoms.

Atoms as building unit ,

- ***Atomic level***: this level represents the arrangement of atoms within special building units known as unit cells. It is also known as "***Crystal or lattice structure***".

Grain level.

- ***Microscopic level***: this level is concerned with structural features which can be viewed by the aid of a microscope (either optical or electron microscope). It is most commonly known as the "***Microstructure***"

- ***Macroscopic level***: this level is concerned with structural features which can be viewed by the naked eye or by the aid of low magnification microscope (normally below x25),. It is normally referred to as "***Macrostructure***"

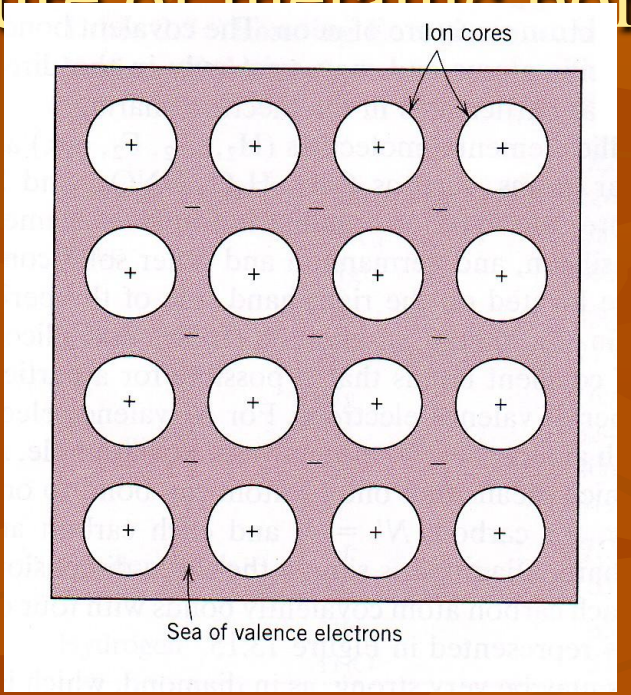
- The most important two structural levels pertaining to mechanical properties are the second level (crystal structure) and the third level (the microstructure)

  → atomic / Lattice.

- Before elaborating on the different types of structure it is beneficial to look at the unique case of bonding in metallic materials

*

Nature of metallic bonding



* metalic bonding.

Schematic illustration of metallic bonding

- Good thermal conductivity
- Good electrical conductivity
- Normally fail in a ductile manner and show some permanent (plastic) deformation before fracture.

Crystal Structure

In a crystalline or polycrystalline solid the crystal structure is normally the result of solidification from the liquid state into the solid state

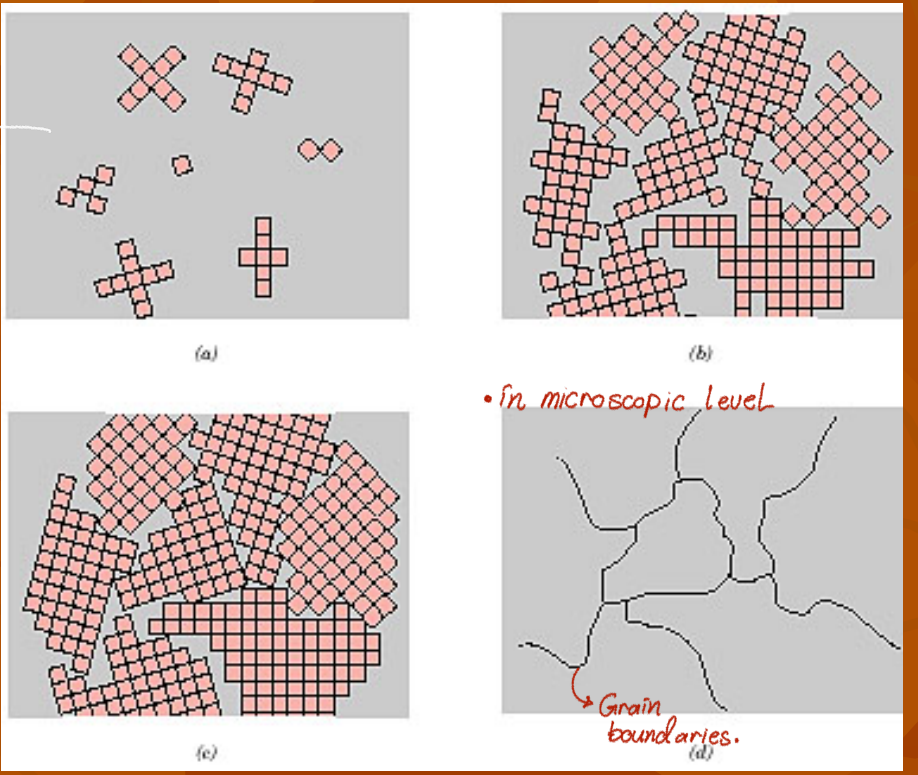
solidification proceeds by the following:

- The formation of solid nuclei "***crystals or grains***" at various positions with random orientation

• Growth during Solidification

□ : unit cell (Lattice).

* atomic Level.



– Lattice structure (crystal structure).

• In microscopic level

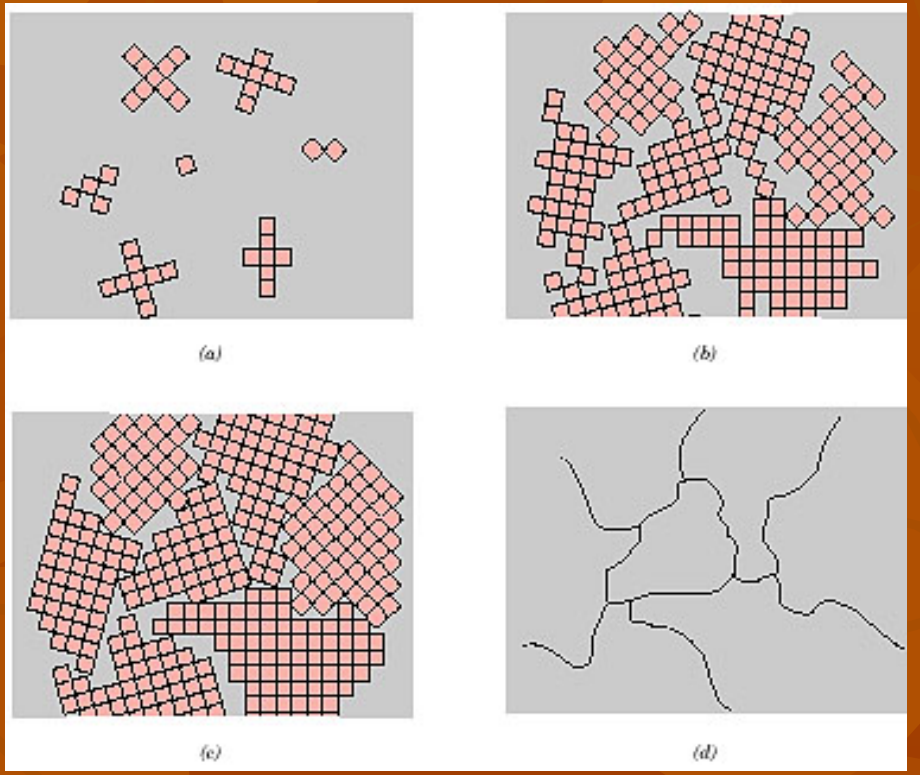
Grain boundaries.

Grain Structure.

*microstructure.

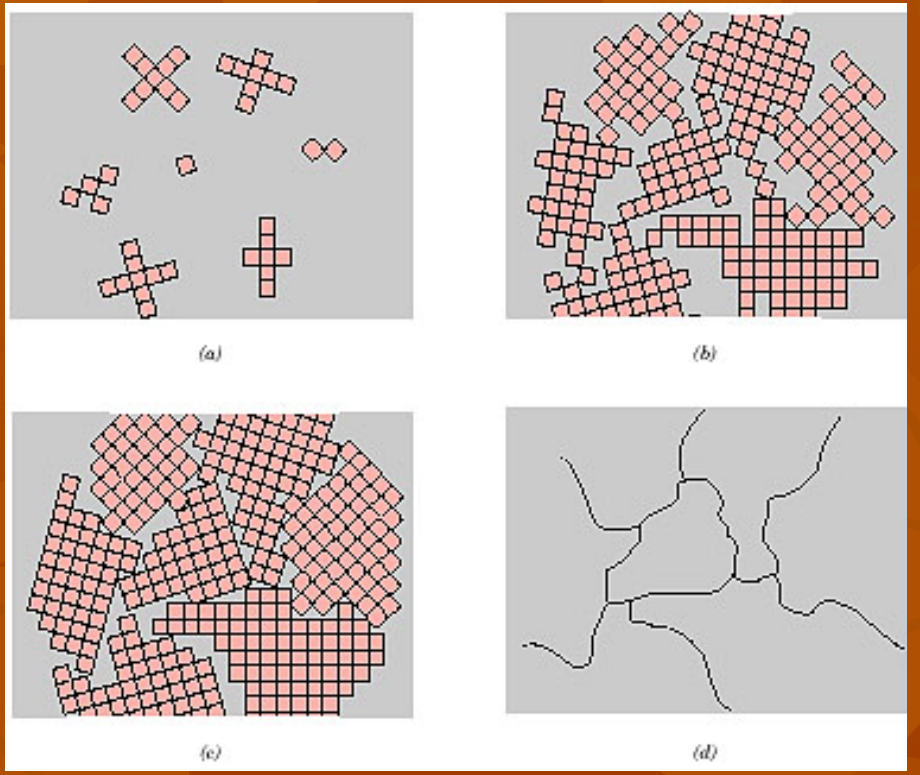
- Growth of the small nuclei by the successive additions of atoms from the surrounding liquid upon cooling

- Upon completion of solidification the crystals or grains impinge (اصطدام) on each other forming what is known as "***grain boundaries***" at boundary mismatch locations


(a)
(b)
(c)
(d)

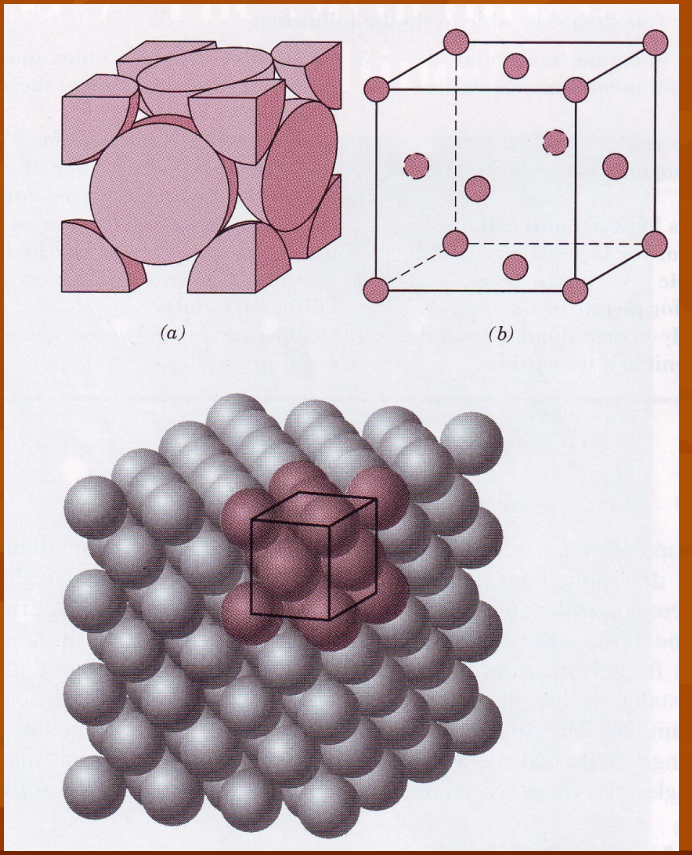
Crystal structure or lattice structure refers to “ ***arrangement of atoms in a three dimensional repetitive array over long atomic distances inside a crystal***”.

These three dimensional building units are known as “***unit cells***”


(a)
(b)
(c)
(d)

Main types of crystal structure in metals

Face-Centered-Cubic (FCC) Crystal Structure



- In this type of lattice structure the unit cell has a cubic geometry with atoms located on the corners of this cubic cell and on the centers of all the six cube faces

- Typical metals having this lattice structure include gold**, silver, copper, nickel, aluminum and lead**.

- The edge cube (a) known as "***lattice parameter***" and the atomic radius (R) are related through the relationship:

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

- In an FCC unit a total of four atoms is contained within each unit cell (one eighth of the eight atoms on the corners plus one half of the six atoms on the faces).

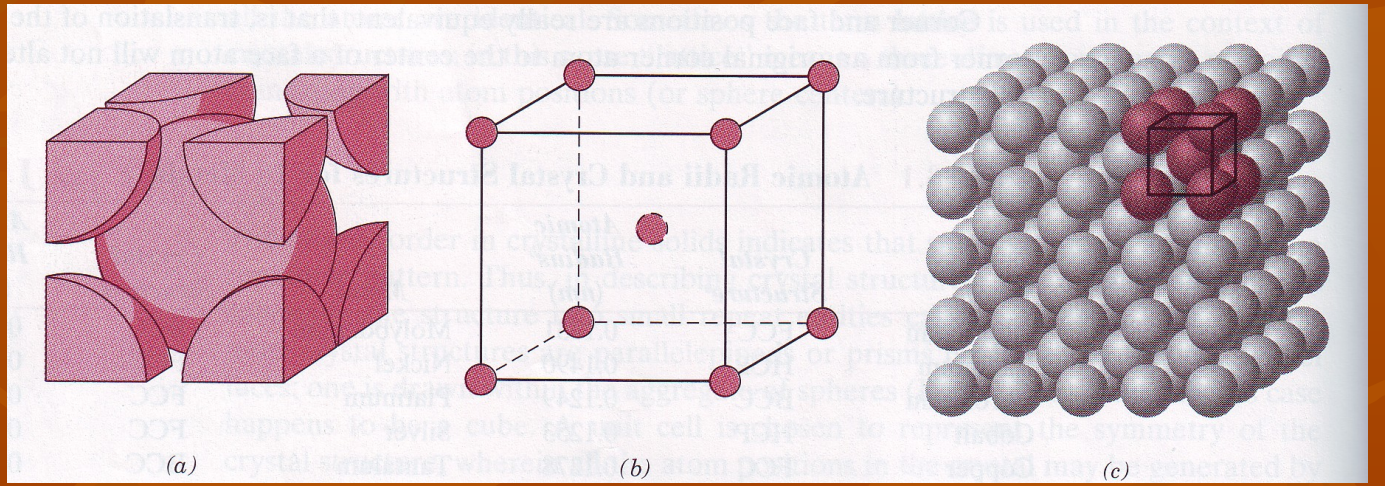
- The ***coordination number*** (number of nearest neighbors or touching atoms) in the FCC unit cell is equal to 12

- The ***atomic packing factor (APF)***

- *APF = (volume of atoms in the unit cell)/(total unit cell volume)*

- In FCC lattice the APF is equal to 0.74 or 74%

Body-Centered-Cubic (BCC) Crystal Structure



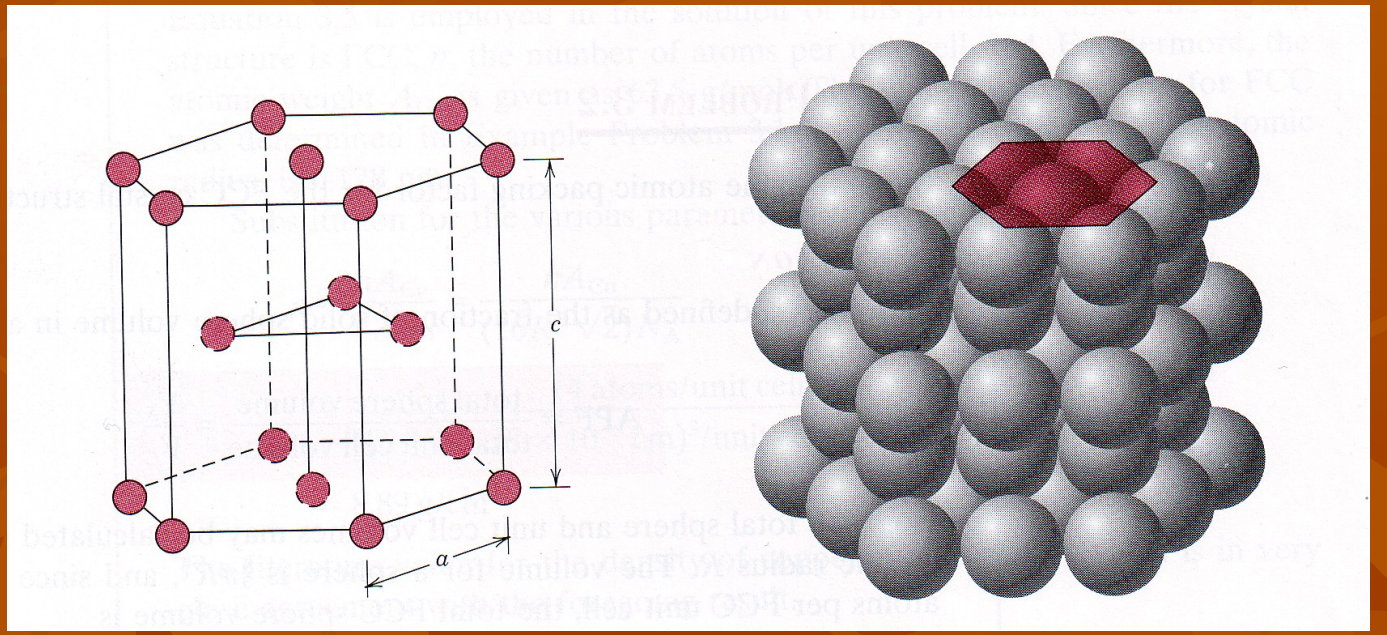
In BCC crystal structure, eight atoms occupy cube corners in addition to one atom occupying the center of the cube.

Typical metals having this lattice structure include **iron, chromium, molybdenum and tungsten**.

Relevant information to the BCC structure are:

- **Coordination number = 8**
- **APF = 0.68 or 68%**

Hexagonal Close-Packed (HCP) Crystal Structure



- In the HCP crystal structure, the top and bottom faces of the unit cell consist of six atoms that form regular hexagons and surround a single atom in the center.
- Another plane situated between the top and bottom plane provide extra three atoms

- The coordination number and APF for the HCP unit cell are the same as those of the FCC, i.e., **12 and 74 %**, respectively.

- HCP unit cell has two lattice parameters; “a & c” representing the short and long unit cell dimensions, respectively. Typical metal having this lattice structure include; **magnesium, titanium and zinc**.

Crystallographic Directions

- A crystallographic direction is defined as "***a line or a vector between two lattice points*** "
- Each crystallographic direction is normally defined be a set of three directional indeces
- The three directional indices of crystallographic directions can be determined as follows:

- A vector of convenient length is positioned such that it passes through the origin of the coordinate system.

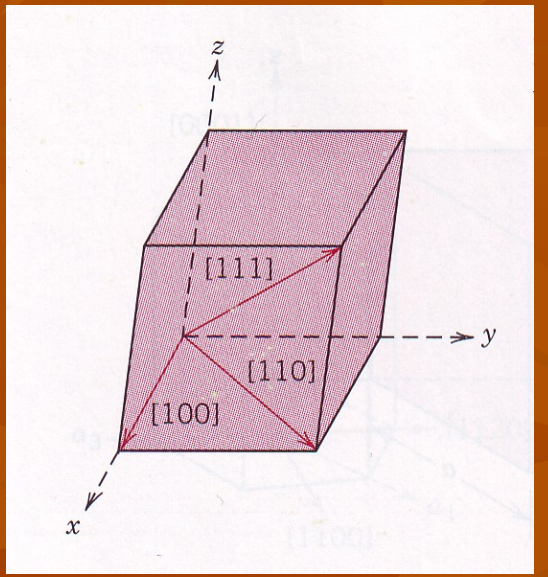
- In case the vector does not pass through the origin it can be translated throughout the crystal lattice without alteration if parallelism is maintained.

- The length of the vector projection on each of the three axes is determined in terms of lattice parameters (a, b and c).

- These numbers are multiplied or divided by a common factor to reduce them to the smallest integer values.

- The three indices, not separated by commas, are enclosed in square brackets, thus [u v w]. the u, v, and w values represent the x, y and z projections, respectively.

- Negative coordinates are represented by a bar over the particular index (indices).



The [100],[110], and [111] directions within a unit cell

Crystallographic Planes

- Crystallographic planes (except in the hexagonal unit cell) are represented by three indeces known as **Miller indices (h k l)**

- Any two planes parallel to each other are equivalent and have identical Miller indices
- The three Miller indices of any crystallographic plane can be determined as follows:

- If the plane passes through the selected origin, either another parallel plane must be constructed or a new origin must be established at another unit cell corner
- At this point the plane either intersects or parallels each of the three axes.
- The length of the planar intersect for each axis is determined in terms of the lattice parameters (a, b and c).
- A plane that parallels an axis is considered to have infinite intersect

- The reciprocals of these intersects are taken
- If necessary, these three numbers (indices) are reduced to the smallest integer values
- The integer indices, not separated by commas, are enclosed within parentheses such as (h k l).

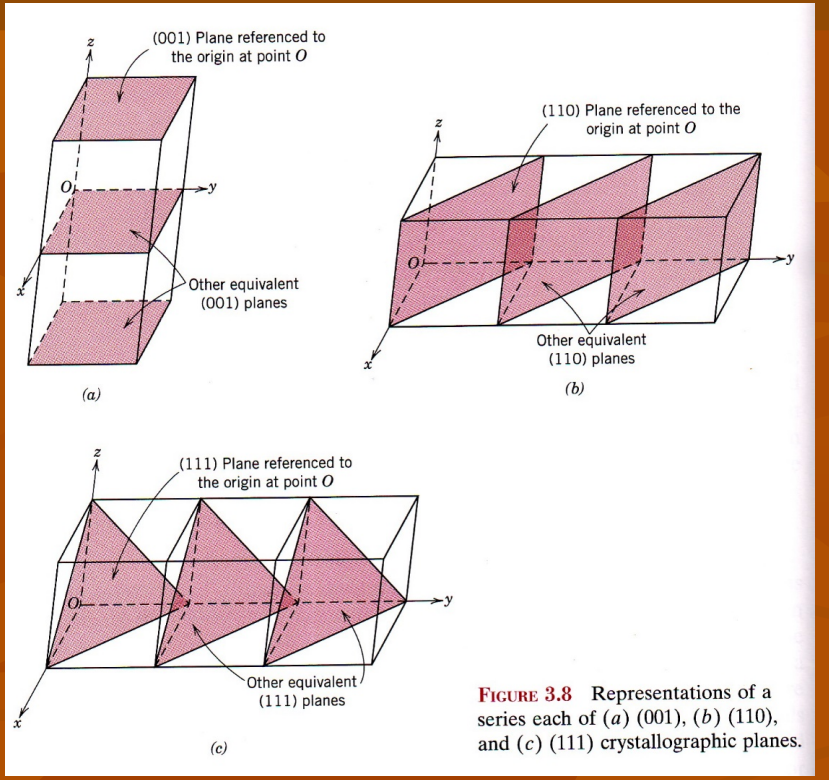


FIGURE 3.8 Representations of a series each of (*a*) (001), (*b*) (110), and (*c*) (111) crystallographic planes.

Representation of a series of (a) (001), (b) (110), and (c) (111) crystallographic planes

Imperfections in solids

- A defect-free solid is considered to be an idealized condition which does not exist in reality.
- All solids contain large numbers of defects or imperfections.
- As a matter of fact many properties of metallic materials are greatly sensitive to this deviation from the idealized condition - not necessarily adversely.

*properties depends on defect not in negative ways.

* Defect could improve properties.

- A crystalline defect or imperfection can be thought of as "A ***lattice irregularity having one or more of its dimensions on the order of an atomic diameter***".

at least one.

② atomic Dim. = $\frac{\pi}{4} D^3$, - two atomic diameter

- Classification of crystalline defects is based upon dimensionality as follows:

① irregularity: when a continuance arrangement of lattice structure is interrupted in certain point.

1. point
2. Linear
3. Interfacial

- each lattic has uniform arrangement & Direction with same size & Orientation



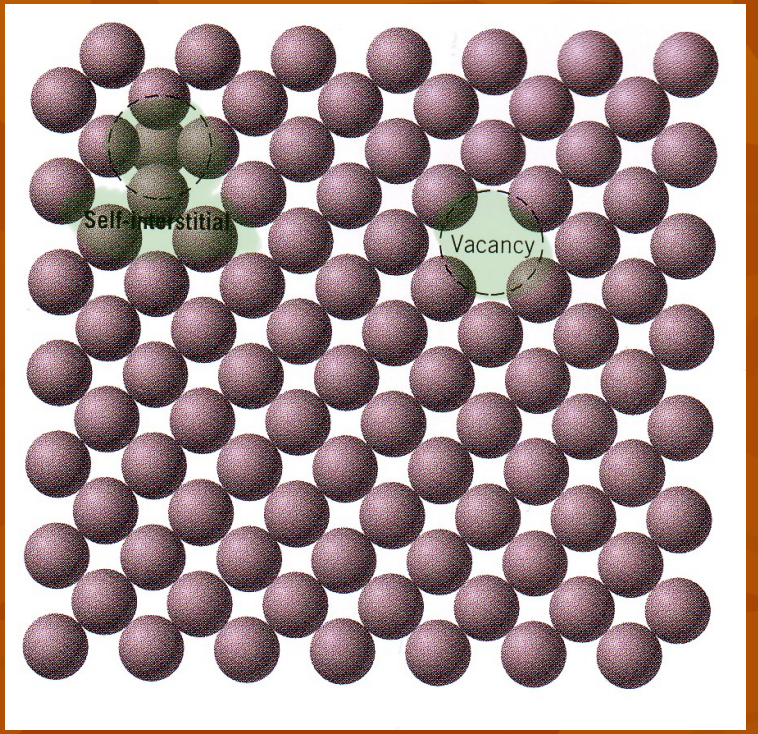
Point defects

- This category contain two major types of defects

- ***Vacancy*** or vacant lattice site, one normally occupied from which an atom is missing.

- ***Self- interstitial*** is an atom from the crystal that is crowded into an interstitial site (a small void space that under ordinary conditions is not occupied)

* Self ⇒ because it's from the same type of metal.



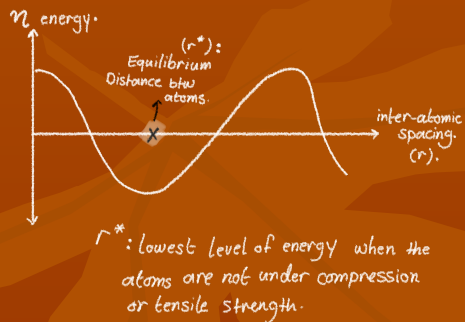
Two-dimensional representation of vacancy and a self-interstitial

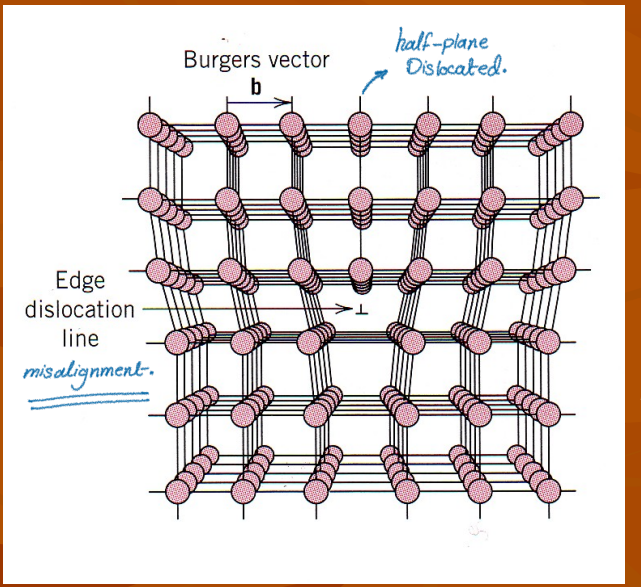
Linear defects

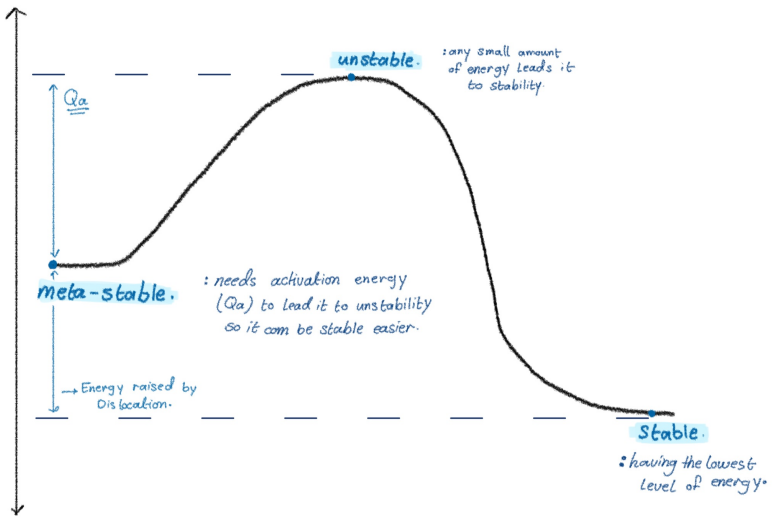
- The main type of linear defects is the presence of "***dislocations***" within the crystal.
- Dislocations are "***linear or one-dimensional defects around which some of the atoms are misaligned***"
- There are two types of dislocations:
  - Edge
  - Screw

Edge Dislocations

- These are linear defects which center around the line that is defined along the end of an extra half-plane (***dislocation line***)







* All systems seek the lowest level of energy. (Equilibrium.),

→ 3 types of systems : - unstable
- meta-stable
- Stable.

* without the dislocation the energy level is always stable.

→ so the existance of Dislocation raises the energy level from stable to meta-stable.

• Less force required, weakening the material,

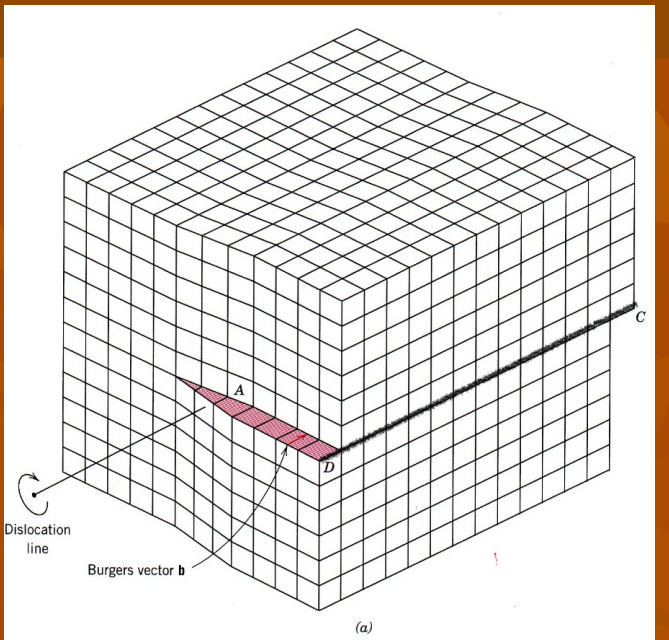
• plastic deformation at the meta-stable Level. (in case of Dislocation).

Screw Dislocations

↳ Force with moment.

This type of dislocation can be thought of as being formed by a shear stress applied to produce the distortion ;

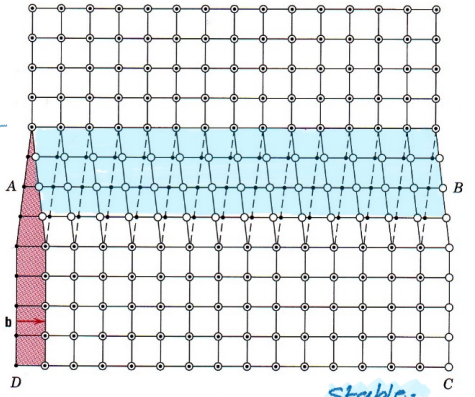
- The upper front region of the crystal is shifted one atomic distance to the right relative to the bottom portion



(a)

Stable.

high level of energy.



Stable.

(b)

Shifted by one atomic Distance.

- Dislocations are considered to play a major roll during the phase of plastic deformation.

the role of the Dislocations is to minimize the yield strength by raising the energy level from the total;

– wackening the material, energy ↑,
ability to move ↑,
ability of plastic deformation ↑.

Yielding (unstable point).



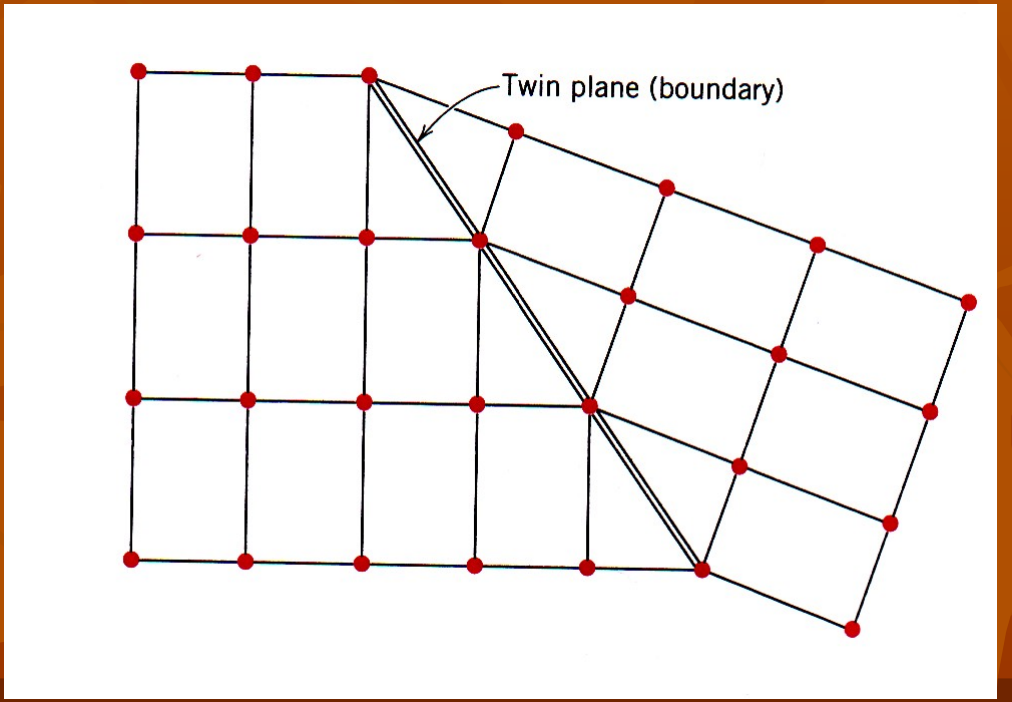
Interfacial defects

Surface defect :

- These contain three major types:
- ***External surfaces*** → End of innersurface regularity.
- ***Grain boundaries*** → no matching btw Grains.
- ***Twin boundaries***. Twin boundaries are special type of grain boundaries across which there is a specific mirror lattice symmetry

- Twin boundaries form as a result of mechanical forming (mechanical twins) and/or during heat treatment (annealing twins).

* Common plane btw 2Grains, but Different Orientation (partially linked).



Lec (1)

* Alloys are used when the material mechanical properties are weak.

Lec (2)
2/3.

Chapter Two
The Formation of Alloys

- Even though pure metals have some appealing properties such as high electrical and thermal conductivities, their mechanical properties generally are weak.

wanted,

Thus alloying is carried out to either ***enhance existing properties*** or to ***introduce some new properties*** such as corrosion resistance.

* Two Levels of requirements: — to produce alloys btw 2 or more metals.

→ 100% Solubility.
— one Single homo. Liquid solution.

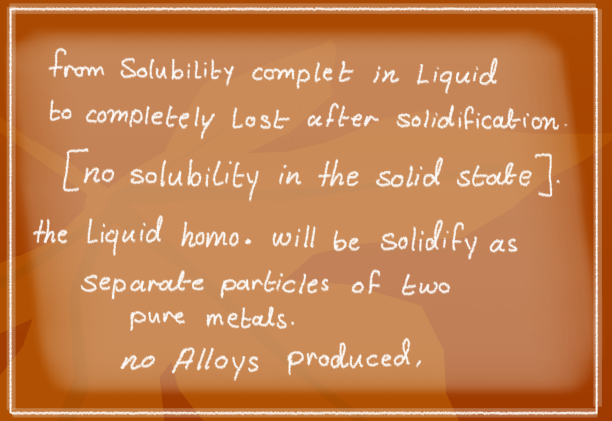
- must, Main requirement: ***complete solubility in the liquid state***, i.e. the two metals are mutually soluble in each other when in the liquid state.

مش شرط يصير (Alloys) لكن في إمكانية.

- Upon solidification there are three possible scenarios:

1. Solubility is completely lost.
2. completely or partially retained.
3. intermediate phase.

- Solubility is completely lost in the solid state, therefore, the liquid solidifies as separate particles of two **pure metals**



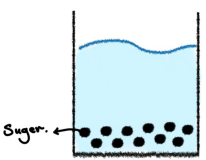
- Solubility is completely or partially retained in the solid state resulting in a single ***solid solution (SS)*** or a mixture of two solid solutions, respectively

Level (2)

- Completely retained: → Single solid solution (SS).
  one homo. Liquid Solidify as one homo. Solid solution.
- partially retained, → mixture of two solid solution. (0 – 100)%
  (A) in (B) & (B) in (A).

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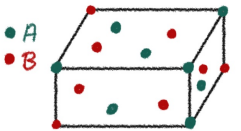
* Solid Solution:



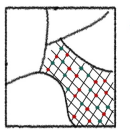
1. if suger within the solubility:
   - homo. liquid solution. (Suger into water).
   Single liquid solution.

2. more Suger, with/or decreasing temp.
   - crystals. (in solid state).
   - solid solution of water into Suger (not pure suger).

1 Completely retained.

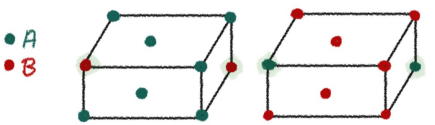


- Single Solid Solution A+B.
- (0 – 100)%.
  ↳ in the same crystal



- Atoms of (A) & (B) in the same lattice.

2 Partially retained:



* from Zero up to 100% the rest will be in the other crystal

- 2 solid solution:
  - A in B.
  - B in A.
- no pure metal.
- not always (A in B) solubility equal (B in A) Solubility.
  the sum = 100%

case (3):

- As solidification proceeds the two metals give rise to the formation of what is known as "***intermediate phase***" or "***intermetallic compound***".

↳ General term.

↳ Extreme phase of intermediate phase.

* Starting from solid solution to intermetallic compound.

— in solid solution the solvent keeps its structure.

phase : 1. pure metal
2. Solid Solution
3. intermediate phase.

- Each of the three types mentioned above resulting from solidification is referred to as a "***phase***".
- Phase can be defined as " ***A single homogeneous substance***".
- In a binary solid no more that two phases can co-exist:

binary alloys : consist of only two pure metals.
in solid state.
2 phases, could be one phase (ss)

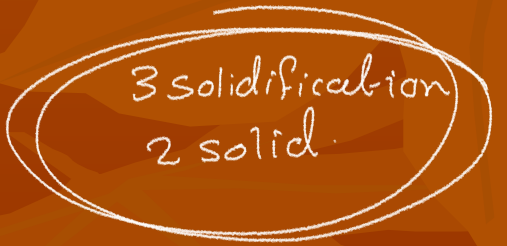
- Two pure metals
- A single solid solution
- A mixture of two solid solutions
- A single intermediate phase
- A mixture of two intermediate phases
- A solid solution and an intermediate phase

and so on

Solid solutions

- A solid solution is formed when two metals which are mutually soluble in each other in the liquid state remain completely or partially soluble in each other in the solid state.

- There are two types of solid solutions



Interstitial solid solutions

- This type of solid solution can be formed when the atoms of the added element (***solute***) are very small compared to those of the parent metal (***solvent***), thus enabling them to fit into the interstices or interstitial sites of the solvent metal

* the only condition is the size of the solute.

تعني أصغر الذرات.

- Interstitial solid solutions can form not only as a result of solidification[1] but also when the parent metal is in the solid state[2].

Diffusion.

- A common example is plain carbon steel, which is basically an interstitial solid solution of carbon into iron

in the Solid state.

*Diffusion depends on,
-Difference in concentration
- high temp.

تعويض أو إحلال.

Substitutional solid solutions

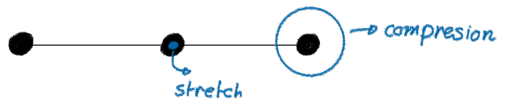
- In this type of solid solution the atoms of the solvent are replaced by atoms of the solute metal in the lattice sites.
- Substitutional solid solutions can be either ordered or disordered.
- There exist some preferred conditions for substitutional solid solutions to occur:

- Size factor (the difference in atomic radii should be less than 14 %)
- Electrochemical properties should be similar (the two metal should be in close proximity in the periodic table)
- The two metal having the same crystal structure (FCC into FCC and so on) → نفس عدد الروابط داخل الذرة

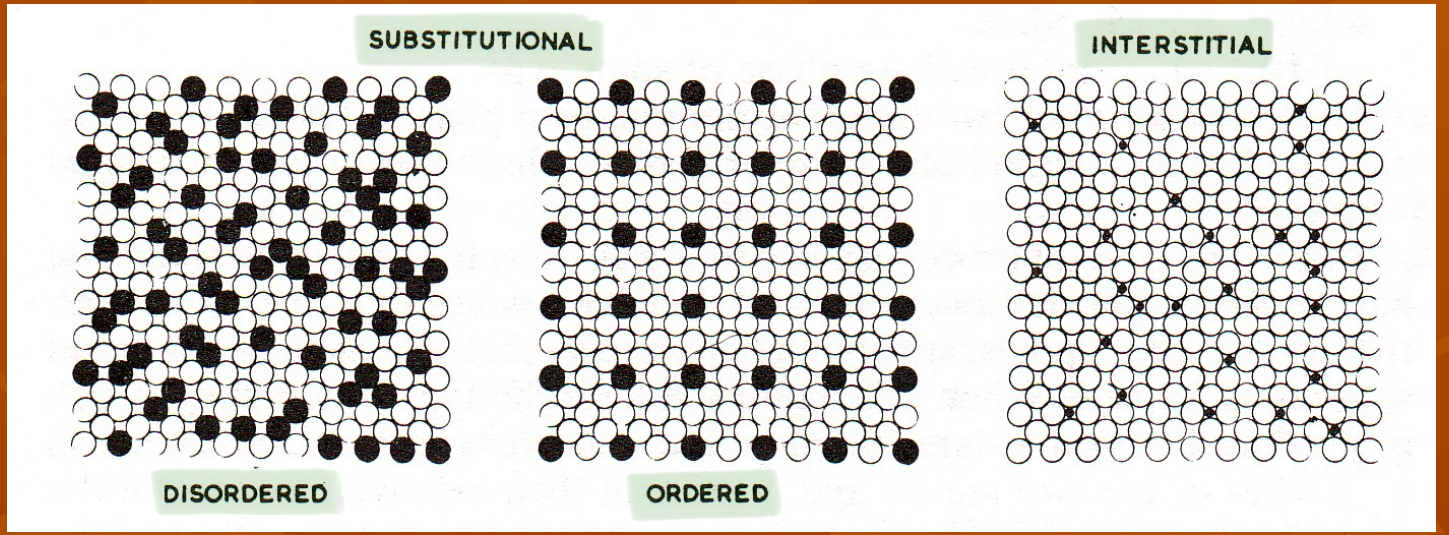
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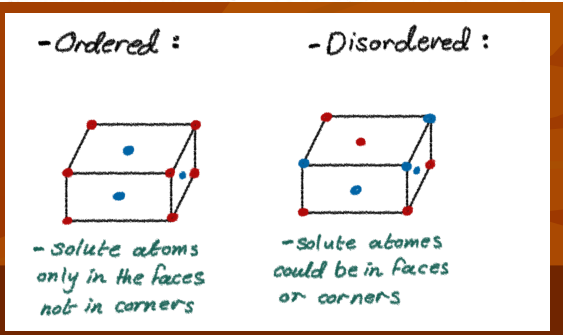
* Better chance to get solid solution when the atoms are stable

Size factor: – if more than 14% there will be no substitutional solid solution or it will not be stable. because the energy will be high.



* related to the value of (r^*) → Directly affect the energy level.


SUBSTITUTIONAL
INTERSTITIAL
DISORDERED
ORDERED


-Ordered :
-Disordered :
- solute atoms only in the faces not in corners
- solute atomes could be in faces or corners

Intermediate phases

- In contrast to solid solutions intermediate phases result when the two metals have divergent electrochemical properties, in which case a strongly metallic element such as magnesium would combine with weakly metallic element such as tin forming an intermetallic substance Mg_2Sn

* Solid solution → wide range.
* intermetallic → Fixed range.

middle phase btw solid solution & intermetallic solution.

- Solid : (%) of solute (0 – 100 max solubility)%
- intermetallic : has a fixed ratio (chemical compound).
- intermediate : its extreme is the intermetallic · but with range : 1. Small range 2. not always fix

Ni_3Al : actual range Ni (2.6-3.2) Al (0.85-1.1)

- Phases between the two extremes of solid solution and intermetallic compounds are termed intermediate phases having graded properties depending on the degree of association. → physical & chemical.

→ from Solid Sol. properties to the intermetallic prop. (Btw).

- Intermediate phases have several types including

→ chemical association: عناصر تركب على بعض

Solid Solution عناصر بعاد عن بعض

intermediate.

* the Structure in intemediate is variable, but in the S.S it has the Solvent's structure.

as an extreme phase

Intermetallic compounds

- These are phases in which laws of chemical valency are apparently obeyed such as in Mg2Sn, Mg2Pb and Mg3Bi

(Fixed)

Electron compounds

- In these compounds there is a fixed ratio between the number of total valence bonds of all atoms and the total number of atoms. According to this ratio three types of structures exist:

$$\text{ratio} = \frac{\text{Tot. valence bonds.}}{\text{Tot. number of atoms.}}$$

- β structures (ratio of 3/2 or 21/14) such as in CuZn, Cu3Al and Ag3Al.

+2 +1 +2

3/2 4

- γ structures (ratio of 21/13) such as in Cu5Zn8, Cu31Sn8 and Ag5Al3.

- ε structures (ratio of 7/4 or 21/12) such as in CuZn3, Cu3Sn and AgCd3.

→ as an intermediate phase (not fixed ratios).

Size factor compounds

- These are intermediate phases in which compositions and crystal structures arrange themselves in such a way as to allow the constituent atoms to pack themselves closely together.

- These include MgNi2, MgCu2, TiCr2 and different types of metal carbides

⊡ Types of intermediate phase:
1- intermetallic
2- electron
3- Size factor

⊡ Composition: the concentration of the solute in the solvent.

⊡ Closely packed:
Ex: higher in FCC than BCC (better to have closely packed structure.).

بالسلايدات ؟؟

→ the concentration (ratio) of the first metal to the second one (solute to solvent) allows the structure to be closely packed.

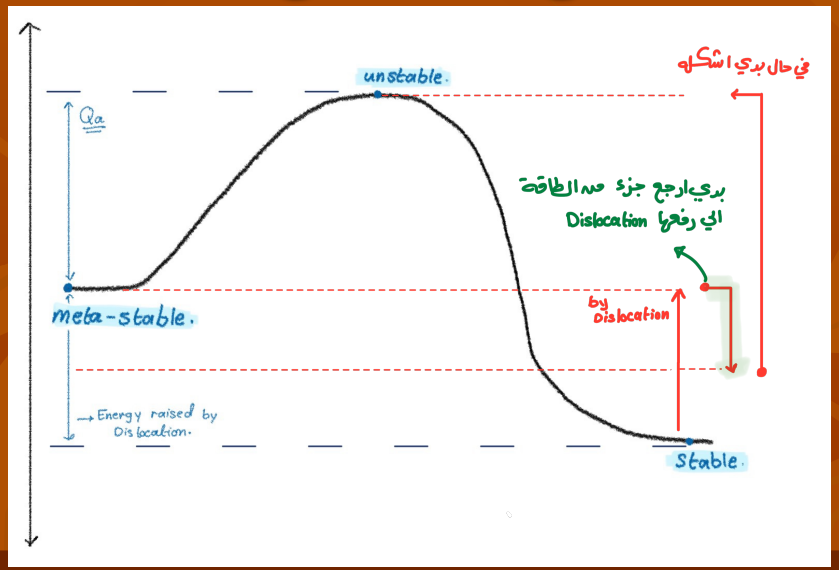
كيف الـatoms بترتب حالها ؟

* Strength: materials resistance to deformation when it's Subjected to load.

→ plastic deformation is based on the movement of atoms (Dislocations).

↳ Higher energy because of the stretching & compresion.

Strengthening mechanisms in alloys



. alloys used to enhance some properties.

- espcially the mechanical (Strength).

لازم ارجع جزء من الطاقة اي رفعتها (بعكس عملية جزئيًا).

- more stability
- hard to deform.

بدي ارجعها حتى ال stable اصبح بزيد الstrength

$$Energy \propto \frac{1}{strength}$$

?

Solid solution strengthening

Strengthening :

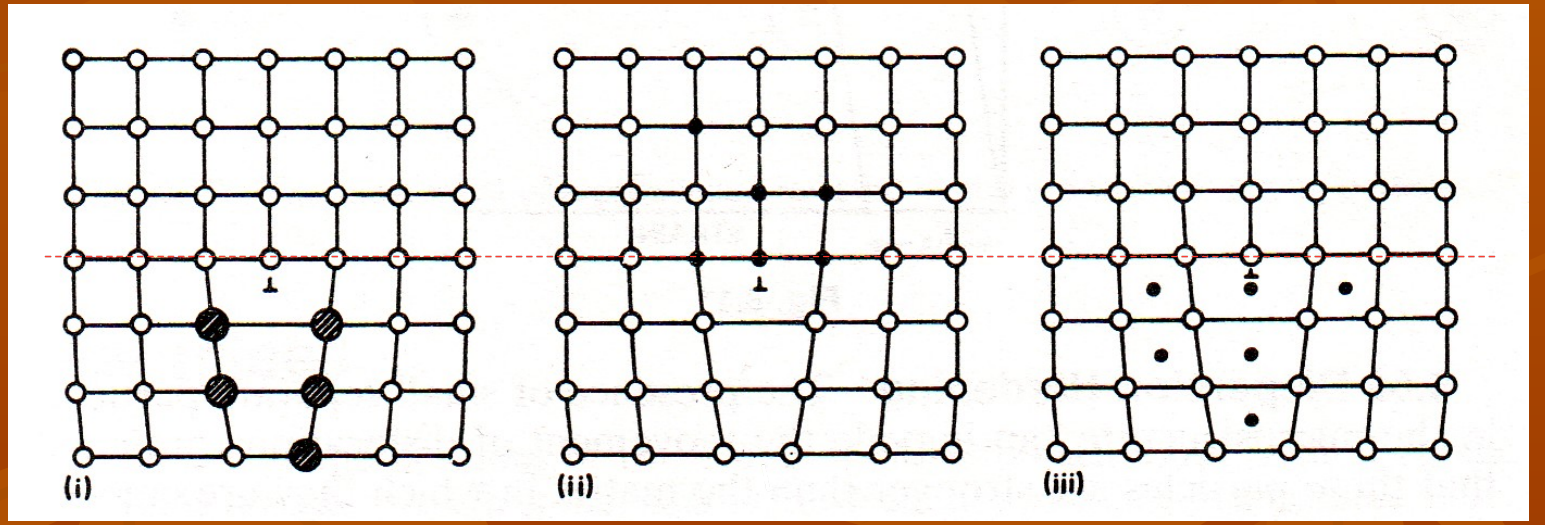
method (1) :

Solid Solution

1. Substitutional.
2. interstitial.

case (1)

case (2).



- Large atoms in stretching, (r^*)↓ → Energy↓
- under the Dislocation

* small atoms for compresion.

- above the Dislocation.

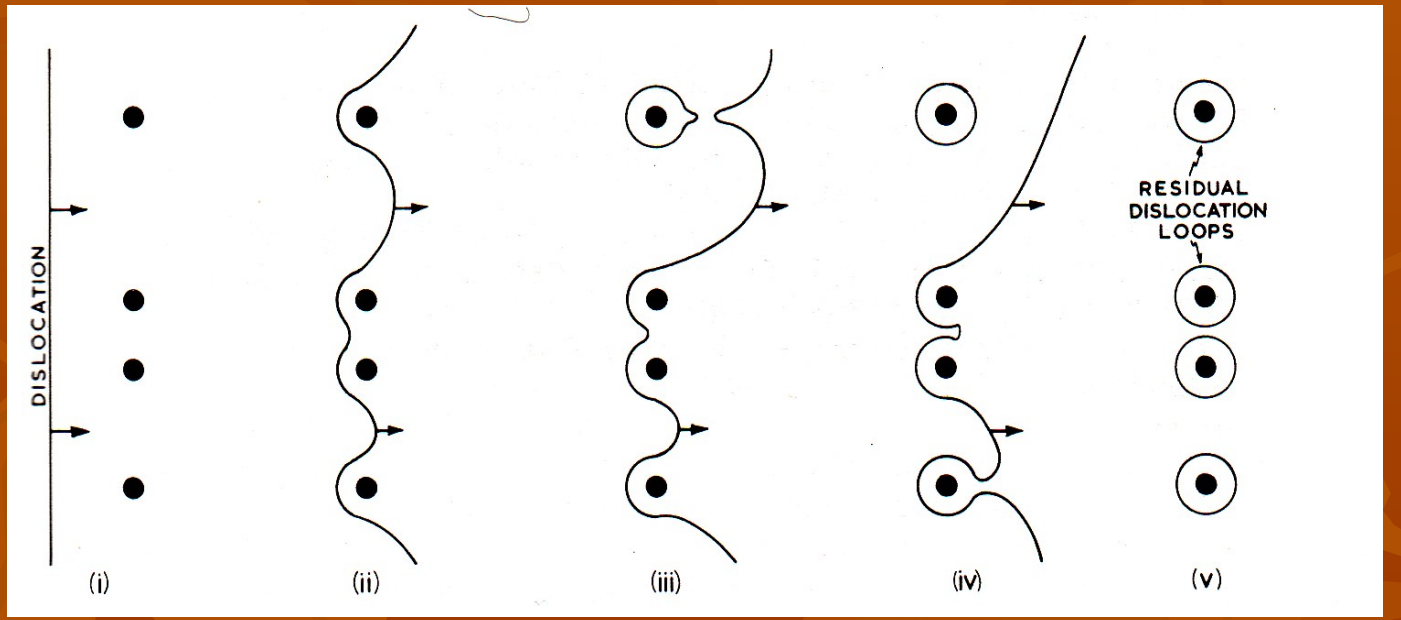
- Small atoms for stretching,
- because of its compresive effect.

- In substitutional solid solutions, large solute atoms can occupy sites where the lattice is being stretched, while small solute atoms can occupy sites where the lattice is compressed.
- This decreases the lattice distortion and reduces the energy level and, hence impeding the movement of dislocations.

small sized atoms.

- In interstitial solid solutions, solute atoms would normally occupy sites where the lattice is being stretched and having similar effect on movement of dislocations.

Dispersion strengthening



method (2):

- To disperse an Extremely hard particles (Fine particles) distributed within the melt.
  - melting point of the particles is higher than the matrix.
    ∴ higher hardness.
  - reduce the movement of Dislocations.

- The presence of small particles in the microstructure can impede the movement of dislocations provided that the particles are stronger than the matrix in which they are embedded

- The degree of strengthening depends on:
- The particle size
- Inter-particle spacing
- Type of particles (hardness); and
- The volume fraction (content) of the strengthening particles

Chapter Three

Thermal Equilibrium Diagrams (Phase Diagrams)

- Thermal equilibrium diagrams are "***charts showing the relationships between chemical composition, temperature and phases present***".

- Equilibrium means **a state of balance**, i.e., the system (alloy) is allowed enough time to reach this state of equilibrium normally through slow cooling rates.

– Composition :
the concentration of the solute in the alloy.

this phase diagram can only be applied for slow cooling. (Equilibrium).
not for the fast cooling (non-Equilibrium).

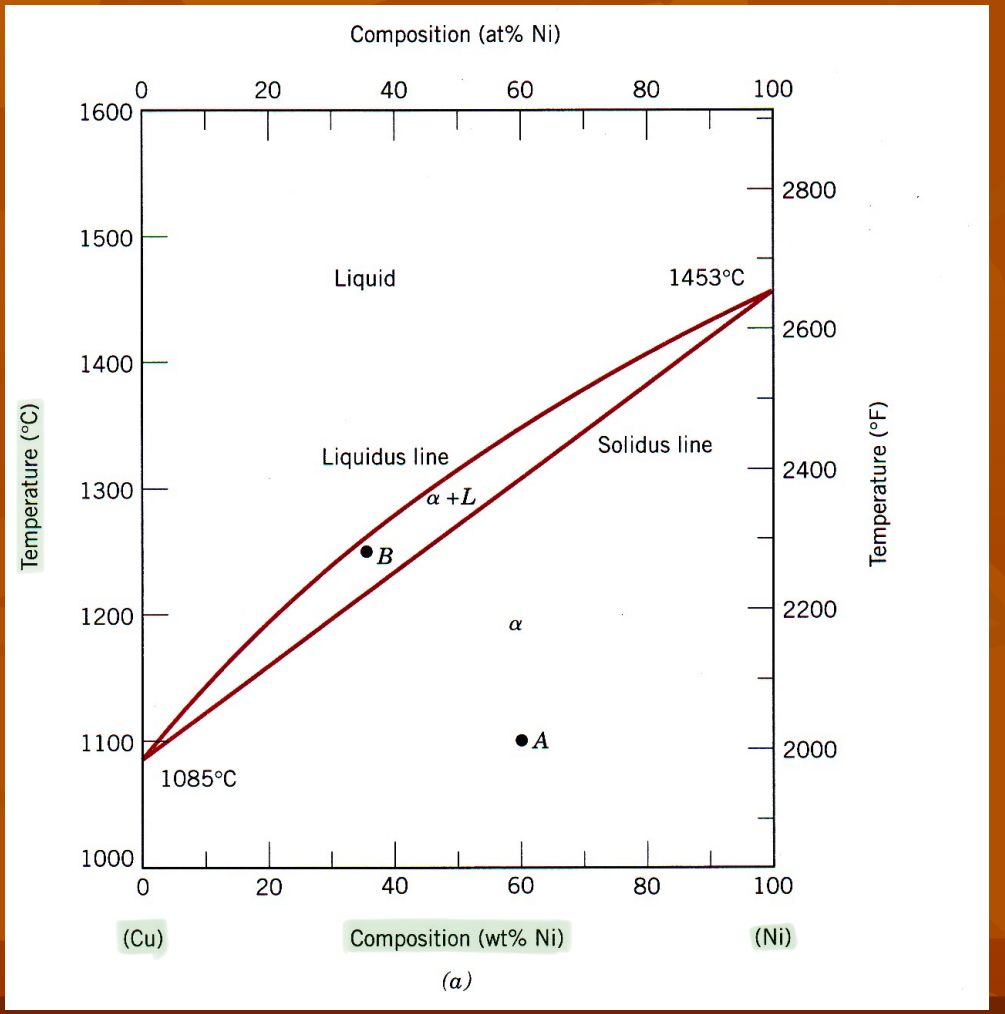
- Several types of binary phase diagrams exist depending on the relation ship between the two components (alloying elements) such as solubility limits, electronegativity properties, atomic size, etc.

يكون متماثل
(أحادي الشكل).

Binary (iso)morphous system

- The term isomorphous indicates **complete solubility in both the liquid and solid states**

Solid Solution ?


Composition (at% Ni)
0
20
40
60
80
100
1600
1500
1400
1300
1200
1100
1000
2800
2600
2400
2200
2000
Temperature (°C)
Temperature (°F)
Liquid
1453°C
Liquidus line
Solidus line
α +L
B
α
A
1085°C
(Cu)
Composition (wt% Ni)
(Ni)

(a)

- The reason for this complete solubility in the solid state comes as a result from the fact that both Ni and Cu have the same crystal structure (FCC), almost identical atomic sizes and electronegativities.

- In this diagram several features can be noticed

no limit for solubility btw Ni & Cu (0 – 100)%

(1)

(2)

(3)

جنب بعض في الجدول الدوري .

- The temperature is plotted on the vertical axis while the composition (in terms of solute percentage) is plotted on the horizontal axis.

- There exist three main areas in the diagram (known as **phase fields**) of **liquid, α + liquid and α**, where liquid is a homogenous liquid solution of both Cu and Ni and α is a homogenous solid solution of both Cu and Ni with an FCC crystal structure

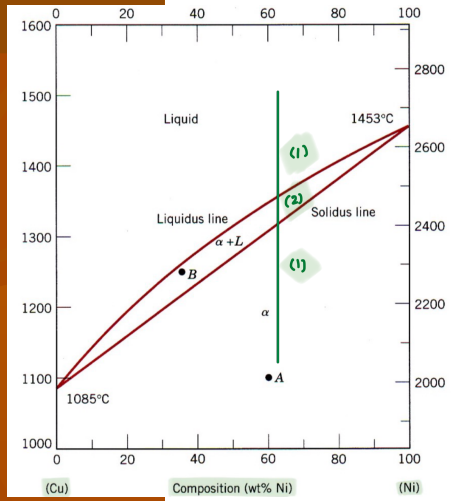
- The line over which all compositions are in the liquid state is termed as the "***Liquidus***"
- The line below which all compositions are in the solid state is termed as the "***Solidus***"

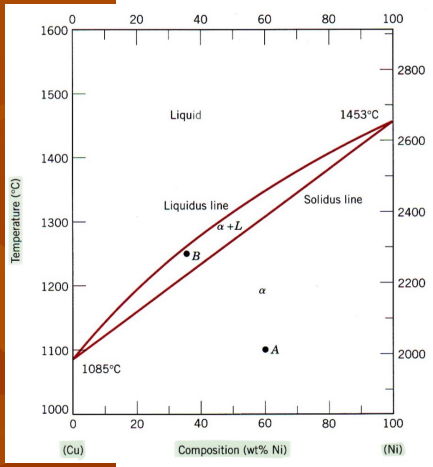
- On the event of a vertical line crossing a sloping line on a phase field, the number of phases changes by one (either increase or decrease).
- A phase which does not have a phase field but appears in a two-phase field is either a pure metal or an intermediate phase.

on its own

intermetallic compound.

بتكون جزء منه معين phase .
بس مش لحالها phase.





Pure metal & intermediate compounds are Solids but not Solid solutions.

- Pure metal → بتكون رمزيا
- intermetallic → حقيقيا
- Solid solution ?

Three kinds of information can be readily obtained from binary phase diagrams:

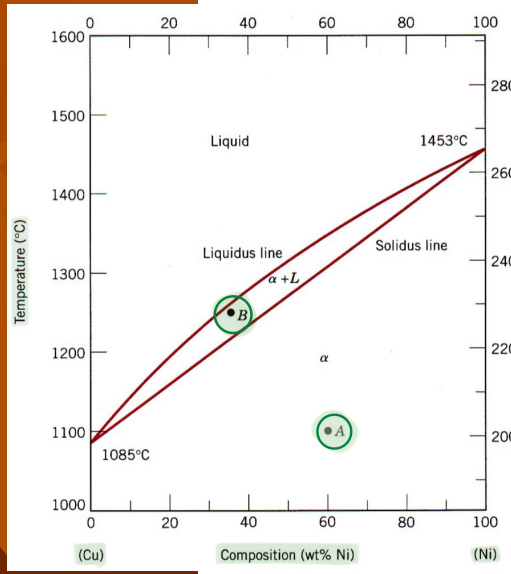
- Phases that are present
- Composition of these phases
- Percentages or fractions of phases

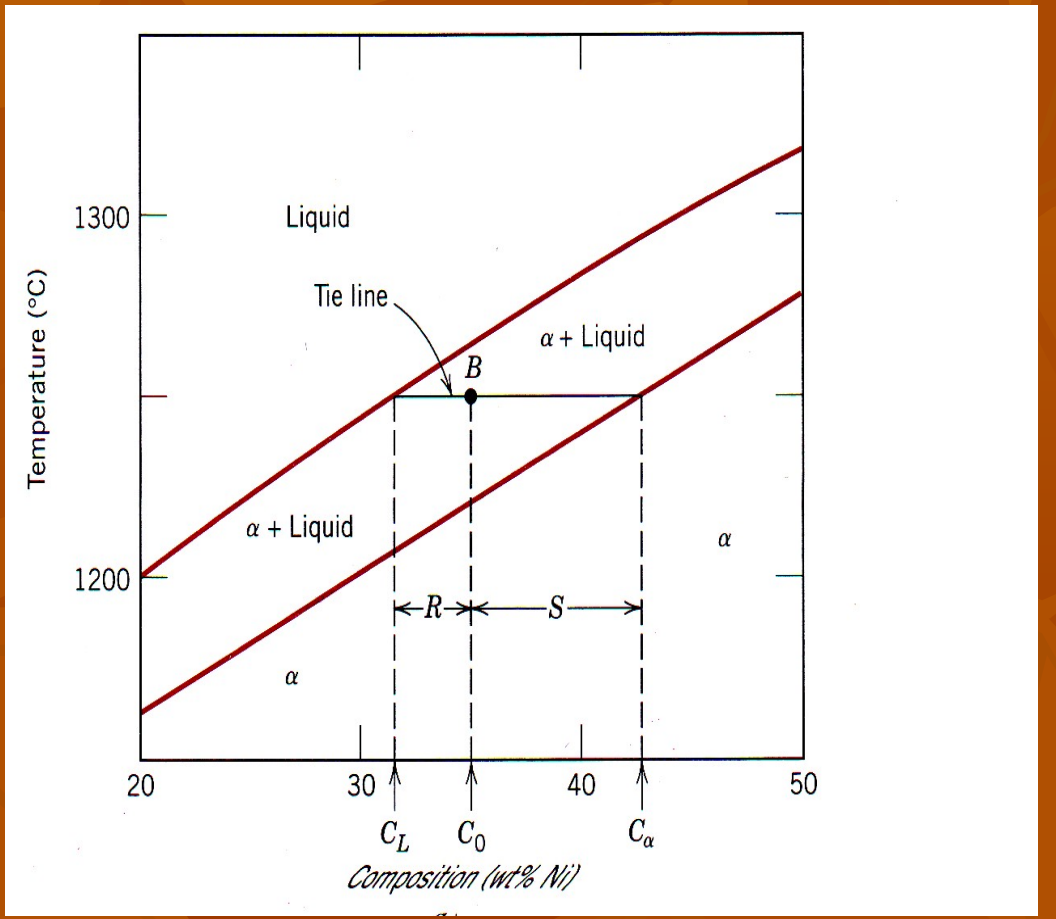
Weight percentages,

Phases present

- Establishing what phases are present is quite simple; one has just to locate the temperature-composition point on the diagram and note the phase(s) with which the corresponding phase field is labeled.

- For example an alloy of composition 60% Ni and 40% Cu at 1100 °C would be located at point A and consist of a single solid solution α.
- On the other hand an alloy of composition 35% Ni and 65% Cu at 1250 °C would be located at point B and consist L + α phases.



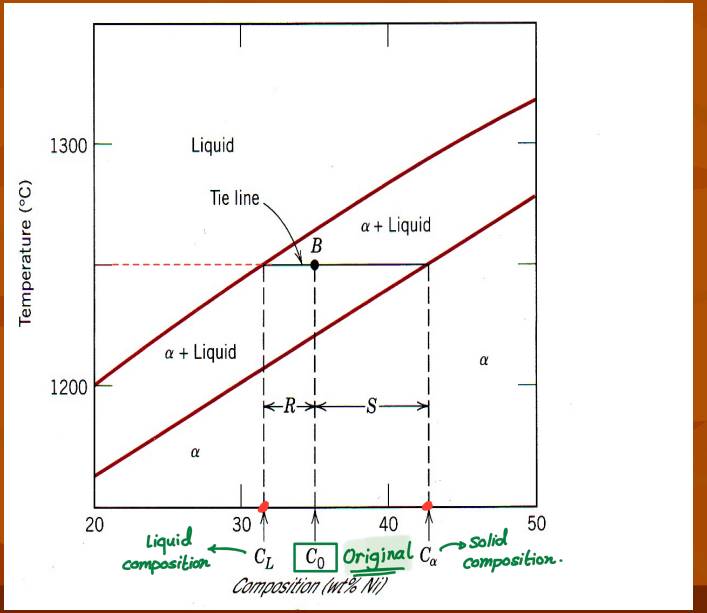

Liquid
Tie line
α + Liquid
B
α + Liquid
α
α
R
S
1300
1200
20
30
40
50
Temperature (°C)
Composition (wt% Ni)
C_L
C_0
C_α

Determination of phase compositions

- The composition of the phases present can be determined through the following steps:
- The temperature-composition point has to be located.
- If this point falls within a single-phase field then the composition of this phase is the same as the original alloy.

- If this point falls within a two-phase field a horizontal line (known as a tie line) is constructed from this point extending both sides until it intersects the two phase boundaries.
- The two intersect on both phase boundaries are noted and perpendiculars (vertical lines) are dropped on the horizontal (composition) axis from which compositions of the respective phases are determined

- Determination of phase compositions for an alloy containing 35% Ni and 65% Cu at 1250 °C is shown point **B** indicating a liquid composition (CL) of 31.5% Ni and an α composition (Cα) of 42.5% Ni.



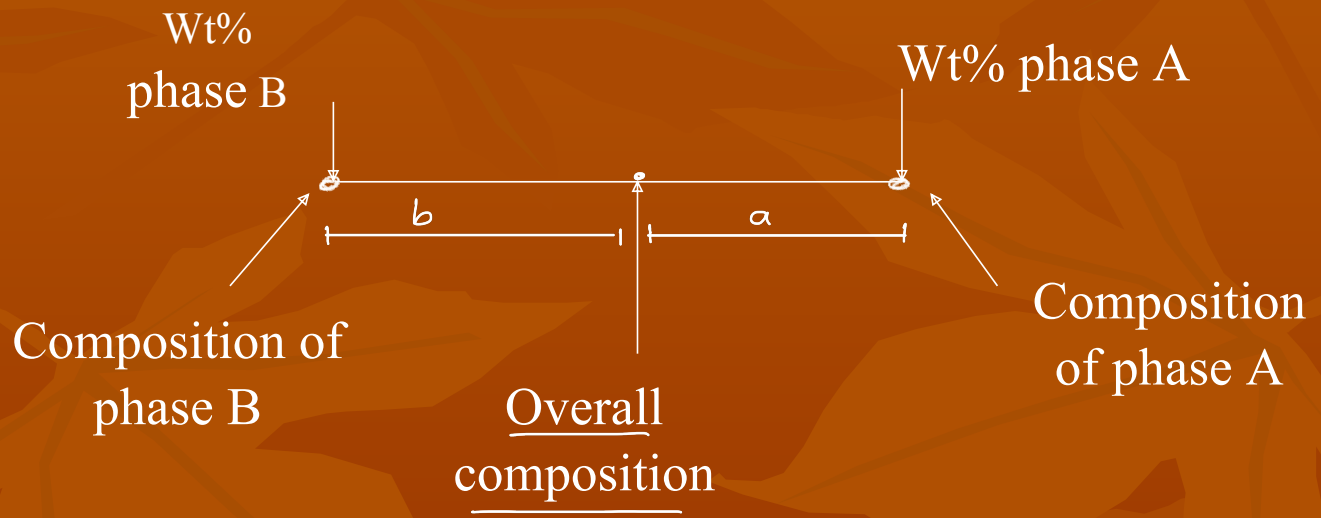
هوه بحكي عن الكميات النسبية.

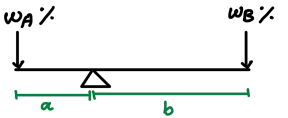
Determination of phase amounts

Weight percentages.

- The determination of phase amounts is quite similar and depend on the determination of phase composition.

- This is done by applying the "***Lever rule***"





$w_A \cdot a = w_B \cdot b$

$w_A \propto b$

$w_B \propto a$.

w % (Force) $\propto \frac{1}{\text{Distance}}$.

$$w_A\,\% = \frac{b}{b+a}$$

$$w_B\,\% = \frac{a}{b+a}$$

- In order to keep the balance around the overall composition then the following condition applies:

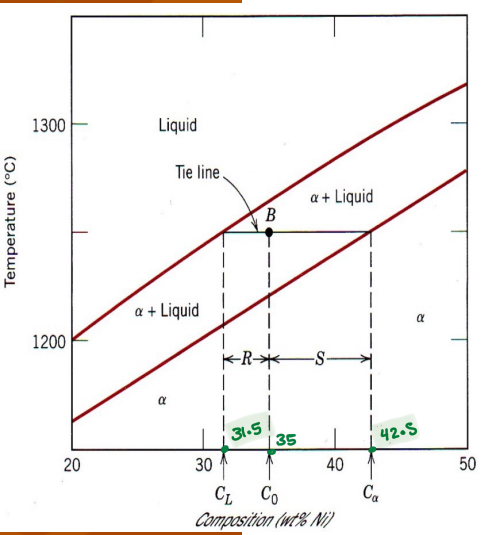
(Wt% of phase A)x(Composition of phase A - Overall composition)

=

(Wt% of phase B)x (Overall composition - Composition of phase B)

- For the alloy of point **B** this results in the following:

$$W_L = \frac{S}{R+S}$$



- Or by subtracting compositions,

$$W_L = \frac{C_\alpha - C_o}{C_\alpha - C_l} = \frac{42.5 - 35}{42.5 - 31.5} = 0.68 = 68\%$$

$W_L\% = \frac{7.5}{7.5+3.5}$

$= \frac{7.5}{11} = 68.1\%$

$L_{(L)} < L_{(\alpha)}$; $W_L > W_\alpha$

- The weight percentage of α phase can be determined in the same manner

$$W_\alpha = \frac{R}{R+S} = \frac{C_o - C_L}{C_\alpha - C_L} = \frac{35 - 31.5}{42.5 - 31.5} = 0.32 = 32\%$$

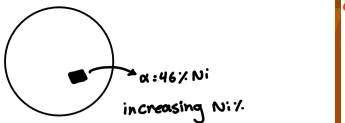
Lec Monday 9/3

Determination of microstructural developments under equilibrium and non-equilibrium conditions

*non-equilibrium = Fast cooling

- The development of microstructure can be determined by following a solidification path of an alloy of a certain chemical composition.
- The previous example of an alloy with over all composition of 35% Ni and 65% Cu will be considered

*Solidification path:
decreasing in temp. from Liquid phase to the lowest temp.
*monitoring the temp. decreasing.

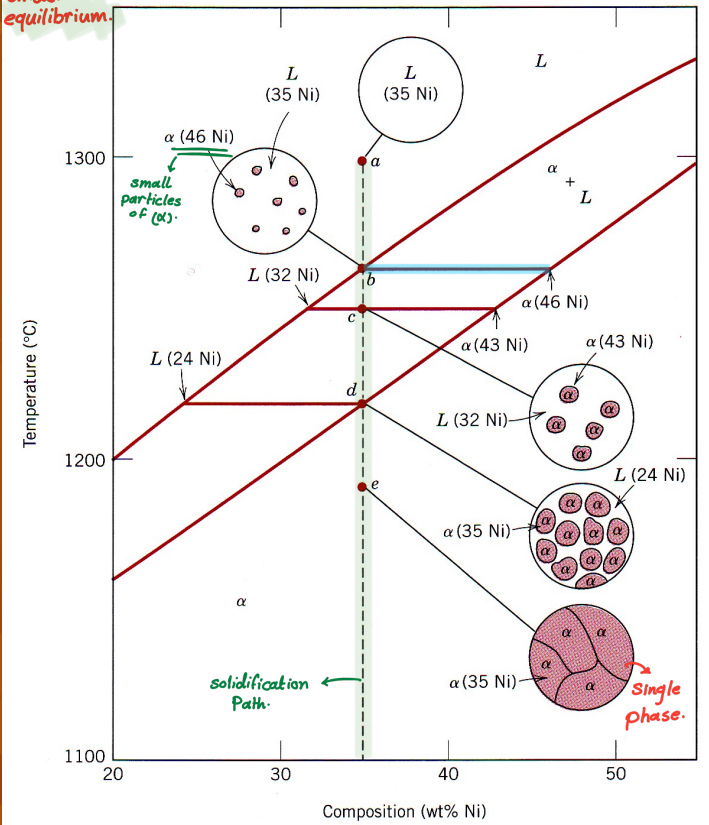


increasing Ni% in (α) phase comes with decreasing Ni% from the Liquid phase.

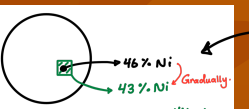
W(α)% increas → Ni% in the Liquid decrease.

W(α)% ↓ → Ni% in α ↑
W(α)% ↑ → Ni% in α ↓
W(L)% ↑ → Ni% in L ↑
W(L)% ↓ → Ni% in L ↓

Under equilibrium.



→ ↑ : W% ↓
amount ↓ , Ni% ↑



* known as equilibrium Diffusion.
Depends on temp. & time.

- Gradual decreasing.

• (α) Totally Liquid.
Composition same as the Original. 35% Ni

• (b) Start of Solidification. (Cross the liquidus.)
the tie line is in (α) Direction
C_L=(35%) → C_α (46%)
so the value of (α) approach to the zero.
W(α)% ≈ 0. , but more Ni% in (α) & less in the Liquid.

• (C) as the temp. decrease the amount of (α) increase → C_α is decreasing
W(α)% is increasing & W(L)% ↓
* كان الكمية مش تفسير كم التركيز متغير ، يعني عدد كم تجد
• Ni% is decreasing in (α) but Still > 35% (the original %).
decreasing Gradually in (α) & Liquid.

• (d) befor Solidus,
the amount of (α) increased, +C(α) close to the original 35%

• (e) or any point below (d)
the whole microstructure will be in the solid state.
• Solid (α) with 35% Ni as a single phase.

Schematic representation of the development of microstructure during the equilibrium solidification of a 35 wt% Ni-65 wt% Cu alloy

- At 1300 ºC (point a) the alloy is in the liquid condition
- This continues until the solidification path (vertical line) crosses the liquidus at about ~ 1260 ºC (point b) where solid α starts to precipitate within the liquid with composition of 46% Ni.

(Solidification path), vertical line → because it's a temp. line.

- Continuous cooling through point c (around ~ 1250 ºC) the amount of □ has grown within the liquid while the compositions of both □ and the liquid change following the solidus and liquidus lines, respectively.
- As cooling continues □ continues to grow with its composition following the solidus line at the expense of the liquid.

- Just below point d (intersect with the solidus line) solidification is complete and the structure is composed entirely of solid α with overall composition as the original alloy.

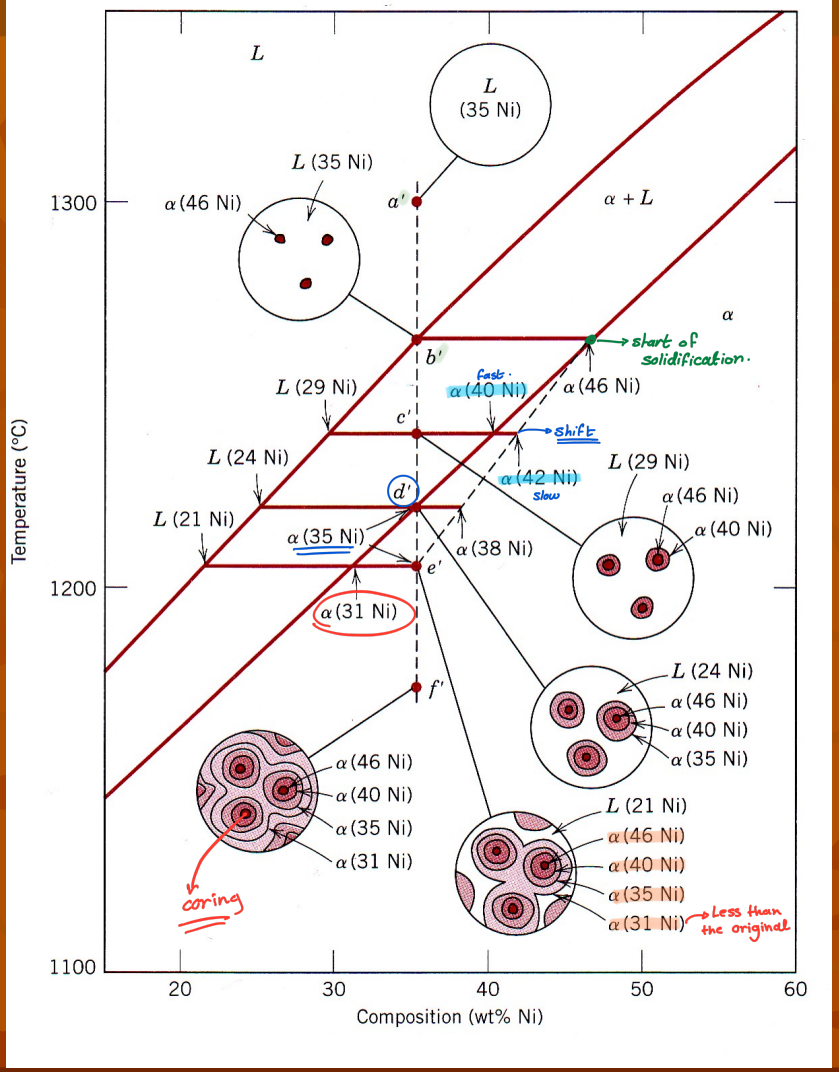
- further cooling to point e will not change the composition of α

Exercise

- determination of microstructural developments under non-equilibrium conditions.
- **Requirements:** Explain the microstructural developments under equilibrium and non equilibrium conditions as shown below.

* in the non-equilibrium, each layer keeps its composition no enugh time to diffuse.

* in the equilibrium the Ni% will Diffuse from high concentration to the low one.



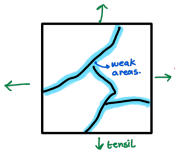
* Starting with (α') having the same as the original composition
α' same as α → Liquid phase.
till the start of solidification.
at point (b').

* the chang begin each layer keeps its composition.
the line will be shifted, the concentration will be less, the fainal layer will be less than the original composition.
(32% < 35%) Ni

* Gradaul decreasing (Gradient) In temp & comp.

the first layers have more solute & it will decrease.
coring: the center of the grain has different concentration of solute than the edges.

– Difference in properties for Grains.
– non-unform structure.



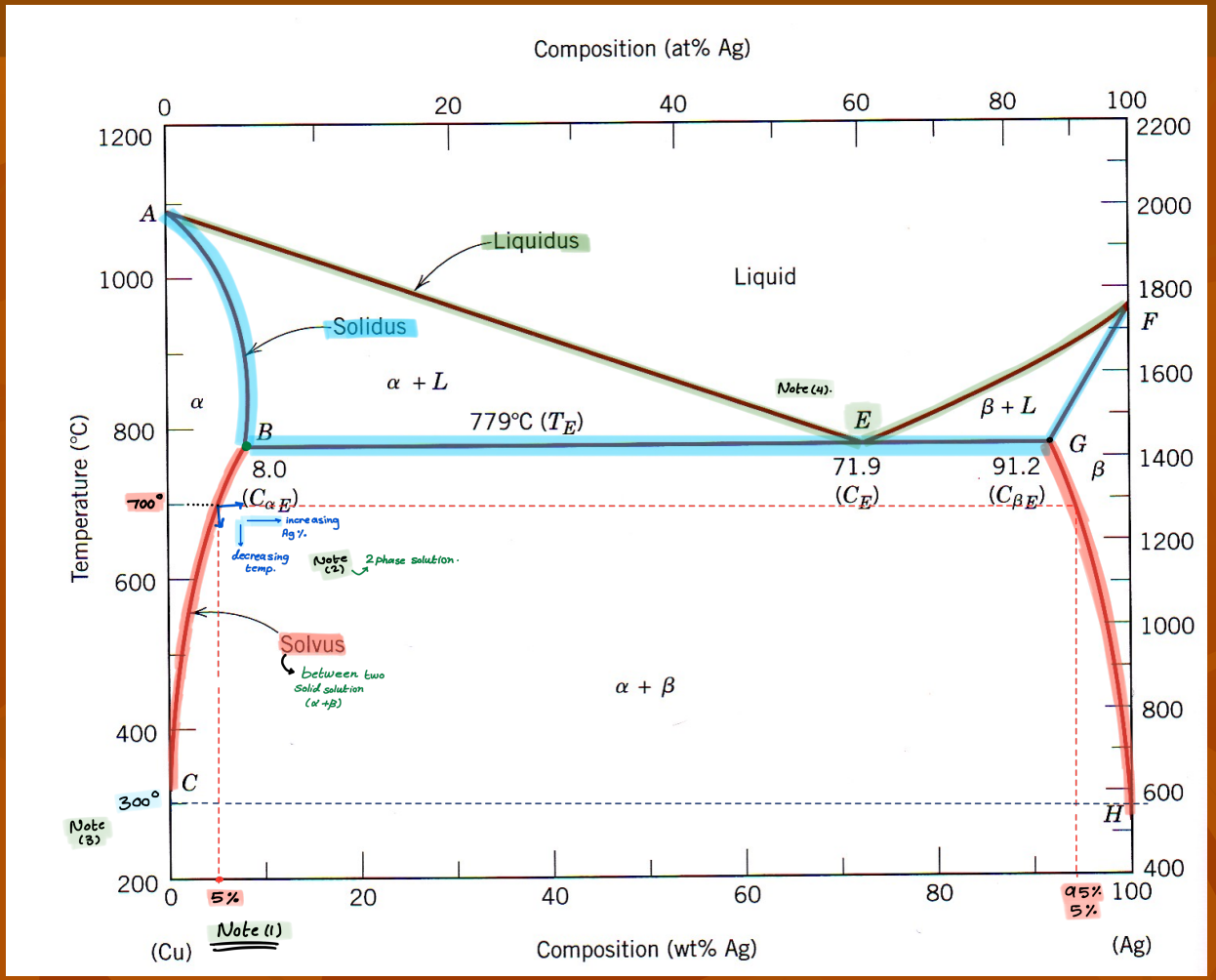
in the solid Solution Strengthening & the solut concentration is affecting the Strength, (Strength Gradient.)

* cracking under tensil strength. (weak Grain boundries.) → use some heat-treatment (Homogenisation); increase temp till Deffusion then slow cooling.
* from non-equ. to equ.

Complete Solubility
Single – Solid Solution.

Binary Eutectic Systems

In this system the two metals which are completely soluble in the liquid state become only partially soluble in the solid state



(1) * When the alloy has up to 5% Ag at temp. 700°C, Only Single phas Cu. (α).

(2) → if more than 5% or decreasing temp. → new solid Solution (β)

(β) at 700° = 95% Ag., 5% Cu

& if the Cu < 5% → Single – solid phase (β)

β: Cu into Ag

α: Ag into Cu.

---

max solubility of Cu at point (B). with 8% Ag.

max solubility of Ag at point (G). with 91.2 % Ag.

---

(3) At 300° the solubility of Cu in Ag (β) = Zero, 2 pure metals.

(E): Lowest melting point at any composition to start Solidification. → or the Eutectic Reaction.

with C_E: Eutectic composition = 71.9%

lowest point in the liquidus (lowest M.p).

(L+β)+(L+α)+(β+α) → 3phases.

The copper-silver phase diagram

- In addition to the points noted for the binary isomorphous system a few points can be added to the binary eutectic system which also are applicable for other types of binary system:

- The line of solubility limit (line separating a single solid solution phase field from a two solid solution phase field) is termed "**Solvus**".

حد الذائبية.

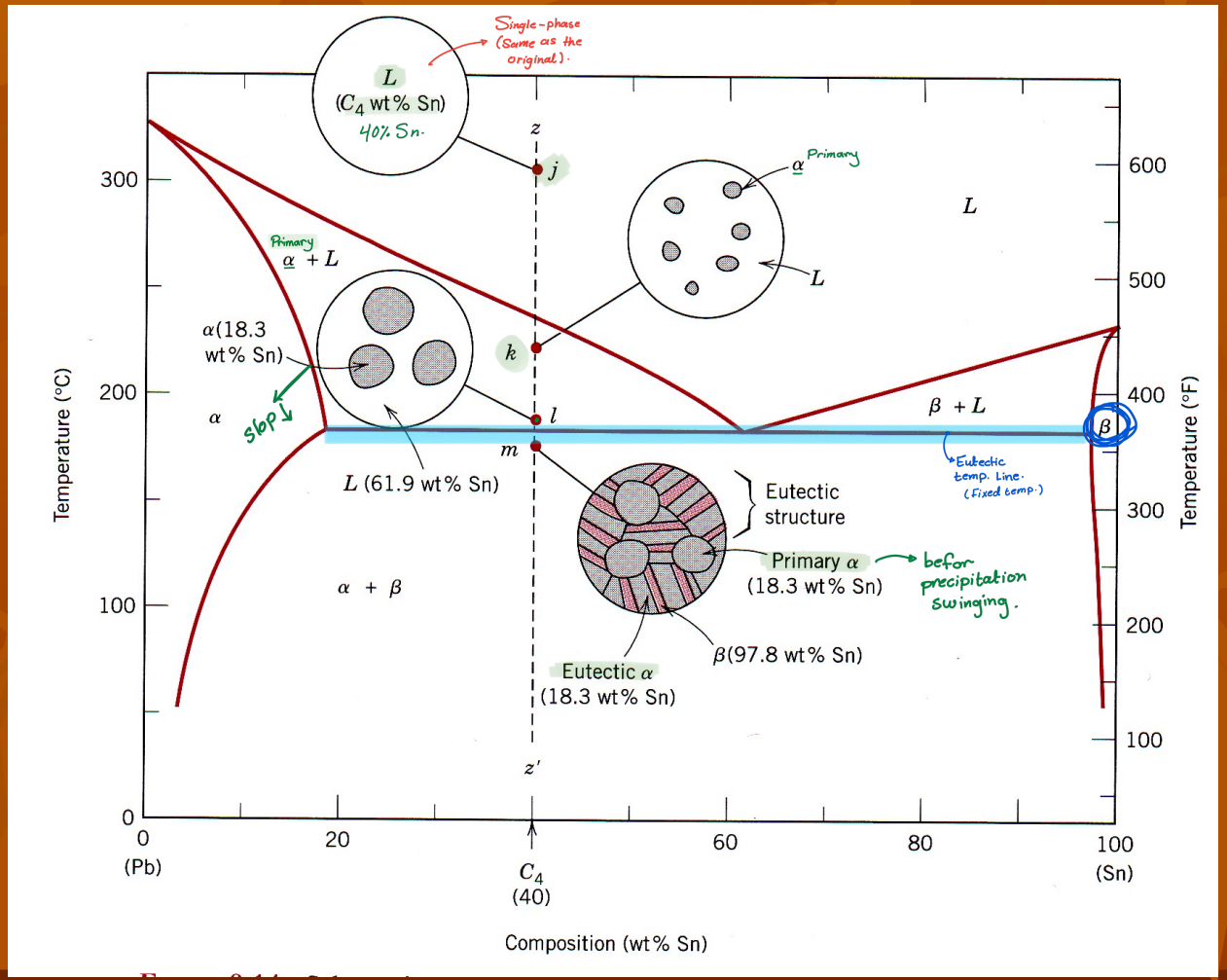
- On the liquidus line there exist a point which intersects the solidus line and ~~is~~ it has a symbol of "**E**" indicating the point at which the "***Eutectic reaction***" takes place

* no solubility limit in the isomorphous diagram (Completely Soluble)

- This point is the only point that three phases can co-exist and is termed the "**invariant point**". Alloys of the eutectic composition will have the lowest melting point.
- The general principles of determining phase composition and phase amount still apply.

* in the binary sys., more than two phases can't exist
* in Solid binary (2) or less phases only
(because it's completely soluble).
↳ one solid phase.
but if there is more than one Solid phase ($\alpha+\beta$), then 3phase co-exist
. (Liquid + 2solid solution)

- The lead (Pb)-Tin (Sn) phase diagram, will be used to explain the Eutectic binary system as follows:



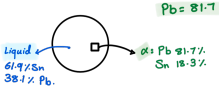
* Microstructural development: with the Solidification Path.

(α): when the line crosses the liquids line. not just at (k).

k: when the temp. decrease, amount of Liquid decrease w% ↓
* the amount of (α) increase w% ↑
Less slop ?
so the amount of increasing α not the same as decreasing the Liquid.

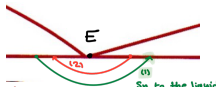
at point (L):

as the temp. decrease, α will precipitate with Sn = 18.3 % Pb = 81.7 %



the Liquid will precipitate with 81.7 % Pb instead of 38.1 % Pb
* Sn 18.3 % instead of 61.9 %
· يعني ال يترجع ح يعوض (Pb) ويتخلص من (Sn) ·
· (Liquid) في محيط

Sn concentration will increase in the Liquid.
* Pb conc. will decrease.



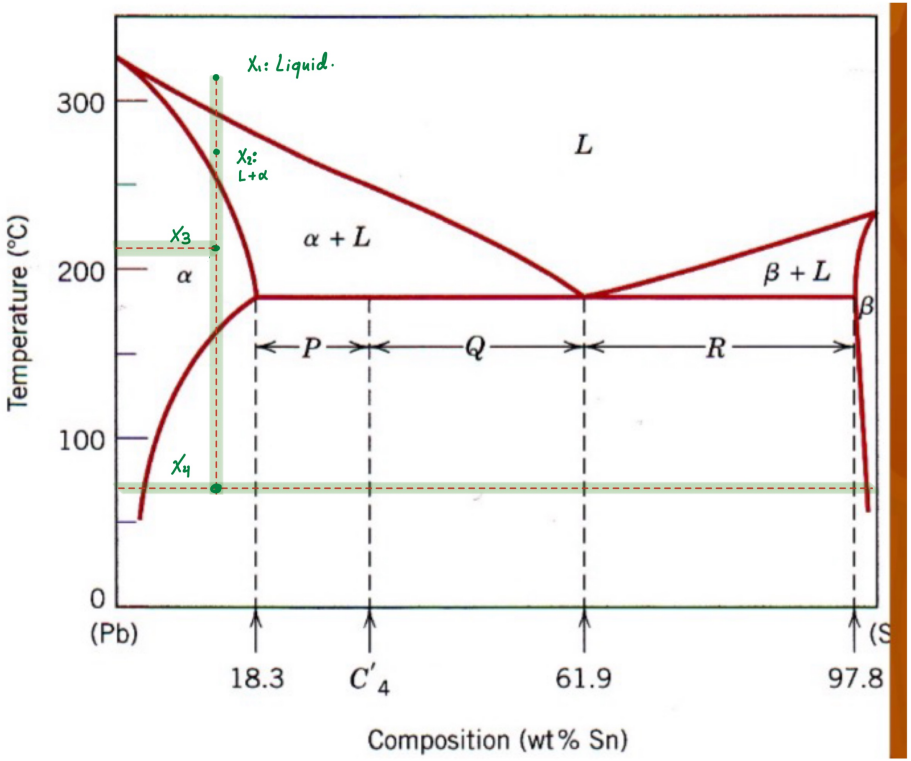
back to precipitating (α)
Same Scenario over again

Sn to the liquid.
Pb from the Liquid.
(Liquid solution rich with Sn. (B+L)).
*precipitate β
B: Sn ↑
Pb ↓
يستحي (Sn) و يتخلص من (Pb) ·

Precipitation Swinging

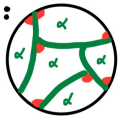
till precipitating all the Liquid, as layers from (α+β) at the eutectic temp.

the faimal structure:
1. primary α
2. Eutectic structure; Layers from α+β



*no eutectic reaction in this case,
because when the temp. decrease → will have a totally Solid Solution. (α)
without any Liquid.

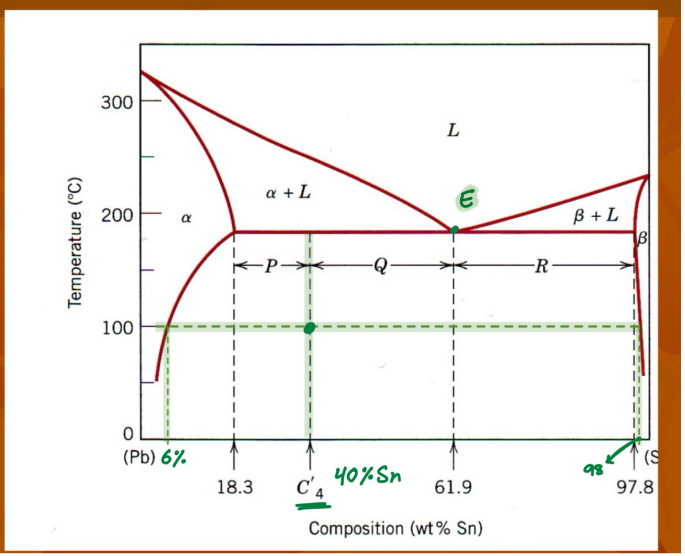
X_3: 

X_4: 

•β

(β) in this case not from eutectic, but from end of solvus.
(precipitate → lack of solubility).
β: solution of (Pb) in (Sn).

* الذراع باتجاه (α) أقصر من الذراع باتجاه (β) لذلك كمية (α) أكبر.
لهيكل متزسيط كتفاصيل صغيرة
(microstructure).



* Find the weight percentage at 100 C° & 40% Sn for:

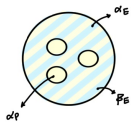
1. $Wt(\alpha_p) = \frac{C_E - C_o}{C_E - C_\alpha} = \frac{61.9 - 40}{61.9 - 6} = 39\%$

* We divide the structure for 2 parts → Primary (α) / Eutectic structure.

* for Primary (α) ⇒ we care about (α) that was formed befor Eutectic.
(tie line from (α) to the eutectic).

* for the primary, the composition not from (18.3) even though it's the Original in the eutectic, because composition change when the temp. change.

* at 100 C° & 40% Sn:



2. $Wt(E) = 100 - Wt(\alpha_p) = 100 - 39\% = 61\%$

or $\frac{C_o - C_\alpha}{C_E - C_\alpha} = \frac{40 - 6}{61.9 - 6} = 60.8\%$

3. $Wt(\alpha) = \frac{C_\beta - C_o}{C_\beta - C_\alpha} = \frac{98 - 40}{98 - 6}$

$= 63\%$

$Wt(\alpha) = Wt(\alpha_p) + Wt(\alpha_E)$.
$= (0.39 + (0.393 * \underbrace{0.61}_{Wt(E)})) * 100\%$
$= 62.9\%$.

* $Wt(\alpha_E) = \frac{C_\beta - C_E}{C_\beta - C_\alpha} = \frac{98 - 61.9}{98 - 6} = 39.2\%$
or $100 - Wt(\beta_E)$

or $Wt(\alpha) - Wt(\alpha_p) = 63 - 39 = 24\%$.

$24\% = Wt(\alpha_E) * Wt(E)$

$Wt(\alpha_E) = \frac{0.24}{0.61} = 39.3\%$

within E.

4. $Wt(\beta)$: overall

$100 - Wt(\alpha) = 100 - 63 = 37\%$.

or $Wt(\beta_E) * Wt(E)$

or $\frac{C_o - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 6}{98 - 6} = 36.9\%$.

5. $Wt(\beta_E) = (\beta)$ within the Eutectic.

$\frac{C_E - C_\alpha}{C_\beta - C_\alpha} = \frac{61.9 - 6}{98 - 6}$

$= 60.7\%$

* same as taking alloy from the eutectic structure.

61% (E)
- 39% α_p
- 39.3% α_E
- 60.7% β_E

$Wt(\beta) = Wt(\beta_E) * Wt(E)$
$= ((0.607) * (0.61)) * 100\%$
$= 37\%$

$Wt(\beta_E) = Wt(\beta)$.

26/3

- At around 300 °C the alloy is in the liquid state having the original composition of the alloy (40 % Sn)
- α phase starts to precipitate within the liquid upon crossing the liquidus line (point k)

- Just above the eutectic temperature (point l) α phase and liquids co-exist with compositions around 18.3 and 61.9 Sn, respectively.

- As the temperature drops just below the (at the eutectic) eutectic temperature, solidification proceeds by a eutectic reaction forming alternate layers of α and β.

- The eutectic reaction is one in which one liquid phase results in two solid phases:

$$L \Leftrightarrow \alpha + \beta$$

- This reaction takes place at a constant temperature (**the eutectic temperature**)

* as layers from ($\alpha + \beta$) with changing in composition (swinging.)

* temp decreasing: Liquid $\rightarrow \alpha + \beta$
* temp increasing: $\alpha + \beta \rightarrow$ Liquid.

* the original phase is not existed below the E. temp.

horizantal line crosses the eutectic point. (at constant temp.)

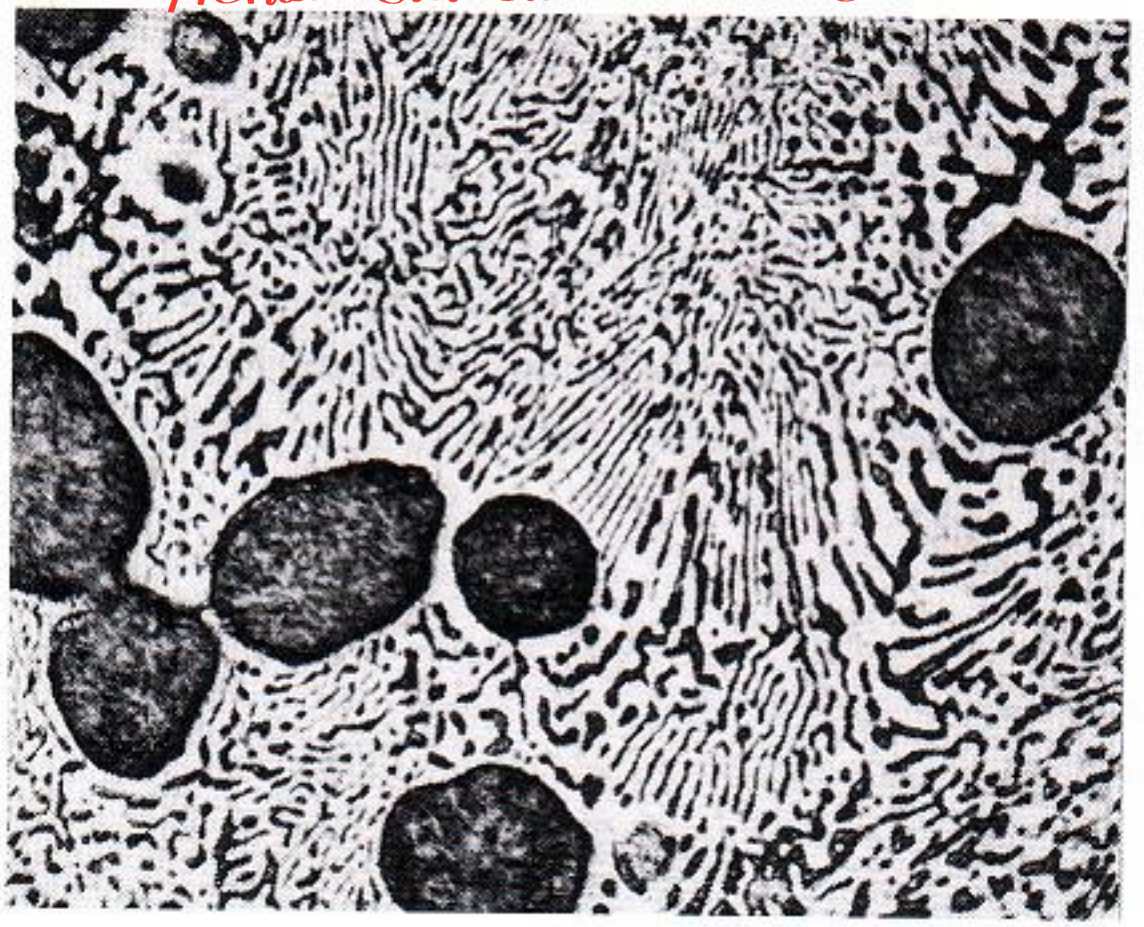
- α-phase which precipitated before the final solidification through the eutectic reaction is termed "***primary α***". * Befor Eutectic temp

- The final microstructure would be composed of a mixture of primary α and the eutectic structure.

* Primary (α) :
- Precipitate at higher temp than the eutectic temp.
- not as layers.

the Eutectic structure is a layers of (α + β).

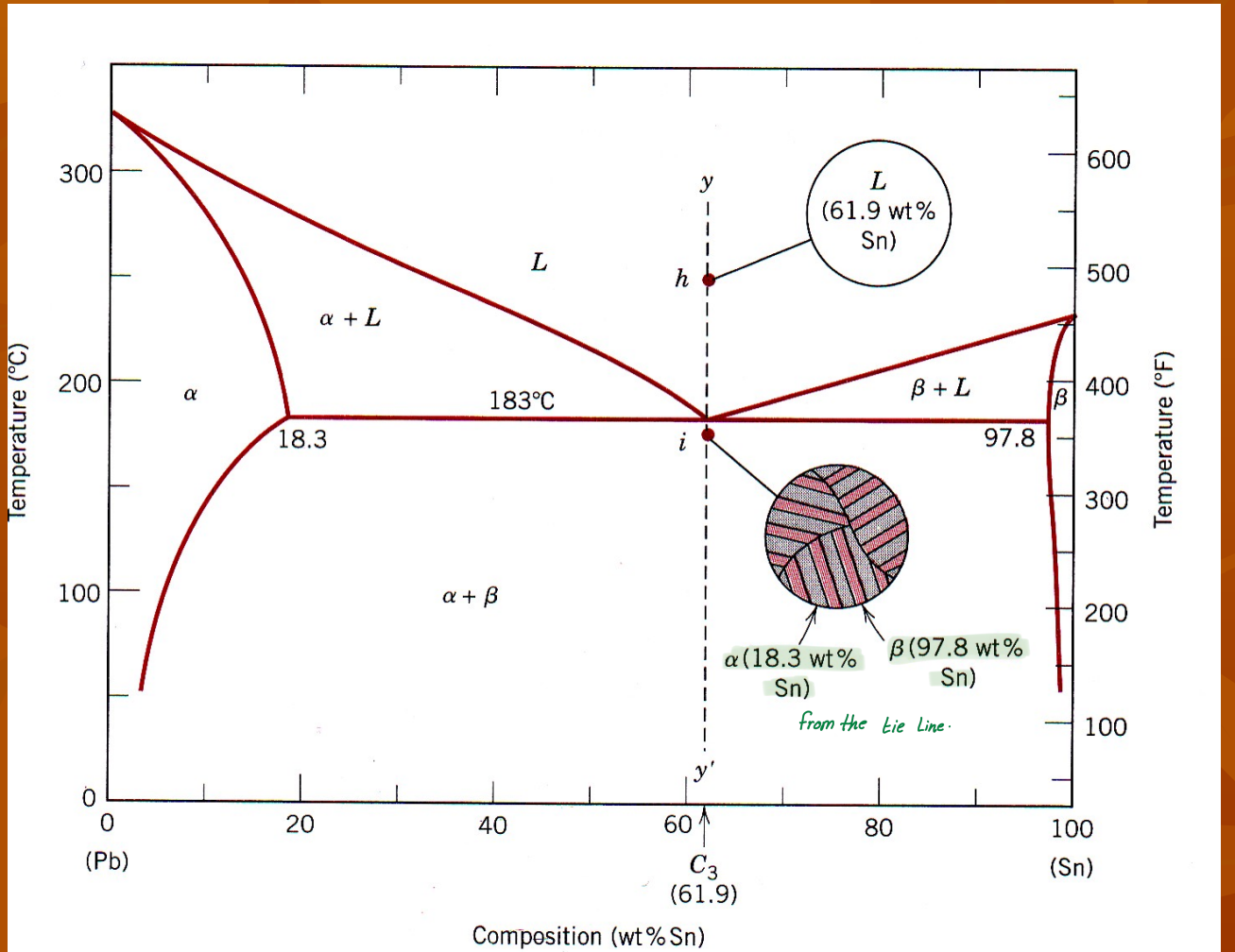
Actual Eutectic Structure.

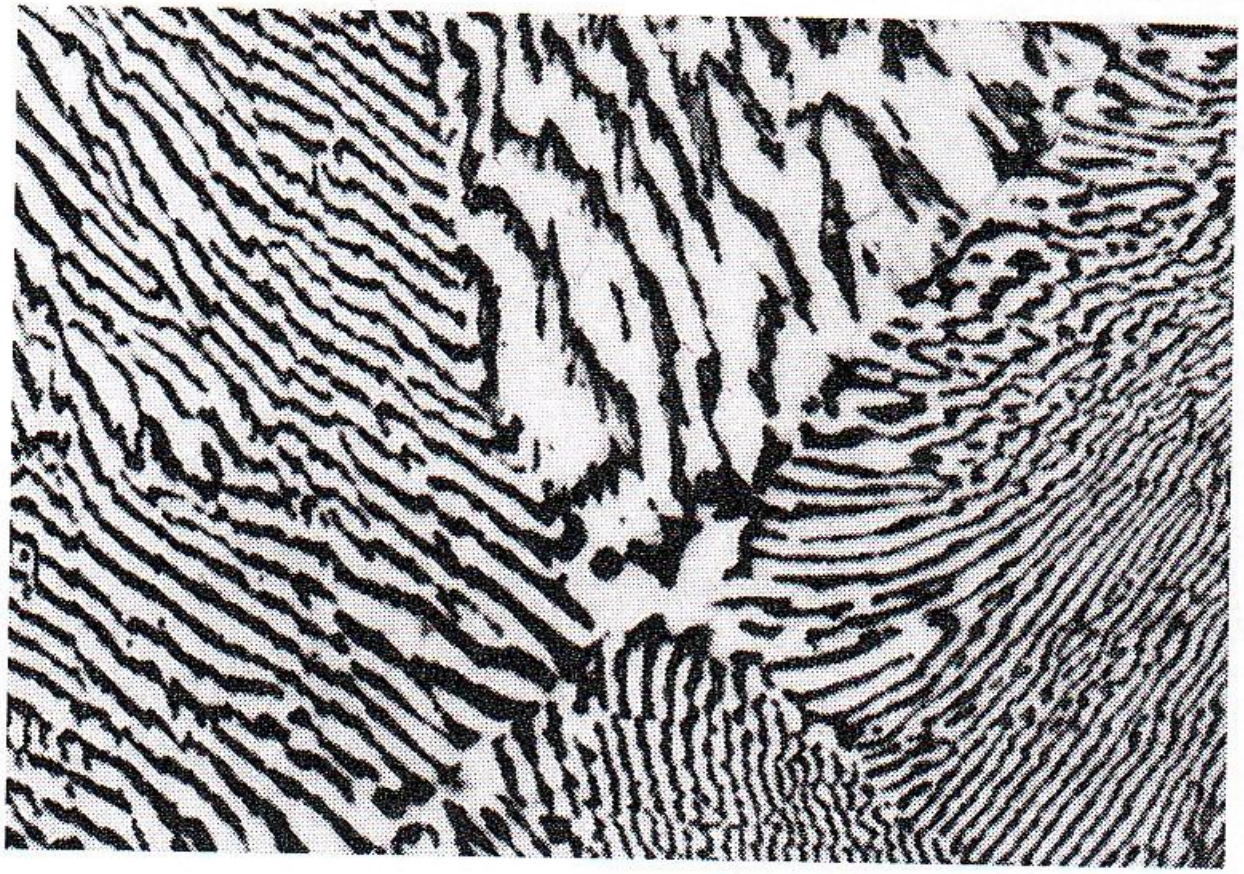


* to the alloys that originally at the left of the Eutectic point. (18.3 – 61.9).

- An alloy of the eutectic composition will solidify at a constant temperature (the eutectic temperature) and the microstructure will be completely composed of the eutectic structure (layers of α and β)

with an primary phase.


Temperature (°C)
Temperature (°F)
300
200
100
0
600
500
400
300
200
100
0
20
40
60
80
100
(Pb)
(Sn)
Composition (wt % Sn)
C_3
(61.9)
L
(61.9 wt % Sn)
h
y
y'
i
α
α + L
L
β + L
β
α + β
183°C
18.3
97.8
α (18.3 wt % Sn)
β (97.8 wt % Sn)
from the tie line.



100% Eutectic Structure (no primary).

- *Alloys with eutectic composition are termed* ***eutectic alloys***

- *Alloys with composition lower than the eutectic composition are termed* ***hypoeutectic alloys***

- *Alloys with composition higher than the eutectic composition are termed* ***hypereutectic alloys***

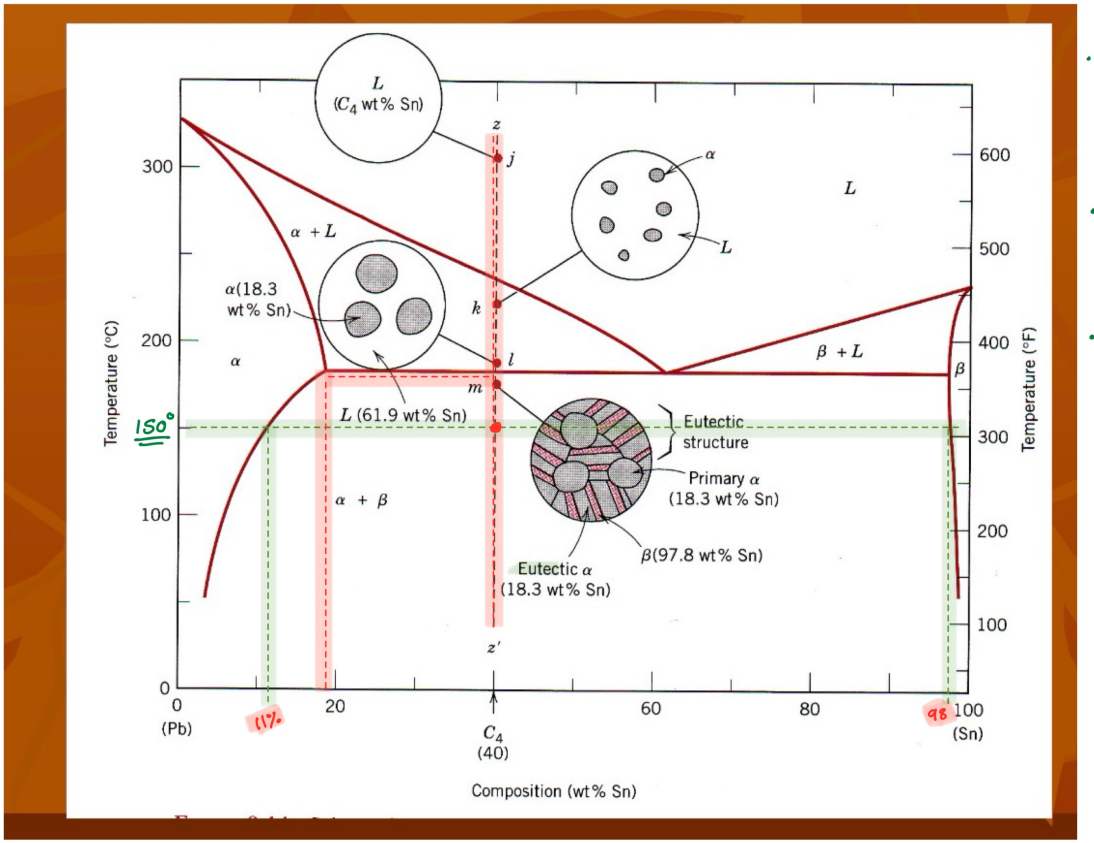
→ at the left of the eutectic point (18.3 – 61.9)

→ at the Right of the eutectic point.

Exercise

- Determine the phases present, phase composition and the amounts of phases in an alloy containing 40% Sn at 150 ºC

- Explain the microstructure development under non-equilibrium conditions in



* Exercies:

150 C°, 40% Sn.

- Phase present → Locate the temp. composition point. (Phase field).

* Primary α + Eutectic.

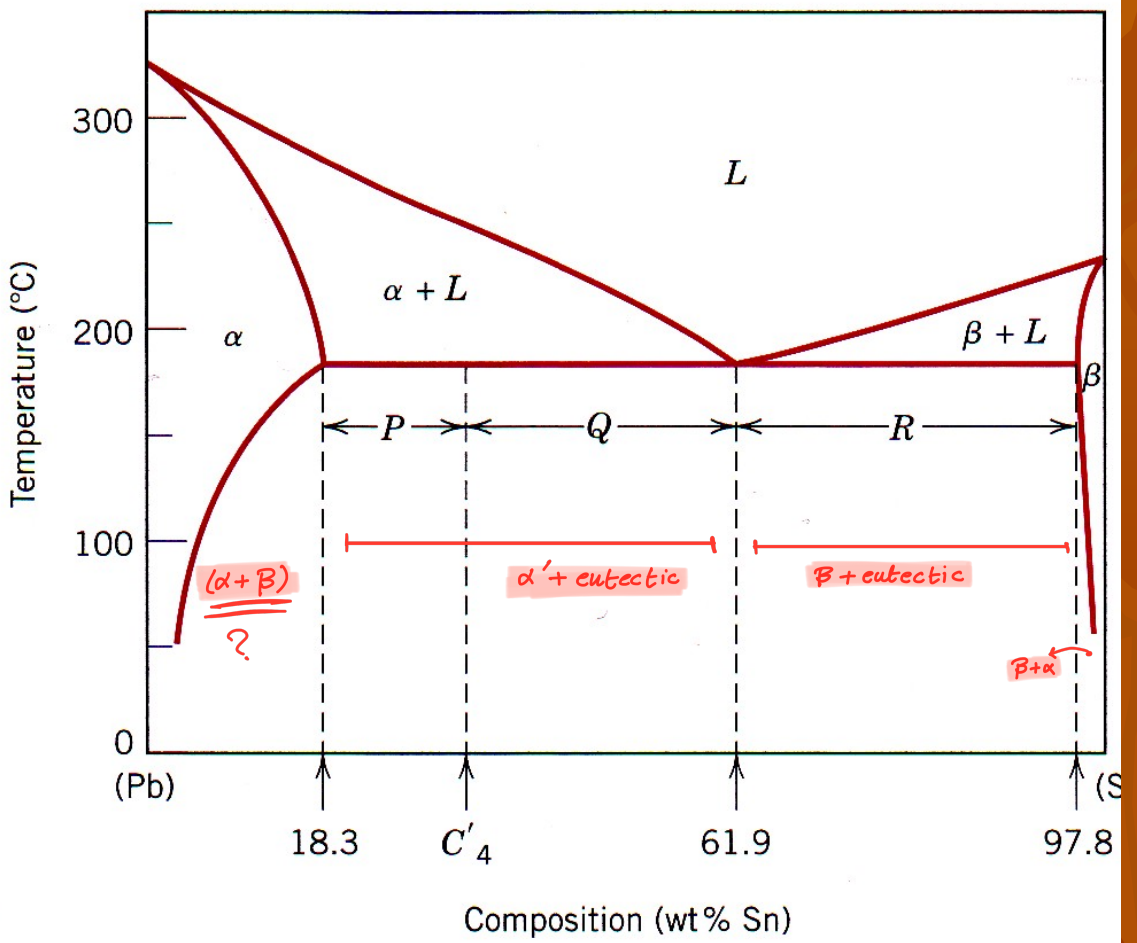
- Phase composition:

11 % Sn (α) , 98 % Sn (β).

61.9 % Eutectic.

- Amount of phases:

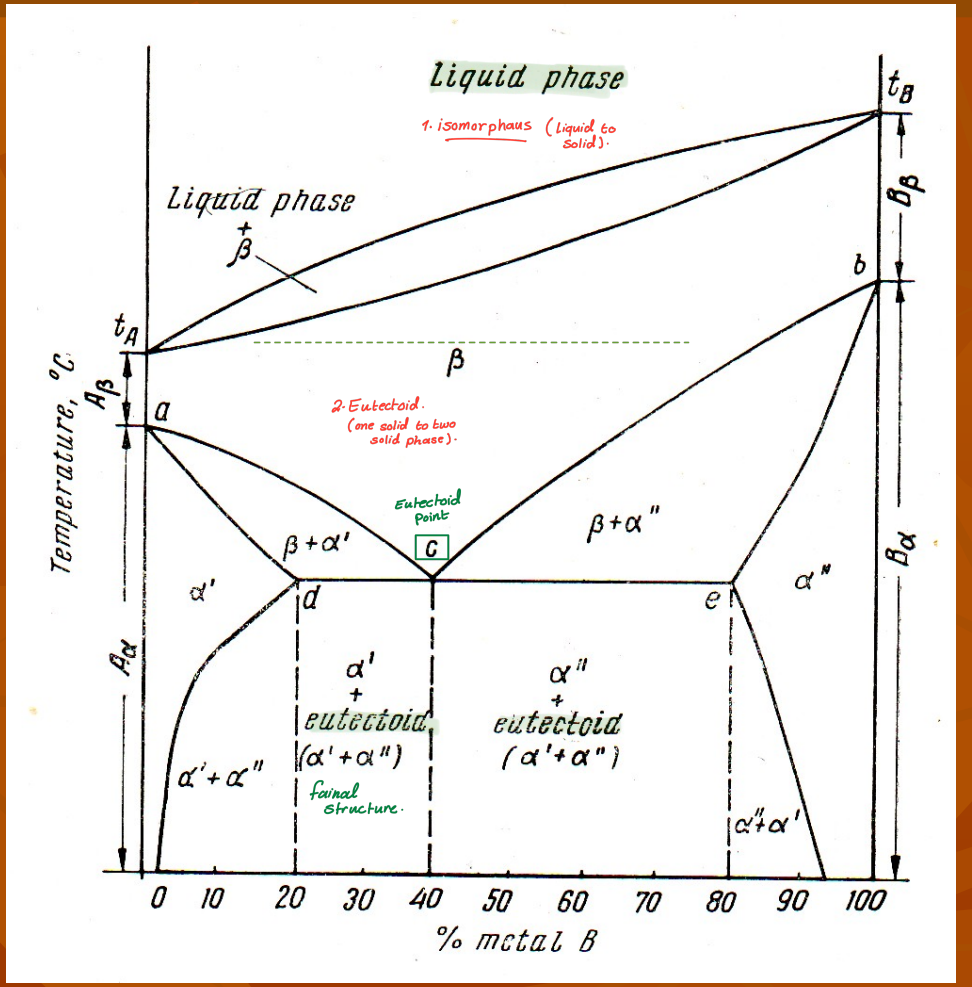
$\alpha = \frac{98 - 40}{98 - 11} = 66\ \%$, $\beta = \frac{40 - 11}{98 - 11} = 33\ \%$


300
200
100
0
Temperature (°C)
L
α + L
α
β + L
β
P
Q
R
(α+β)
?
α′ + eutectic
β + eutectic
β+α
(Pb)
(S
18.3
C′4
61.9
97.8
Composition (wt % Sn)

The eutectoid reaction

- If the original phase resulting in the two new phases is a solid phase the reaction is termed a "***Eutectoid***" reaction.

* the Original phase was Solid.



* 2 phase diagram.
isomorphaus & Eutectoid.
α', α": two Single phases.

- In this example the eutectoid reaction is:

$$\beta \leftrightarrow \alpha' + \alpha''$$

- As in the case of eutectic alloys:
- *Alloys with eutectoid composition are termed eutectoid alloys*
- *Alloys with composition lower than the eutectoid composition are termed hypoeutectoid alloys*
- *Alloys with composition higher than the eutectoid composition are termed hypereutectoid alloys*

Binary systems in which a peritectic transformation is involved

- Sometimes in an alloy system two phases which are already present interact at a fixed temperature to produce an entirely new phase.

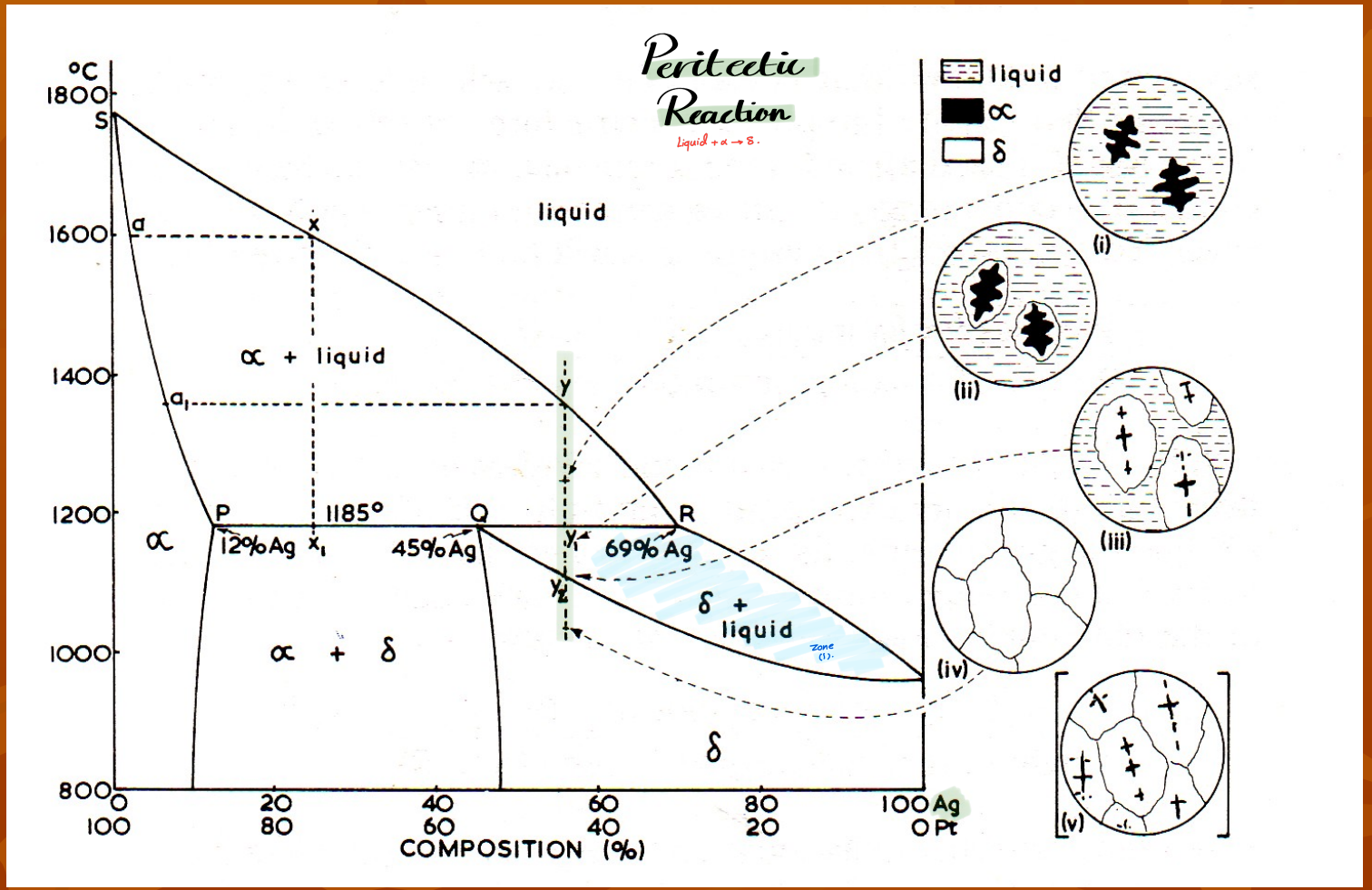
: 2 phase combine to produce new phase.

- If one of the interacting phases is a liquid the transformation is termed ***peritectic*** transformation.

$$L + \alpha \leftrightarrow \beta$$

- If both interacting phases are solid the transformation is termed ***peritectoid*** transformation.

$$\alpha + \beta \leftrightarrow \gamma$$



(Ag) : solut (from 0% to 100%).

at point (y): Y : δ

above the point ⟶ Liquid alloy.

decreasing in temp. till the solidus: precipitation of α.

then at 1185° (Peritectic temp.)

(Liquid + α) interact to produce (δ)

Liquid + α → δ

at zone (1) : Liquid + δ

α interact with the liquid to produce γ.

* تبدأ النقطة (a) ذراع (α) يكون له نقطة (P) لذا نبدأ أول مثلث. بس لما انزل لقت بعيد احسب لعند Q.

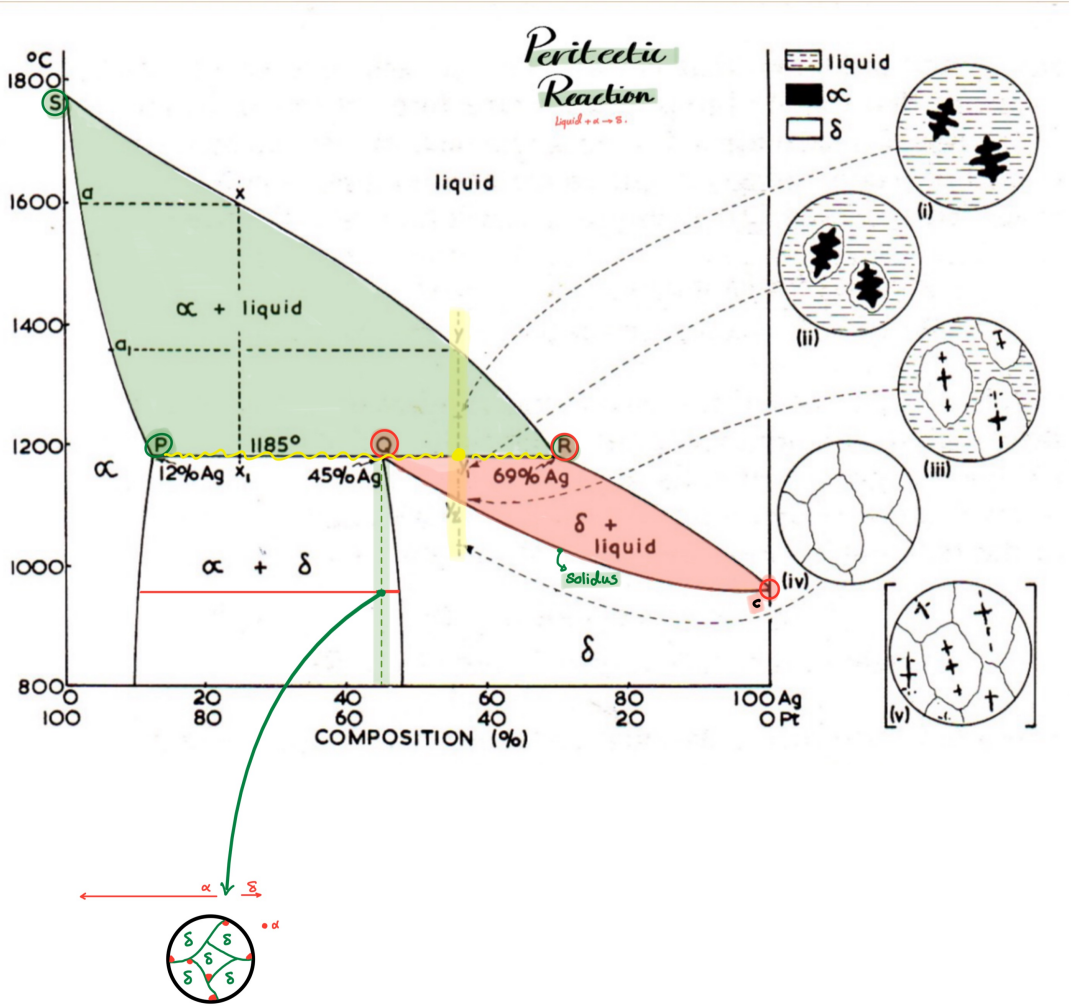
X : δ + α

α% = 12% Ag , Liquid = 69% Ag. , Solute = 25%.

25 − 12 = 13% , 69 − 25 = 44% (الذراع باتجاه Liquid) 44% > 13%

wt(α) > wt(Liquid) ⟶ Large amount of (α) to combine with small amount of Liquid.

* the Liquid will be totally consumed unlike (α). α + δ



from 1185C° → 2 parts [above, below]. (SPR, QRC)

y :

[1] α + Liquid

wt%(Liquid) > wt%(α)

no intersect with point (Q) → (P-y) & (y-R), Q just below.

→ (y-R) = $\frac{1}{4}$ (P-y).

Liquid = $\frac{1}{4}$ (α).

the temp. decrease:

[2] δ + Liquid

• (α) totally reacted, the amount of (α) Less than the Liquid

---

* At 1185 C°, what is the (wt%) for (α+L) & (L+δ).

2 cases : Right of Q → (QRC) just below. δ + Liquid. → point (y)

Lift of Q → (PRS) just above α + Liquid. → point (x)

* note that at point (Q). Liquid is smaller, and the Liquid is consumed.
لذلك هي سائل السبب تكون (1:1).

- The Platinum-Silver phase diagram will be used to explain the peritectic reaction.
- In this system peritectic reactions will take place in alloys containing between 12 % and 69 % silver.

- Considering an alloy with original composition of 25% silver and 75% platinum
- Above 1600 ºC the alloy is in the liquid state
- At about between 1600 ºC and 1185 ºC the, solidification proceeds by precipitating solid □ with its composition moving along the solidus line (SP) while the composition of the liquid moving along the liquidus line (SR).

- Just above 1185 ºC the structure is composed of solid □ with composition (12% silver and the remaining liquid with composition 69% silver with wt. % as follows:

$$W_{\alpha} = \frac{x_1 R}{RP} \qquad W_L = \frac{x_1 P}{RP}$$

- At 1185 ºC (the peritectic temperature) the peritectic reaction takes place where the solid starts to interact with the liquid and producing the new phase “”, i.e.,

$$L + \alpha \leftrightarrow \delta$$

- The solid solution □ contains 45 % silver.
- At this point all the liquid was used up during the transformation and the final structure will be composed of a mixture of □ and □.

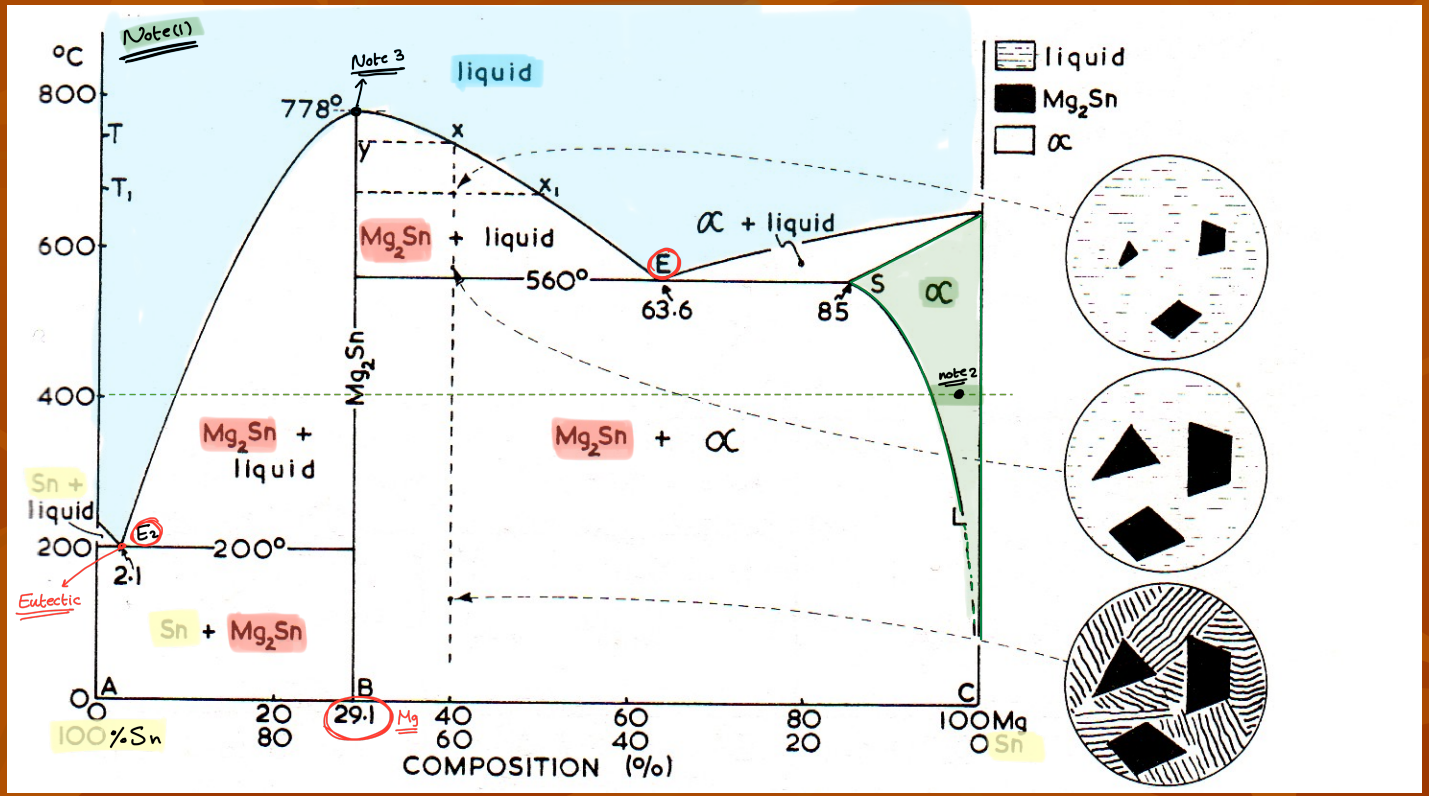
- At 1185 ºC wt. % will be as follows:

$$W_{\alpha} = \frac{x_1 Q}{PQ}$$

$$W_{\delta} = \frac{x_1 P}{PQ}$$

- It should be noted that in an alloy originally containing more than 45% silver the solid phase □ will be used up before the liquid and the final structure will be composed of a single solid phase □.

Systems containing one or more intermediate phases



*(Mg_2Sn) as intermetallic phase, (Extreme of intemediate).

Note (1): at the temp. Lines the pure metal exist as 100% Sn. / 100% Mg.

Note (2): at temp. 400C° (α) exist with range of composition → (area).

but (Mg_2Sn) → Fixed composition. width = zero area = zero.

Note 3: in the previous systems, the melting point of the alloys always between the solvent & the solute.

but in case of intermetallic compound:
1. chemical bonds. + physical.
2. Higher melting point.
3. Higher strength than the original metal.

---

*Mg_2Sn composition = 29.1 % → wt %. not an atomic %.

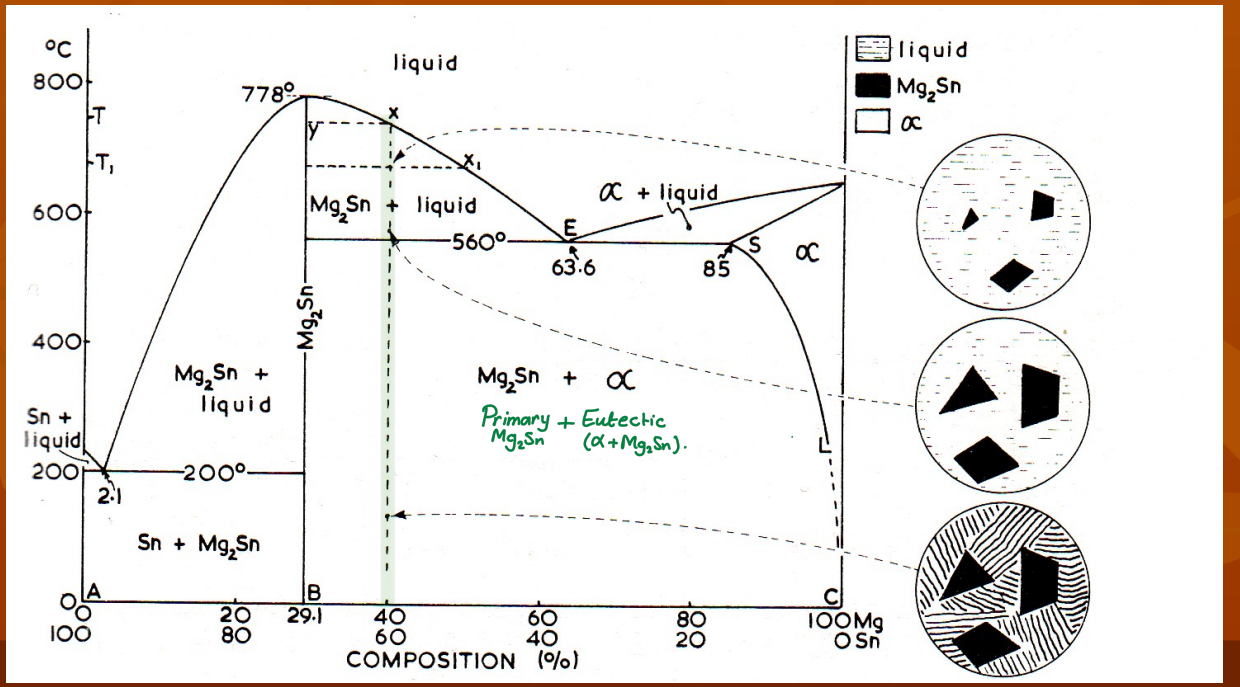
Mg atomic % = $\frac{1}{3}$ = 33 %

- An example of this binary system is the Magnesium-Tin phase diagram
- Intermediate phases do not have a single-phase field but appear in a two-phase filed as in this example.
- In fact, due to the fixed composition the actual phase field is a straight vertical line (having a width of zero).

- It should also be noted that the intermediate phase (in this case an intermetallic compound) has the highest melting point due to the additional "chemical" effects on the bonding between the alloying elements.
- Apart from these points the previous discussion applies to this binary system.

Exercise:

- Follow the solidification path of an alloy of original composition of 40 % Mg.



The Iron-Carbon Binary System

- Perhaps the most important binary system is that of the iron-carbon, as this represents the phase diagram of all plain carbon steels and cast irons.

- For steels, the useful part of this system is actually the iron-iron carbide (Fe-Fe3C) phase diagram

* One of the most used diagrams.

* Carbon Composition:
  - Plane carbon: low (0.05%)
  - cast iron: High (2%)

* mechanical properties:
- Plane carbon: - High Strength
  - Ductile
- cast iron: brittle.

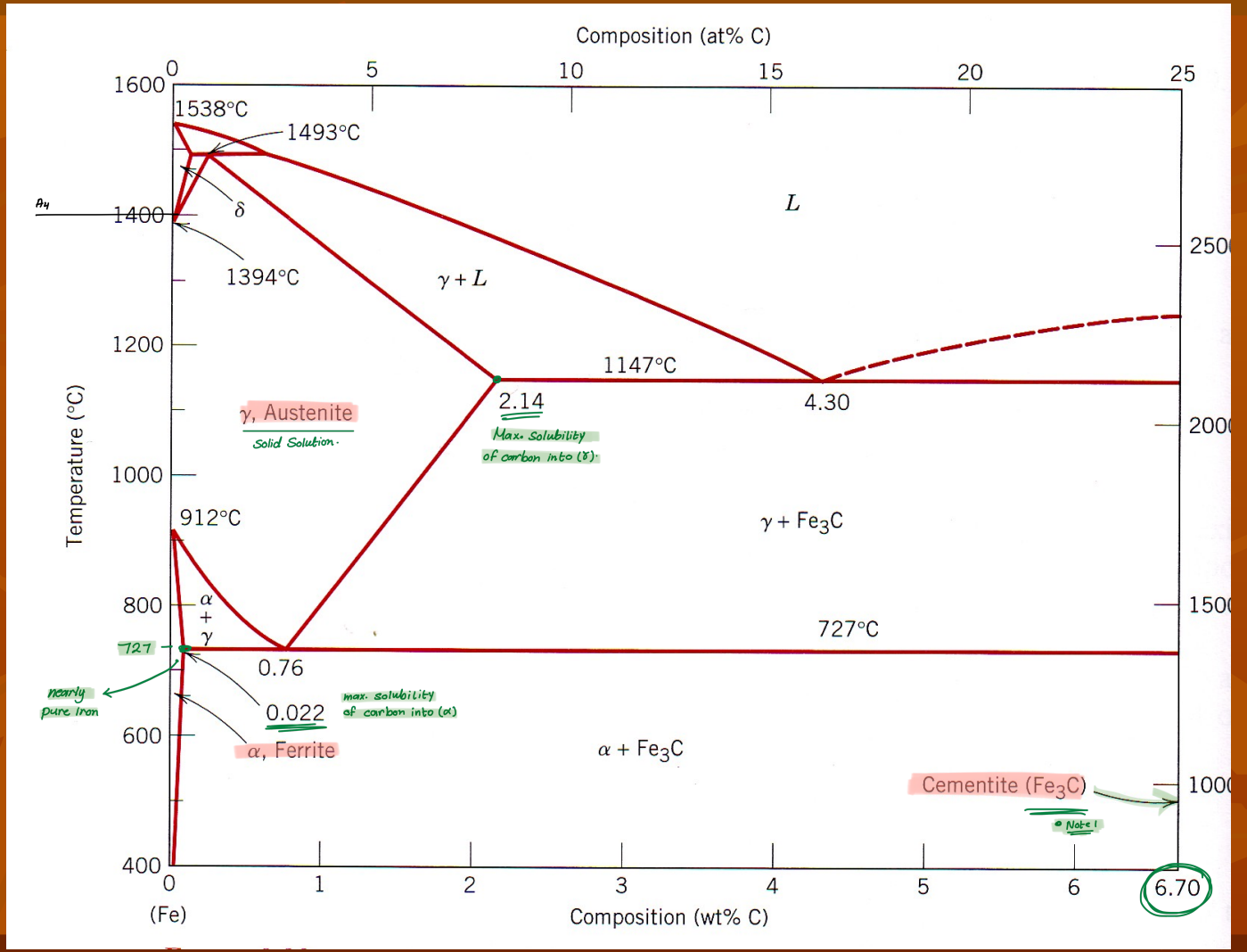
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* plane carbon: فولاذ كربوني بسيط
Carbon + Iron + Mn

* There is no solubility 100% for Carbon because (C) is non-metalic.
will form (intermediate / intermetallic).

non metal

Note (1): there is no area for (Fe_3C) because it's an intermediate phase → constant (Fixed) composition (Straight Line).



- Ignoring the upper left corner of the diagram, the important phases present are:
- ***γ phase or "Austenite"***. This phase has an FCC lattice structure with a maximum solubility of carbon of about 2% at around1150 ºC.

- ***α phase or "Ferrite".*** This is a soft phase (nearly pure iron) with a BCC lattice structure and a maximum solubility of carbon of about 0.02 % at around 727 ºC (in some texts 723 ºC).

- ***Fe3C (iron carbide) or "Cementite".*** This is a hard phase with a constant carbon content of 6.67 %.

* Low composition of Carbon = more softness for the metal.

* in (α) phase the solubility of carbon approach to zero; because of the BCC structure, and the solubility of (C) in (BCC) is very low.

Fe_3C : non-metalic / but not steel. till 2% C

- The practical portion of this phase diagram pertinent to plain carbon steels (i.e. with carbon content up to 2%)

2% carbon: max. solubility of carbon into (δ).

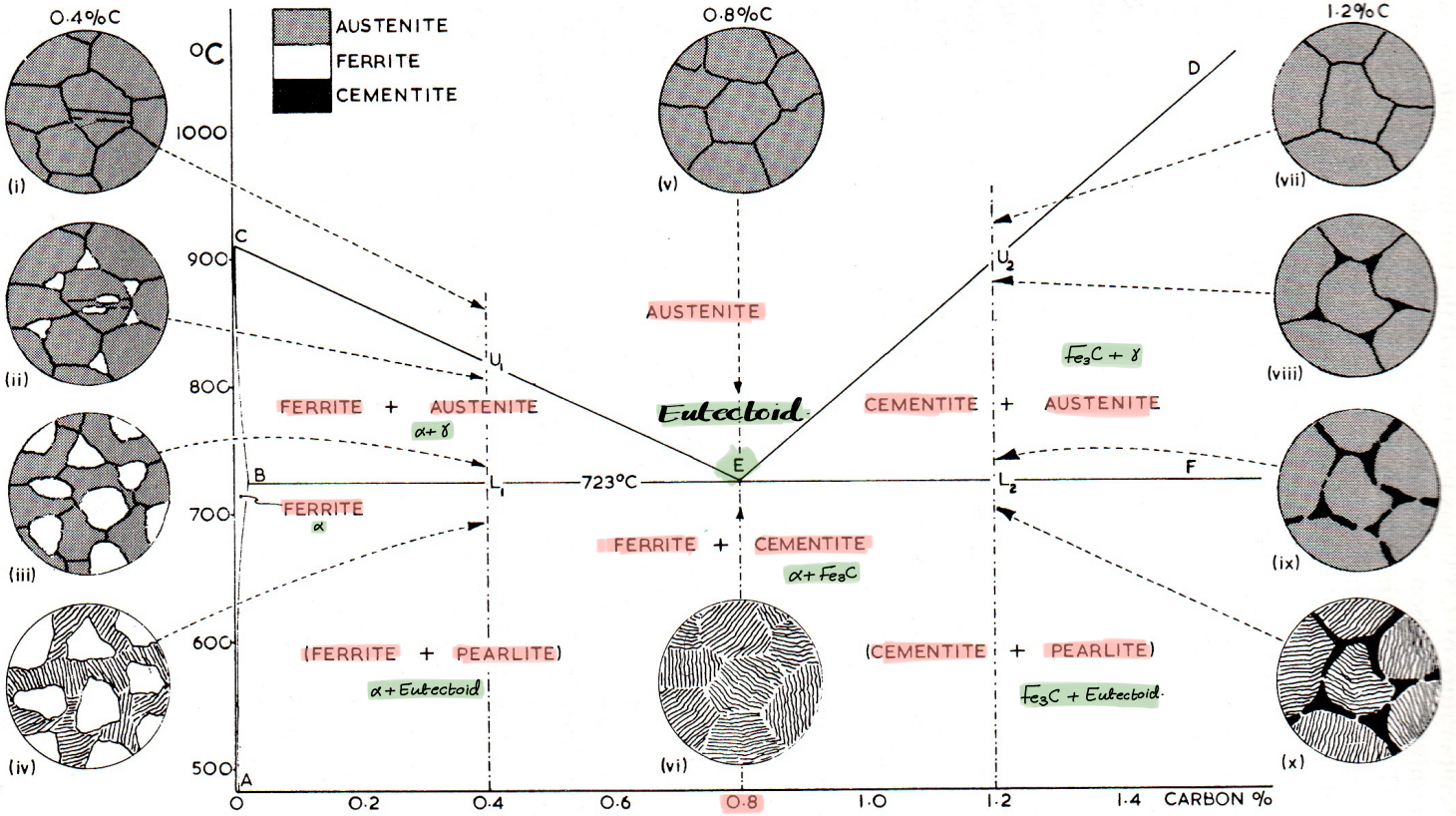
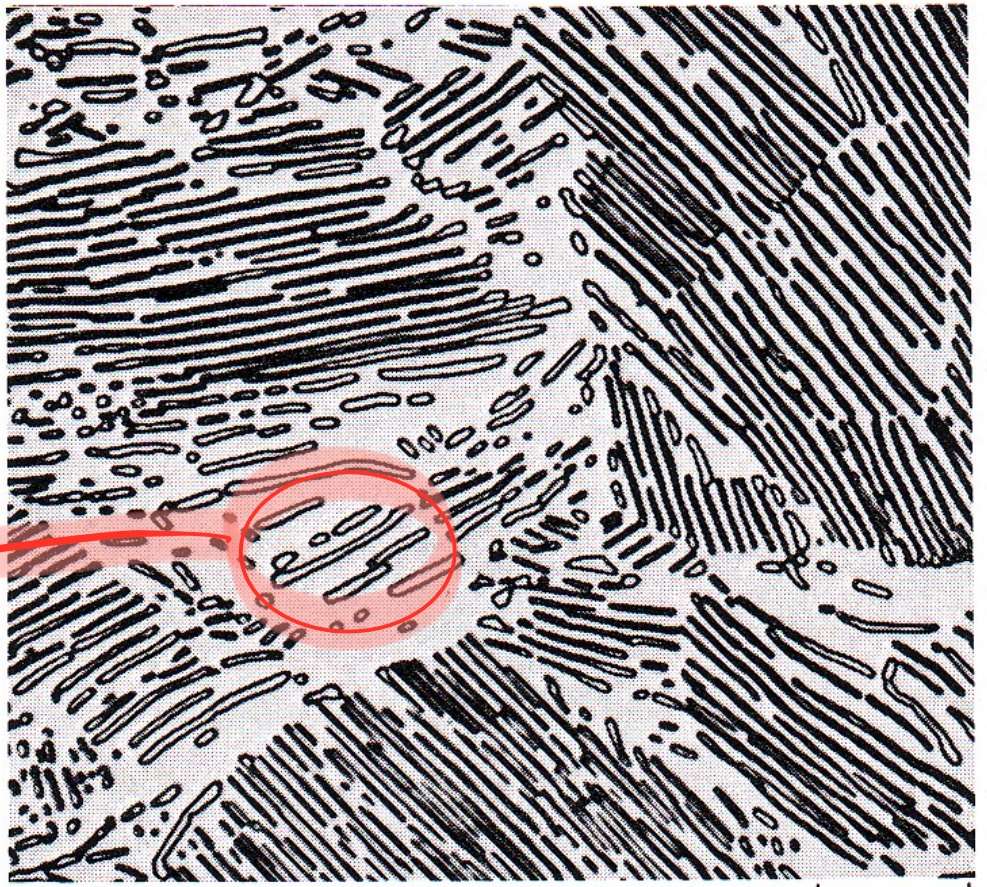


Fig. 7.6 Part of the iron–carbon thermal equilibrium diagram.

- The following can be noted:
- Upon cooling a steel of 0.8 % carbon content from the austenite region, the final structure will be a result of a eutectoid reaction ($\gamma \leftrightarrow \alpha + Fe_3C$) and the structure will be composed of alternate layers of ferrite and cementite.
- This type of structure is called "***Pearlite***".
- The thickness of these layers will depend on the cooling rate (slow cooling will promote course layers). This type of steel is termed "***Eutectoid Steel***"

Eutectoid Steel = Pearlitic steel.
* slow cooling → higher thickness.

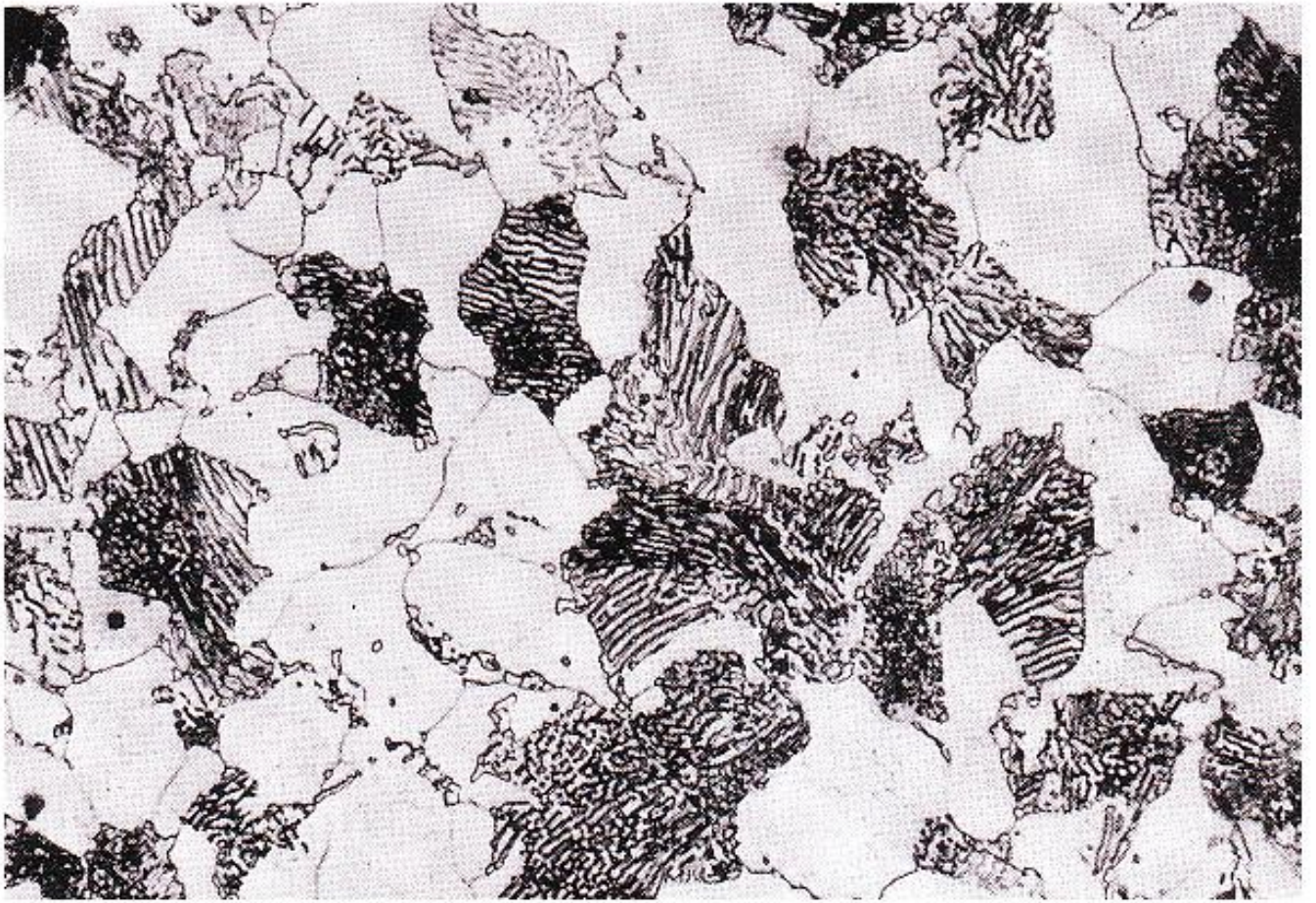


Pearlite

$\alpha + Fe_3C$

- Upon cooling a steel containing less than 0.8 % carbon content from the austenite region, the final structure will be composed of primary ferrite and eutectoid structure (pearlite).

- This type of steel is termed "***Hypoutectoid Steel***"



* Hypoeutectoid :

Primary (α) + Pearlite ·
↳ Eutectoid.
or Layers from $\alpha + Fe_3C$

- Upon cooling a steel containing more than 0.8 % carbon content from the austenite region, the final structure will be composed of primary cementite and eutectoid structure (pearlite).

- This type of steel is termed "***Hyperutectoid Steel***"

Hyperutectoid :

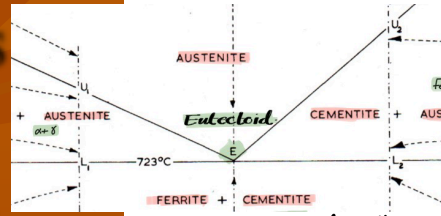
Primary (Fe_3C) + Pearlite.



Cementite in the Grain boundaries.

- The temperature below which austenite does not exist is termed the "***lower critical temperature***" this is a fixed temperature and is equal to the eutectoid temperature.

- The temperature above which ferrite (or cementite for hypereutectoid steels) does not exist is termed the "***upper critical temperature***".



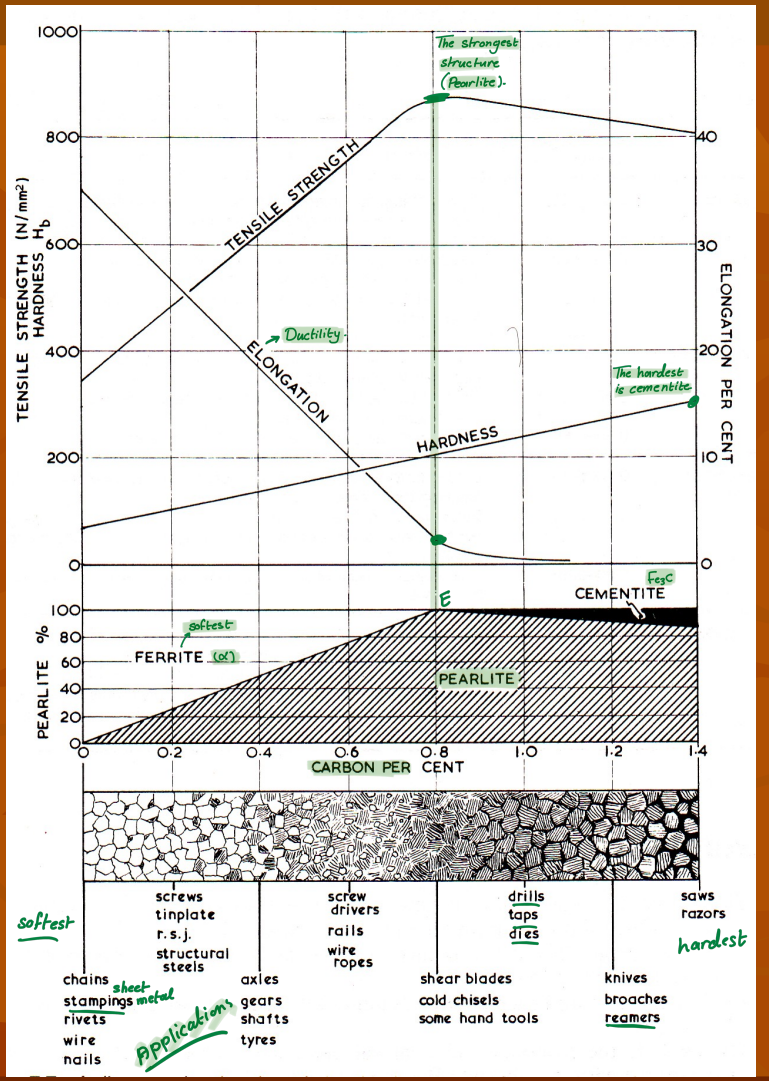
*no Austenite under the eutectoid temp.

Lower critical temp. (Fixed temp.).

not Fixed.

Depends on the composition.

The relationship between carbon content and some mechanical properties of plain carbon steels



0% Carbon ⟶ 100% (α) with BCC structure.

then up to 0.8% ⟶ Primary (α) + Pearlite.

till 0.8% ⟶ 100% Pearlite (Eutectoid).

after 0.8% ⟶ Primary cementite + Pearlite.

- It can be noted that:
- Percent elongation decreases with increasing carbon content
- Hardness increases with increasing carbon content.
- Strength seems to increase with increasing carbon content reaching a maximum with a 100% pearlitic steel and then start to decrease.

Chapter Four

Heat Treatment of Plain Carbon Steels

• Plane carbon steel : فولاذ كربوني بسيط

Low carbon with small amount of Mg.

not for alloying , but just to remove sulfer

Plane : only carbon with the iron.

Heat treatment → only to change the structure
- Higher strength
- stress relive ---

- Heat treatments can be applied to steels for various purposes such as improving strength, stress relieving, increasing hardness, toughness, ductility, etc.

- The various heat-treatment processes can be classified as follows:

- Annealing
- Normalizing
- Hardening
- Tempering
- Treatments involving isothermal transformations (or continuous cooling)
- Case hardening

• Annealing → multiple processes for heat treatment.

• isothermal : non-equilibrium , heat treatment processes (cooling) at constant temp. or continuous cooling.

Case hardening : hardening for a certain depth of the surface.

• The common : Steel is heated slowly to predetermined but not same cooling rate.

- In all these processes the steel is heated quite slowly to a predetermined temperature and then cooled.

- The rate of cooling is the factor that determines the resulting microstructure and the associated mechanical properties.

with thermal processing.

- This may vary from a drastic water quench to a slow cooling in a furnace.

• Properties depends on the structure
x the structure depends on the chemical composition x mechanical or thermal processing.

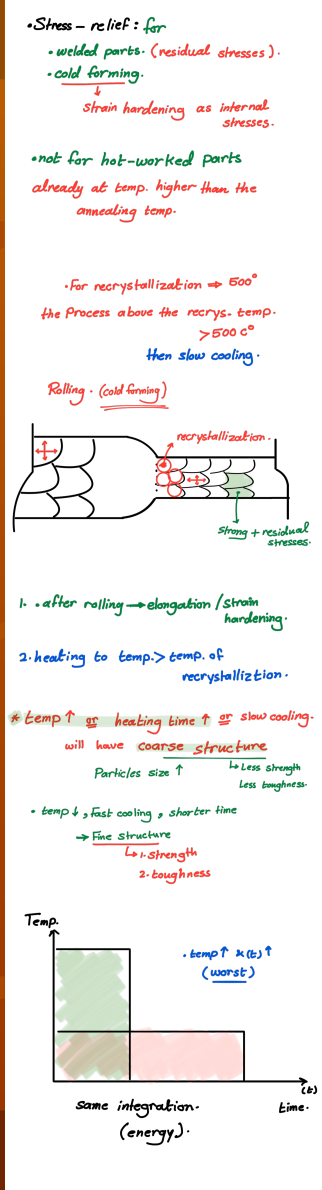
- The various processes will be explained as follows:
- **Annealing**
- The term annealing describes a number of different heat treatment processes applied to metals and alloys and can be classified as follows:

Annealing:
1. Stress-Relief.
2. Spherodising.
3. For Large casting.

→ increasing the toughness. not for hardness.
or increasing ductility or strength, depends on the type of annealing.

Stress-relief annealing

- This type of annealing is normally carried out below the lower critical temperature and is applied to cold worked parts in order to relieve stresses set up by mechanical working (cold forming).
- The process is quite simple and involves heating the steel to above its recrystallization temperature (500 □C) normally to 650 □C and then allow slow cooling.



- Long time heating :

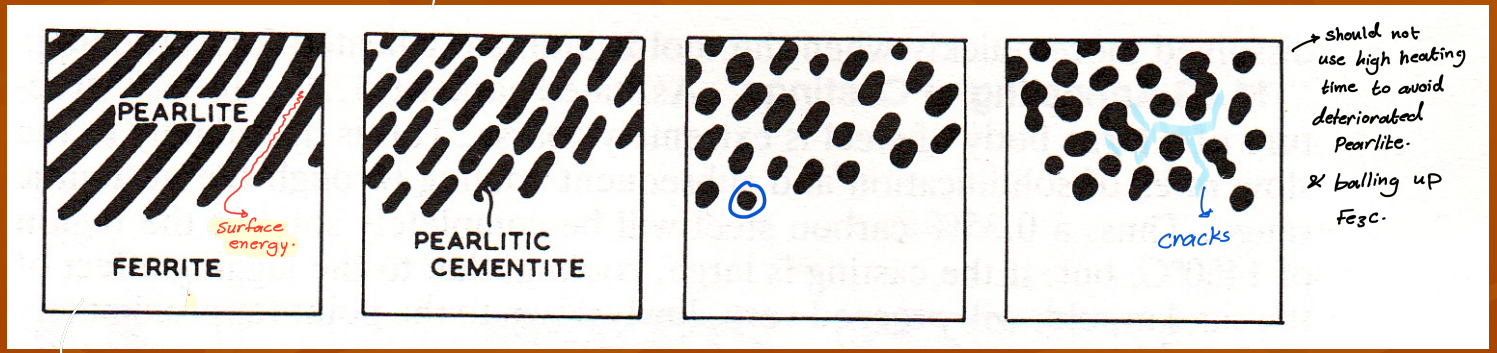
relief the strain hardening.

- It should be noted that although ductility is increased, prolonged annealing may result in deterioration of properties resulting from the "balling up" of cementite layers within the pearlite resulting in a structure known as "***deteriorated pearlite***"

NOT the annealed structure,

The original

• there is a Difference in elongation rate btw Fe_3C & (α) → crack under high temp. → change in volume under the temp. effect.



→ should not use high heating time to avoid deteriorated Pearlite.
& balling up Fe_3C.

→ toughness from (α)
Strength from (Fe_3C.)

Prolonged heating above recrystallization temp.

• after the high surface energy...
the sys. seeks to min. the energy
→ change the shap to spherical (balling up).
↳ surface area to volume (smallest)

• can't reach the spherical shap totally → produce (deteriorated pearlite).
& balling up.

→ then cracks :
• reduce toughness & strength.
• weak & brittle structure.

→ also at recrystallization
energy ↑ & strain hardening
lower surface area (balling up.)
at: 1. slow cooling
2. higher temp.
3. thermal energy.

بهاي الحالة بتضل تتكسر وتتحد مع بعضها وتكون اجزاء اكبر.

Spherodising anneals

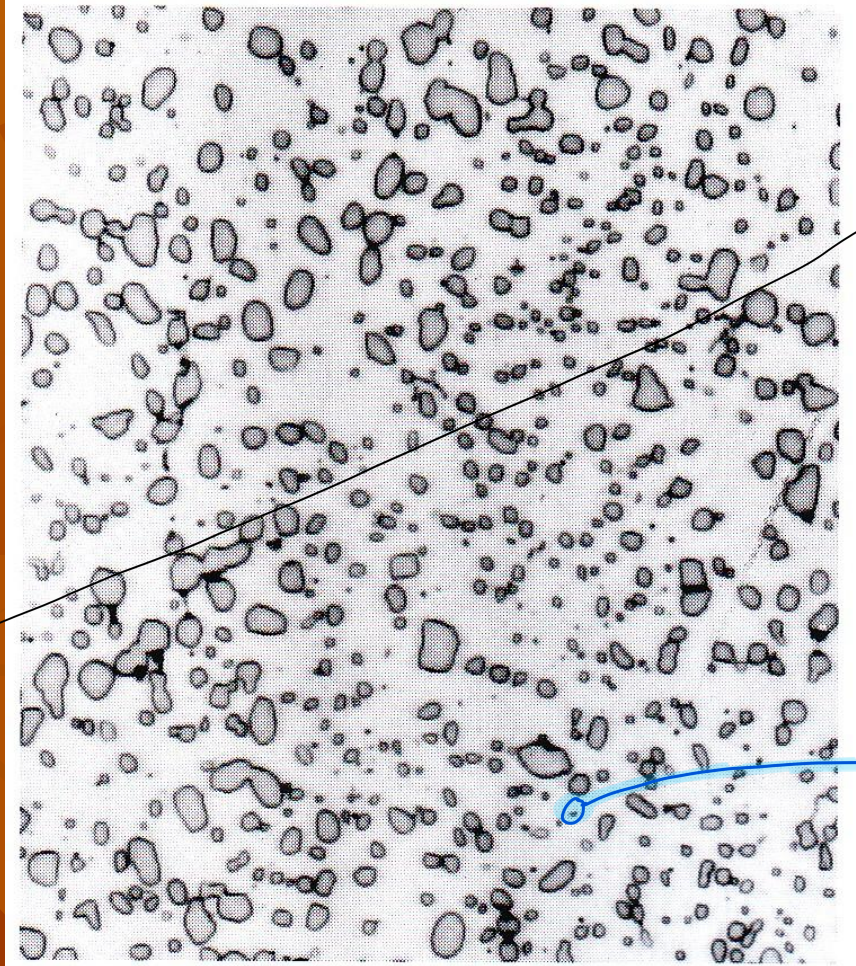
- Spherodising annealing is carried out by heating the steel to a temperature just below the lower critical temperature (between 650 and 700□C).
- This, as expected, would result in globular cementite within the pearlite.
- This is used to improve machinability of steels for subsequent hardening.

Same process as deteriorated annealing.

· just below the critical temp.

not improvement for properties, just improvement for machinability.

*Spherodising is used for steels that are used in subsequent hardening. (hardening conditions).



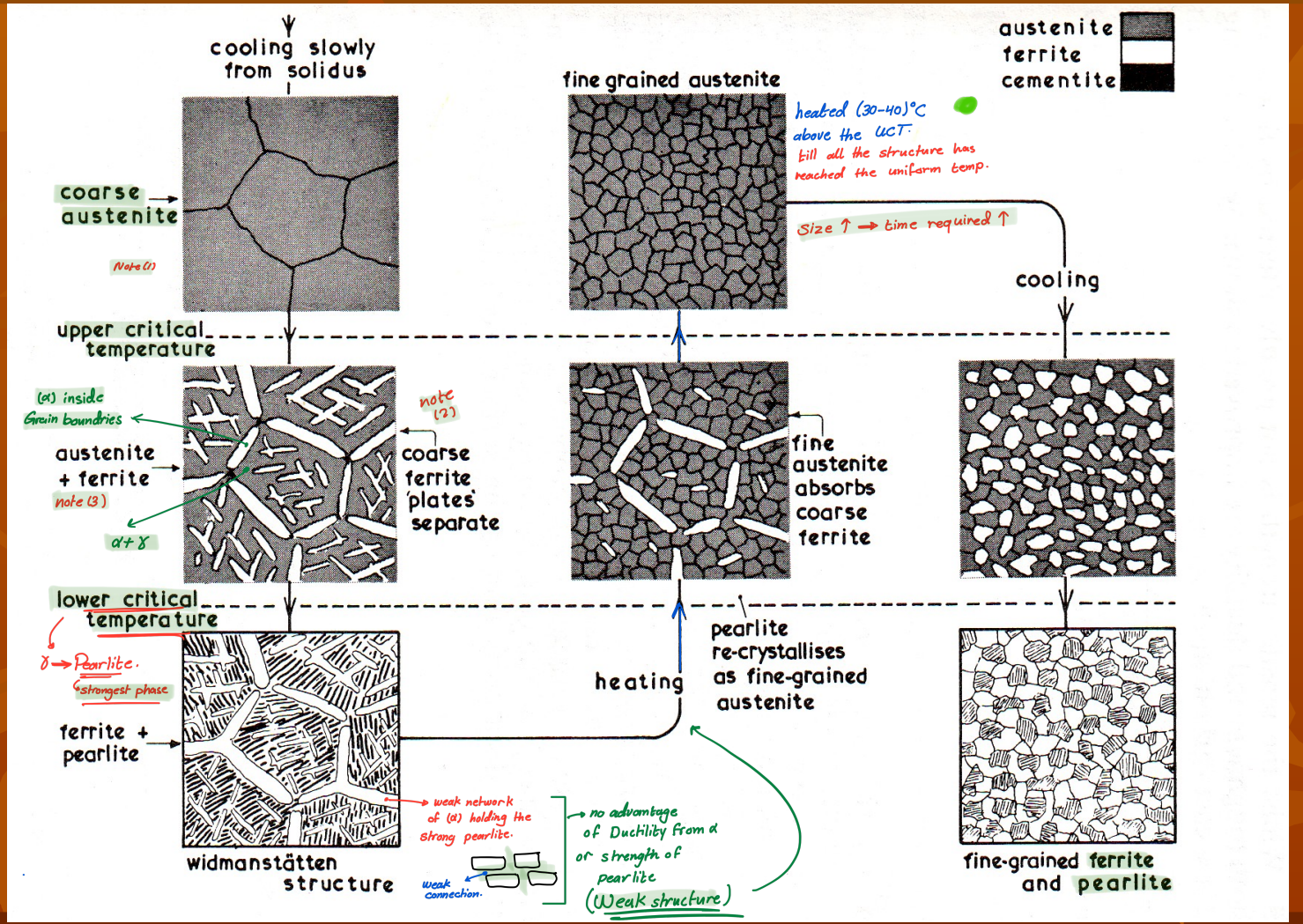
Original thickness for Fe_3C.

- increase machinability.
  (decrease the hardness).
  then return it to the original
  most of the space will be soft Fe

→ the size (thickness) for the spherical increase وبيتحدو مع بعض.

Annealing of large castings

- Sand casting
- Low cooling rate



in sand casting:
- Slow cooling rate.
- coarse structure.

note (1): structure same as high temp & long time.
Extremely coarse (γ).

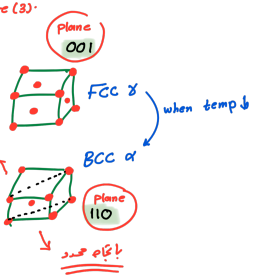
note (2): ferrite starts btw UCT & LCT in the high energy sits (Grain boundries).

Fine Grain (γ):



thickness of (α) starts to be higher the the thickness of the boundries

note (3).



- This process will be explained as follows:
- As large casting cool slowly through the austenite region (above the upper critical temperature), the grain size tends to increase dramatically driven by the high temperatures.

- As the temperature passes the upper critical temperature, ferrite starts to precipitate along austenite grain boundaries and as cooling continues within the grains along certain crystallographic directions.
- As temperature falls to the lower critical temperature, the remaining austenite transform to pearlite.

- This result in islands of strong pearlite separated (or held) by a weak network of soft ferrite. This structure is termed "**Widmanstatten structure**" characterized by brittleness and weakness.

- This structure is heated to a temperature 30 to 40 □C above its upper critical temperature and is held long enough just to allow the part to attain uniform temperature.

- This would result in transformation to austenite, but this time the grain size is small, as the temperature is not too high.

- Upon cooling the final structure will be composed of fine ferrite and pearlite a structure with enhanced strength, ductility and toughness.

Normalizing

- Normalizing is used to provide enhanced strength and toughness.
- The process is basically the same as that of annealing of casting except that after heating cooling is promoted by allowing the part to cool in air.
- This would result in a finer structure and higher strength levels than those attained in an annealed part.

• Normalizing ,
Same as annealing for casting but for smaller sizes.

• much Finer structure , Faster cooling than the annealed casting.

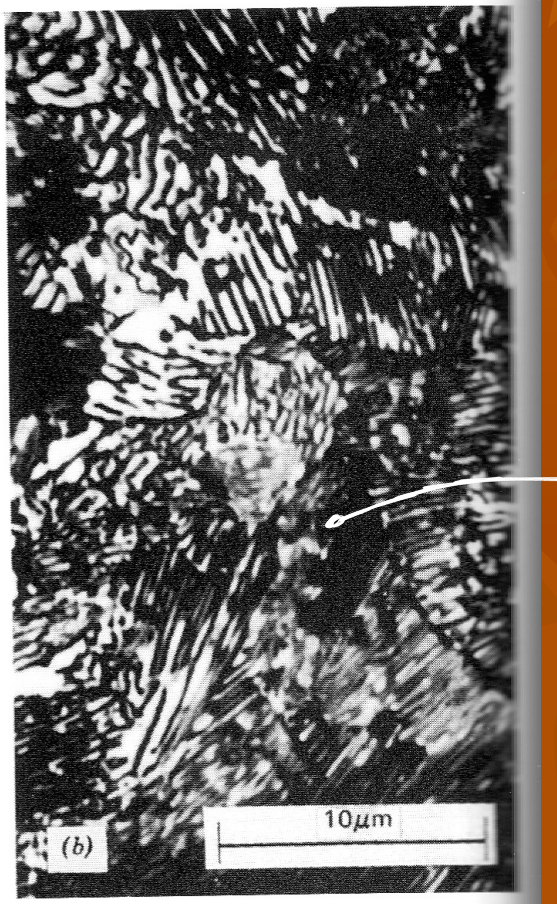
always toughness & Strength related to Fine structure.

Fine structure ⇒ toughness ↑
Strength ↑
Ductility ↑

Large-cast annealing

Normalizing





Normalized

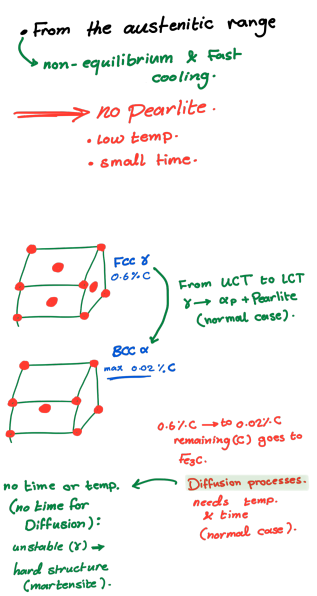
- smaller size

- Faster cooling

Hardening

تبريد سريع بغض النظر عن الوسط

- When plain carbon steel is quenched from its austenitic range the normal transformation to pearlite is not possible due to the low temperature and small time allowed for transformation.
- It is not also possible to “freeze” the austenitic structure due to the fast transformation rates involved in steels.



- Water quenching of a steel containing sufficient carbon produces an extremely hard structure called "***martensite***".

- Martensite appears under the microscope as a mass of uniform needle shaped crystals,



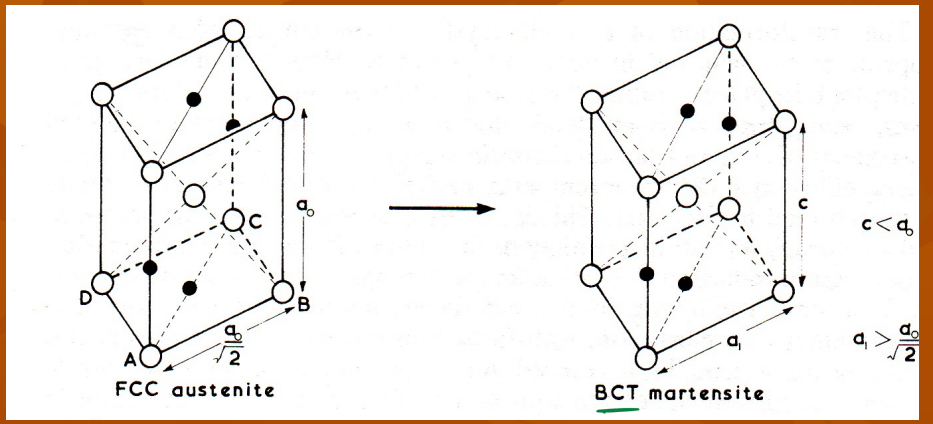
- Needle shape:
  - sharp
  - hard
  - brittle.

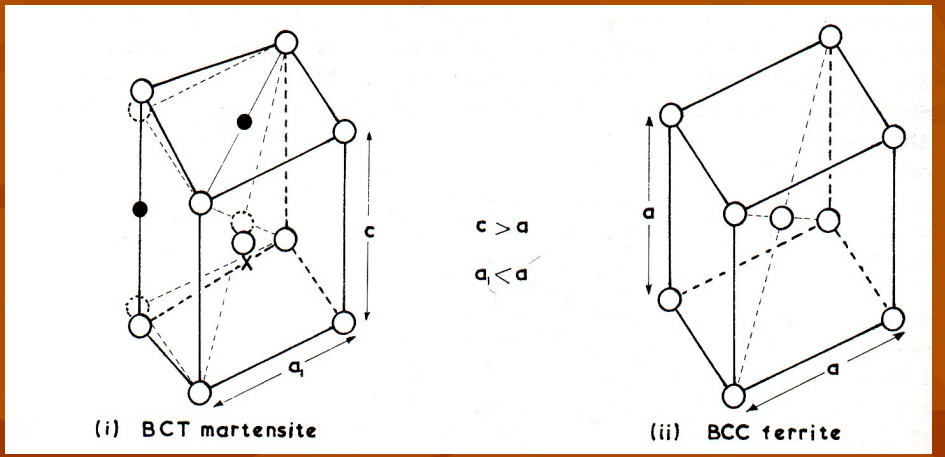
- The lattice changes from that of FCC to one approaching the BCC.
- The BCC however can accommodate no more than 0.06 % carbon at room temperature.
  0.006 %
- This is expected to cause considerable distortion.

- In fact martensite has a ***distorted*** body-centered-tetragonal (BCT) one which is between the FCC and BCC.

- This distortion is perhaps one reason for this increased hardness.

max. for γ = 0.6 % C
" " BCC = 0.006 % C
$\frac{0.6}{0.006}$ = 100 times higher.


C
a_0
D
B
A
$\frac{a_0}{\sqrt{2}}$
FCC austenite
c
a_1
BCT martensite
$c < a_0$
$a_1 > \frac{a_0}{\sqrt{2}}$

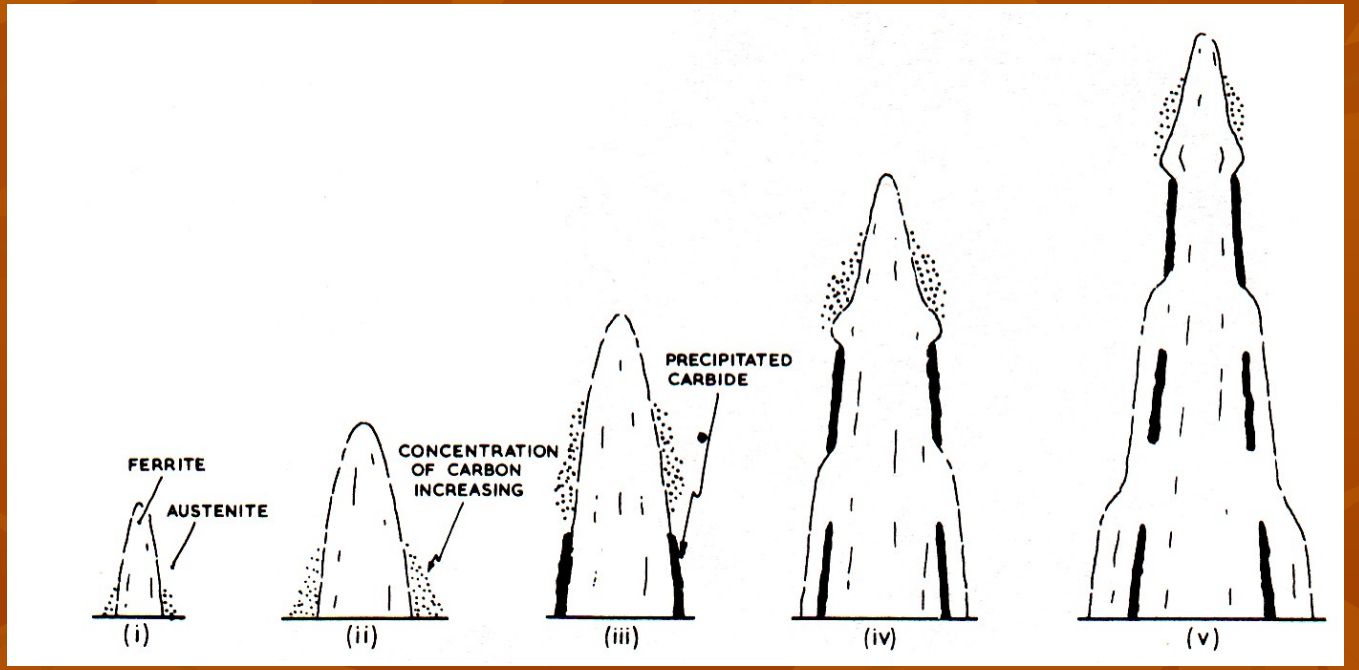

c
X
a_1
(i) BCT martensite
$c > a$
$a_1 < a$
a
a
(ii) BCC ferrite

- Less severe quenching produces a structure known as "***Bainite***".

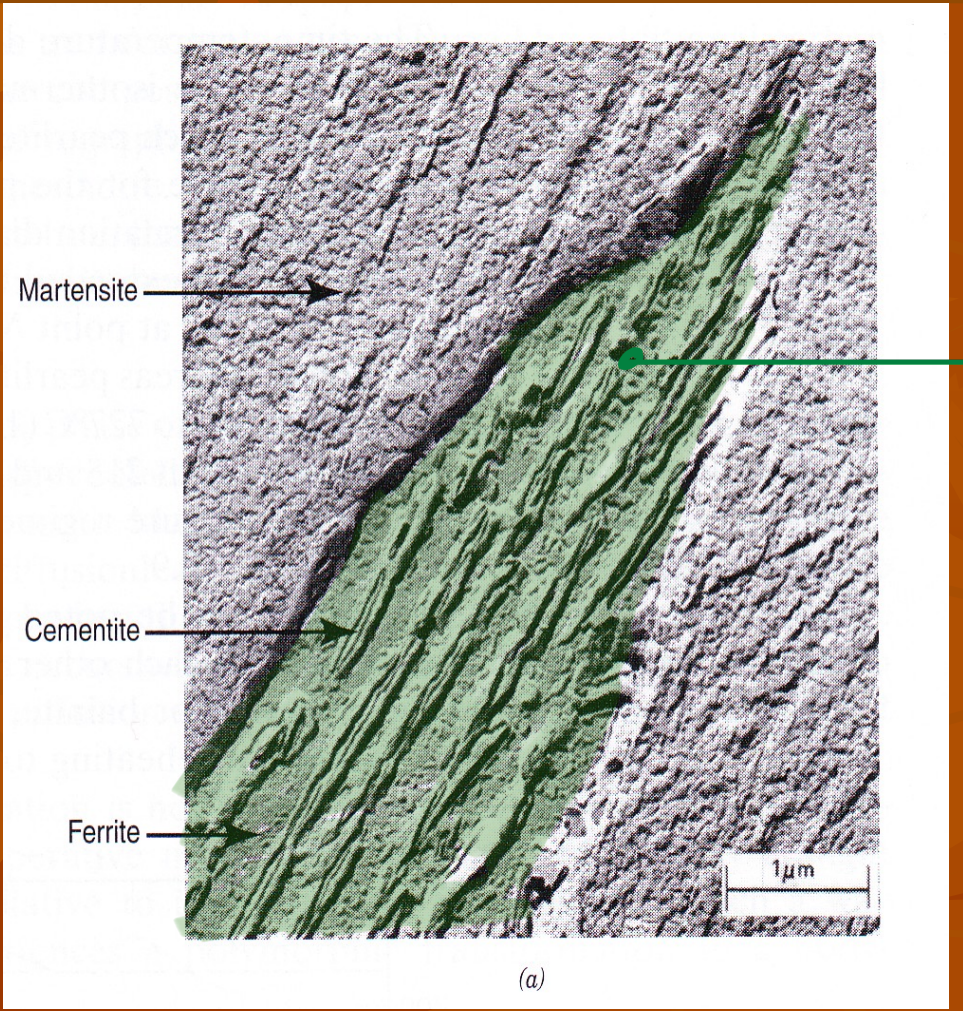
- This phase appears under the microscope of magnifications around X 100 as black patches, but at higher magnifications of X 1000 appears as laminated structure something like pearlite.

• Fast cooling : martensite.
• Slow cooling : Pearlite
btw. them → Bainite
↳ more hardness than Pearlite & less than martensite.

- The growth of Bainite differs from that of pearlite in that ferrite nucleates first followed by carbide, whereas in pearlite the carbide nucleates first.


FERRITE
AUSTENITE
CONCENTRATION OF CARBON INCREASING
PRECIPITATED CARBIDE
(i)
(ii)
(iii)
(iv)
(v)

Martensite & Bainite



(a)

Fe_3C & (α) inside Bainite.

Quenching media

- The quenching medium is chosen according to the desired cooling rate. The following list is arranged in order of quenching speeds (high to low):
  - 5 % caustic soda
  - 5 – 20 % Brine
  - Cold water
  - Warm water
  - Mineral oil
  - Animal oil
  - Vegetable oil

• cooling rate depends on the quenching media.

Tempering

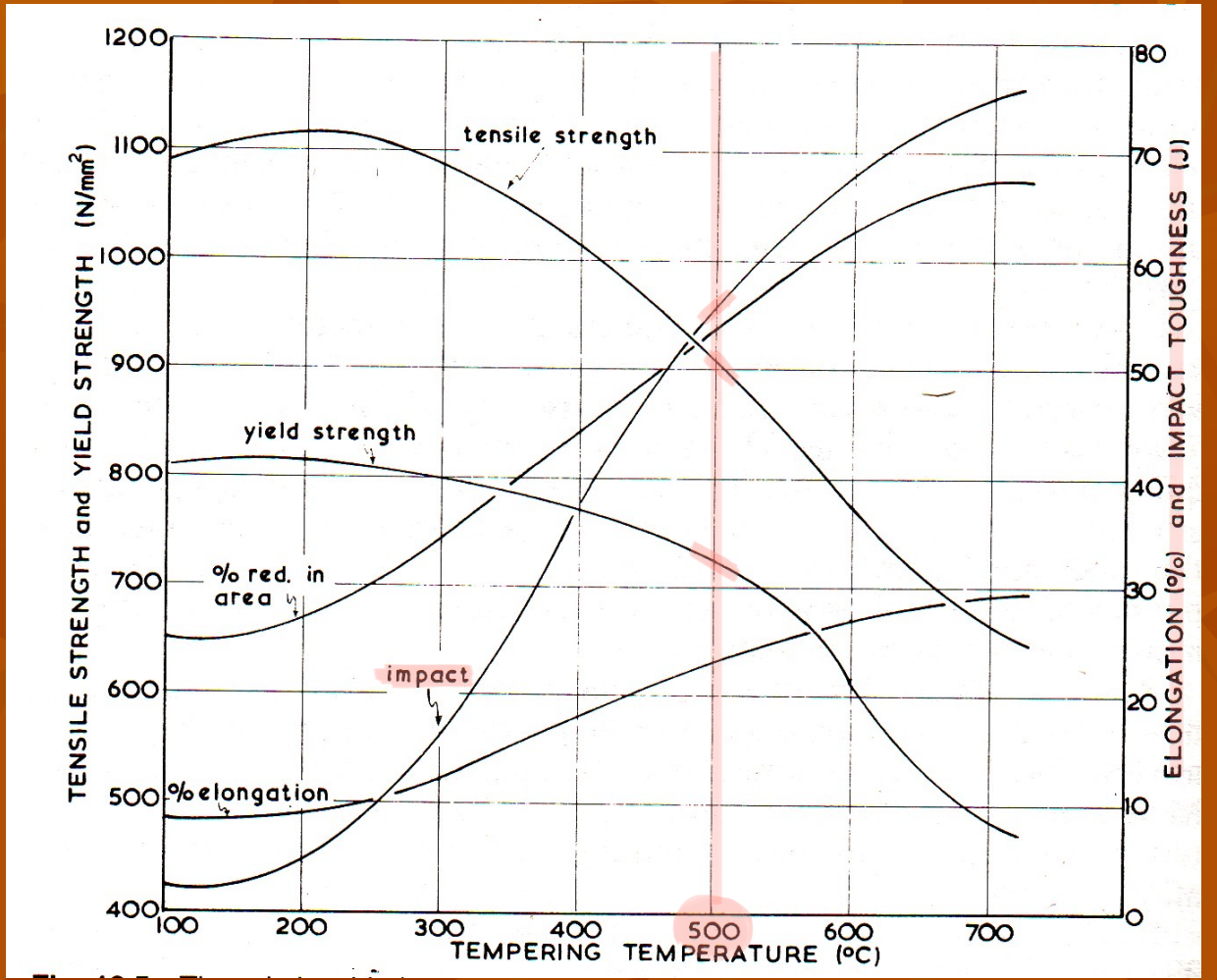
- Tempering is referred to "***re-heating of quenched steel parts in order to relieve stresses set up by quenching and reduce brittleness introduced by the extreme hardness values***"

• martensite : hard but brittle. & high stresses.
→ can't be used when it's quenched. till tempering (re-heating).

increasing toughness & reducing brittleness.

- It is always carried out below the lower critical temperature

- Properties attained depend on the highest temperature reached. Thus the temperature to which a part should be heated must be chosen according to the required properties.



at 500 c°
strength ↓
toughness ↑
Yield ↓

Structural changes during tempering

- The structural changes which occur during the tempering of martensite containing more than 0.3 % carbon takes place in three stages:

First stage: At about 100 ºC

- the existing martensite transform to another type of martensite containing only 0.25 % carbon.
- This is accompanied with the precipitation of very fine particles of ε-type carbide (Fe_5C_2).

- At this stage slight increase in strength and hardness may occur due to the dispersion of fine but hard carbides but brittleness is significantly lowered as quenching stresses disappear in consequence of transformation.

- The rate of transformation is speeded up around 200 ºC

start to release the carbon from martensits. till 0.25%. as Fine particles of ε-carbide.

increase in strength & hardness.

Second stage begins at about 250 °C

- Any "retained austenite" begins to transform to Bainite.
- A further increase in hardness may result due to the replacement of austenite by the much harder Bainite.

but still contain untransformed γ (retained/unstable).

γ: Didn't transform to martensite.

increasing temp. become bainite.

more hardness than (B).

So increase in hardness & strength.

Third stage At about 350 °C

- ε-carbide starts to transform to ordinary cementite and this continues as the temperature rises.
- In the meantime the remainder of the carbon begins to precipitate from the martensite – also as cementite- and in consequence (of freeing carbon) martensite reverts back to its equilibrium form of BCC ferrite.

• Strength starts to decrease.
& toughness increase.

350° btw room temp. & LCT.

From Fe_5C_2 to Fe_3C

ε ⟶ Fe_3C

increasing temp. to allow the (C) to be removed from BCC of martensite ⟶ to Fe_3C.

↳ equilibrium form.

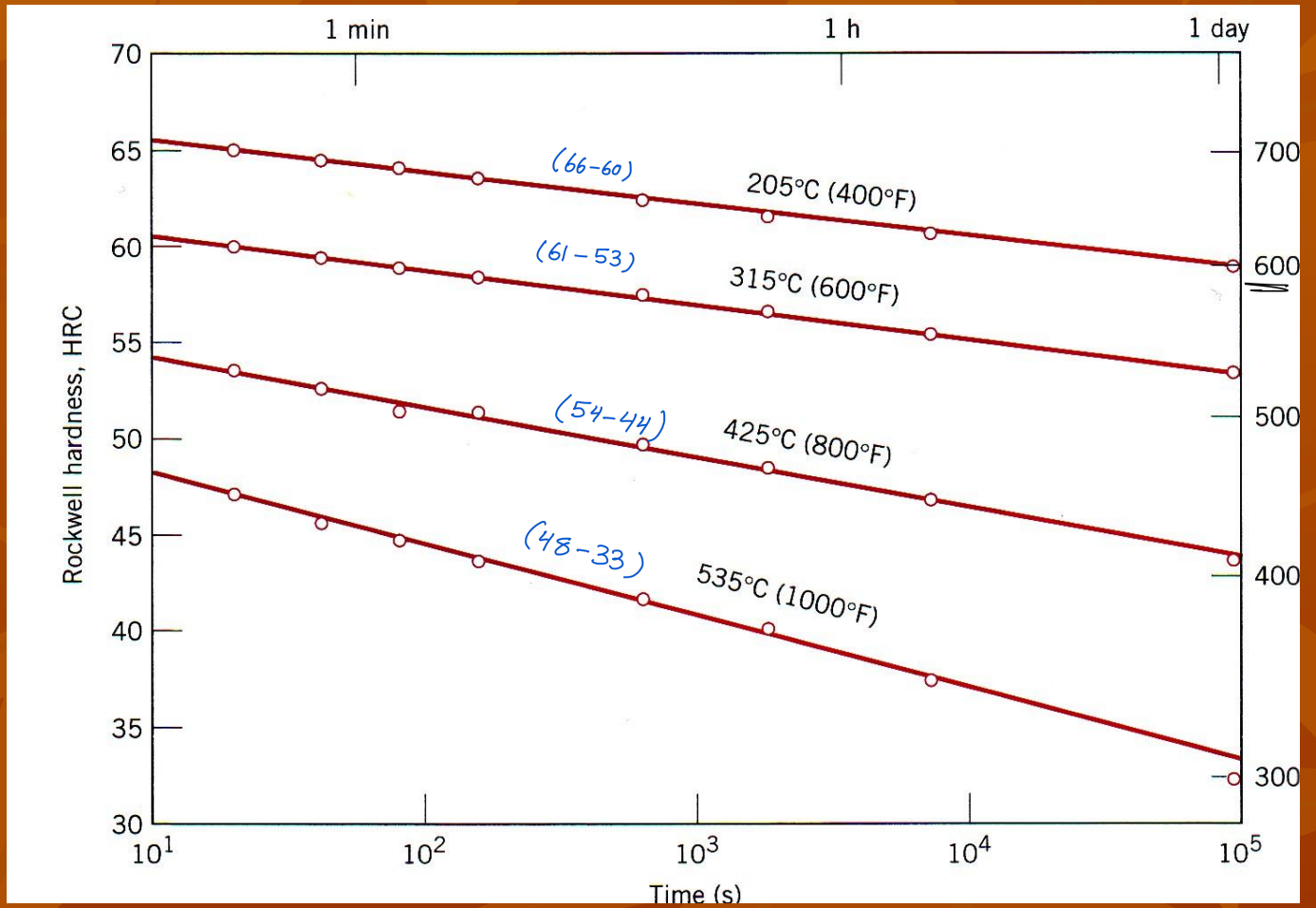
martensite ⟶ (α).

effect hardness & strength.

- Above 500 ºC the cementite particles coalesce into larger rounded globules in the ferrite matrix. This structure is known as "***tempered Martensite***"



close to spherodized steel



- temp. effect > Time effect.

slop in time ↓
slop in temp ↑

temp ↑ → transformation speed ↑
- hardness ↓
- more equilibrium structure.

10^5: time required for decreasing the hardness according to temp.

Table-1. Tempering colors for Plain-carbon-steel Tools

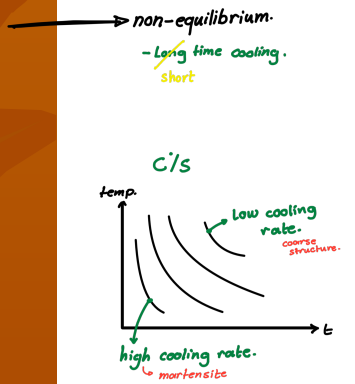
Temperature (°C)	*Colour*	*Type of component*
220	Pale yellow	Scrapers; hack saws; light turning and parting tools
230	Straw	Screwing dies for brass; hammer faces; planing and slotting tools
240	Dark straw	Shear blades; milling cutters; paper cutters; drills; boring cutters and reamers; rock drills
250	Light brown	Penknife blades; taps; metal shears; punches; dies; wood-working tools for hard wood
260	Purplish-brown	Plane blades; stone-cutting tools; punches; reamers; twist drills for wood
270	Purple	Axes; gimlets; augers; surgical tools; press tools
280	Deeper purple	Cold chisels (for steel and cast iron); chisels for wood; plane cutters for soft woods
290	Bright blue	Cold chisels (for wrought iron); screw-drivers
300	Dark blue	Wood saws; springs

temp ↓ → impact resistance ↓
hardness ↑
T. life ↑

Isothermal transformations

- As pointed above the microstructure and properties of quenched steels are dependent on the rates of cooling.

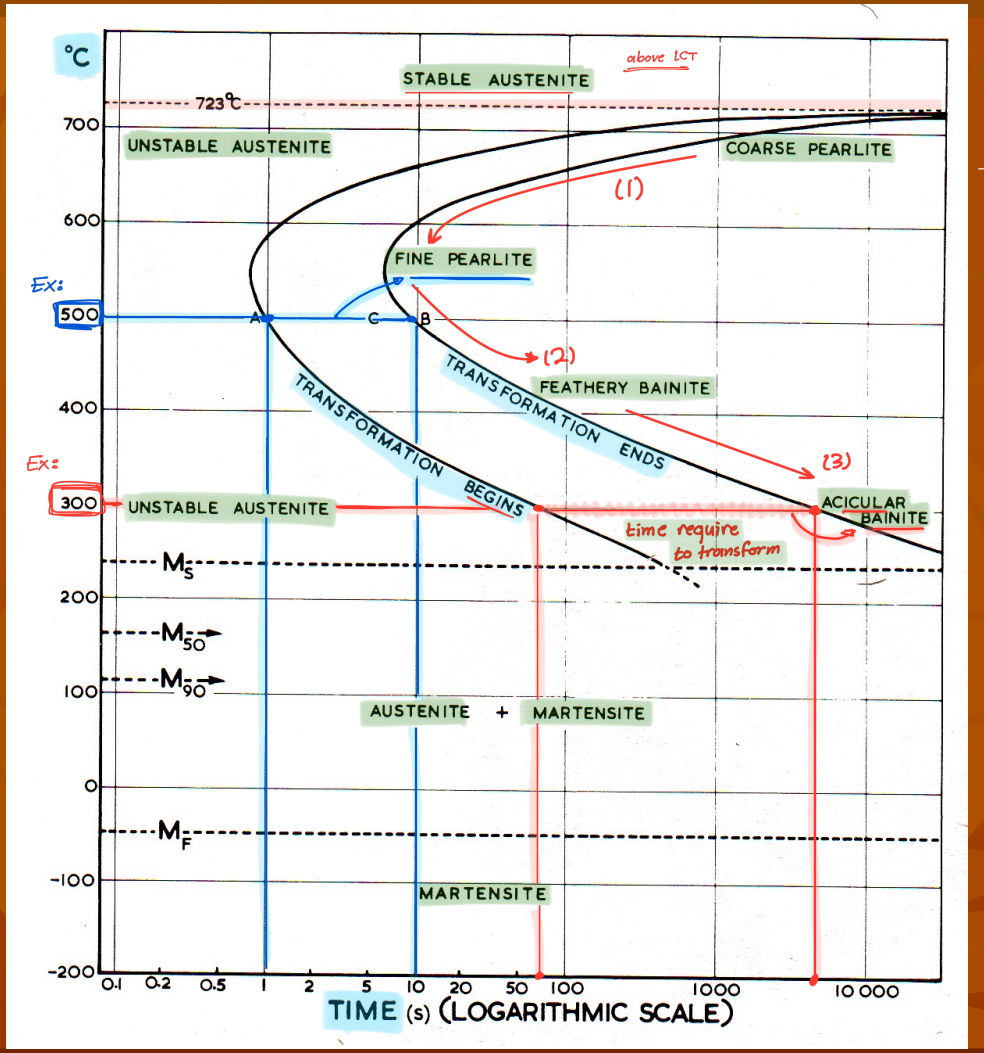
- This relationship between structure and the rate of cooling can be studied by the aid of a set of isothermal transformation curves known as **TTT (*Time-Temperature-Transformation*)** curves.



Part (1) :

→ C-curves

→ For Eutectoid steel.



Difference btw. phase digram & TTT curve :

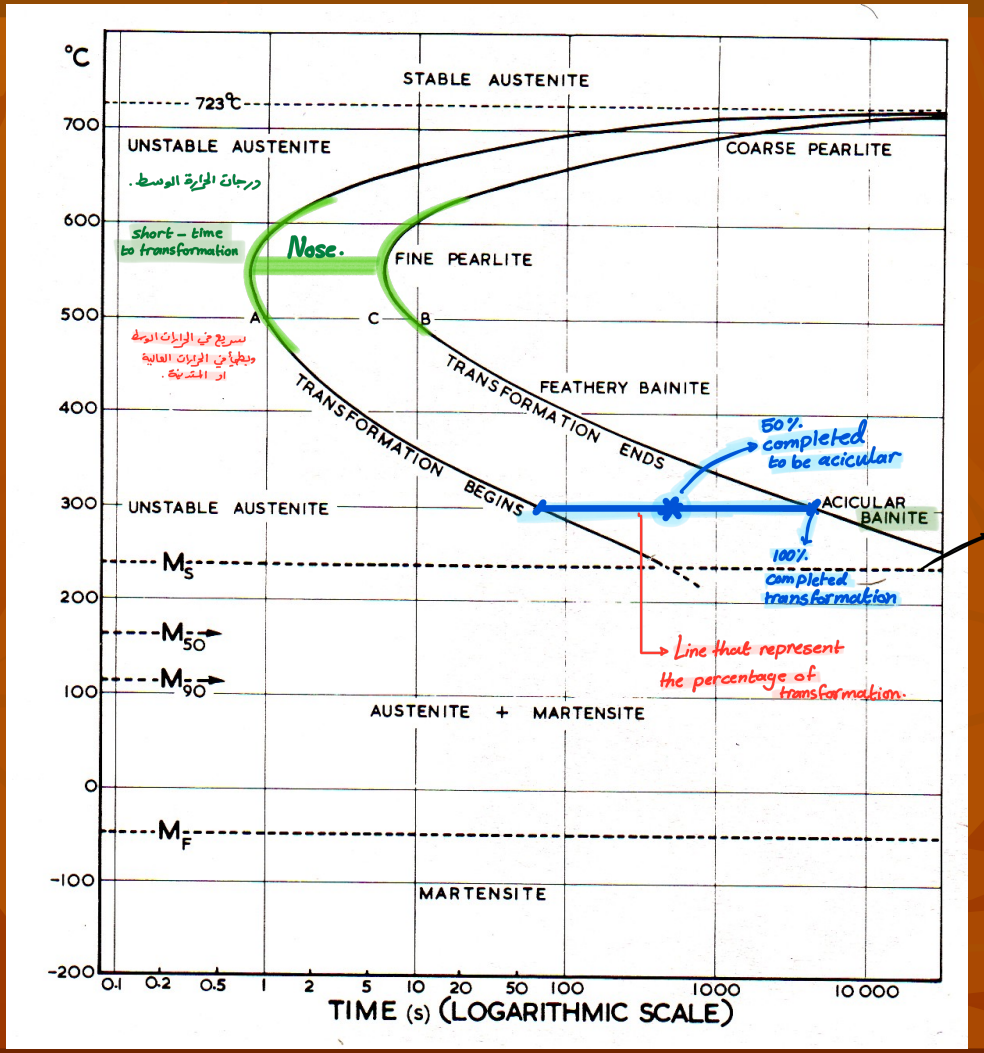
- phase digram represent all steels (0- 1.4) %.C
- TTT curve : seperate curves for each steel.

The only phase that transform to other ⟶ (γ)

cooling rate
- Fast → non-equilibrium (martensite)
- Slow → bianite → if slower → Pearlite & (α).

- (γ) supercooled → high cooling rate. no time to transformation. for stable phase.
  & time close to zero

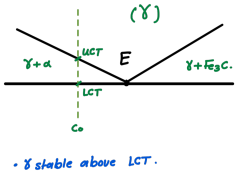
Part (1)(2) :



in tempering at 250c° any remaining (γ) transform to bainite.

- TTT curves indicate the time necessary for transformation to occur, the resulting structure and the time needed for transformation to be completed when austenite is "supercooled" to a predetermined temperature.

- Each steel will have a pair of c-shaped curves indicating the commencement and completion of transformation at a particular temperature.



- These are termed “transformation begins and transformation ends, respectively. It is noted that each curve has a “nose” at intermediate temperatures (in the case of eutectoid steel around 550 ºC), indicating this temperature to have the shortest time for transformation to start and, eventually, end. This can be explained by the following points:

- At relatively high temperatures (close to the lower critical temperature) even though austenite is unstable, the driving force for transformation is not, however, strong, as instability of austenite is not great.

- At relatively low temperature, austenite is more unstable, the temperature is not, however, high enough to promote fast transformations.

Diffusion.

Distance from 723° ↑ → unstability ↑

• unstability ↓ → Driving force ↓
but temp ↑
strength of transformation ↓

unstability ↑ → Driving Force ↑
Low temp
strength of transformation ↓

- At medium temperatures austenite is unstable and the temperature is high enough to promote fast transformations.

- A few extra points have to be made regarding these curves:

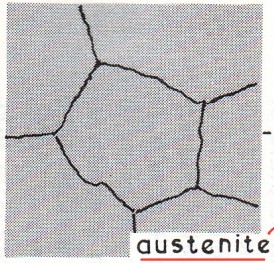
- In order for a steel to develop a completely martensitic structure it "***must not***" cross the transformation begins curve (past the nose), as this would cause other phases (such as pearlite or Bainite) to be present in the final structure.

- The lines MS, M50, M90 and MF refer to temperatures at which transformation to martensite; Starts, 50 % complete, 90 % complete and finishes, respectively.

- As in this case the MF is below 0 ºC, no matter drastic the quenching is, martensitic transformation will not be complete if quenching to room temperature is used. In this case the final structure will contain some "***retained (untransformed) austenite***".

- It should be noted that on these diagrams the time is plotted using a logarithmic scale, whilst temperature is plotted using a linear scale.

3 cooling Scenario,



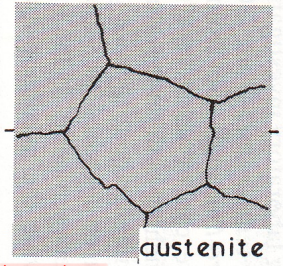
austenitising bath (730°C)

austenite — Stable.

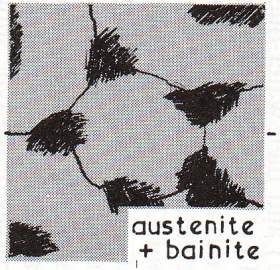
A_1 temperature (723°C) — LCT.

incubation bath (500°C)

before the nose temp.



austenite



austenite + bainite

transformation complete.



bainite

cooling after 1s. 1s to room temp.

cooling after 5s 5 s then quenching.

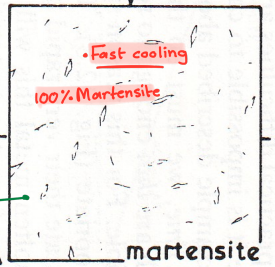
10 s

water quench

martensite because it's before the nose. trans. not ended yet.

• Fast cooling

100% Martensite



martensite

A



martensite + bainite 500°

C

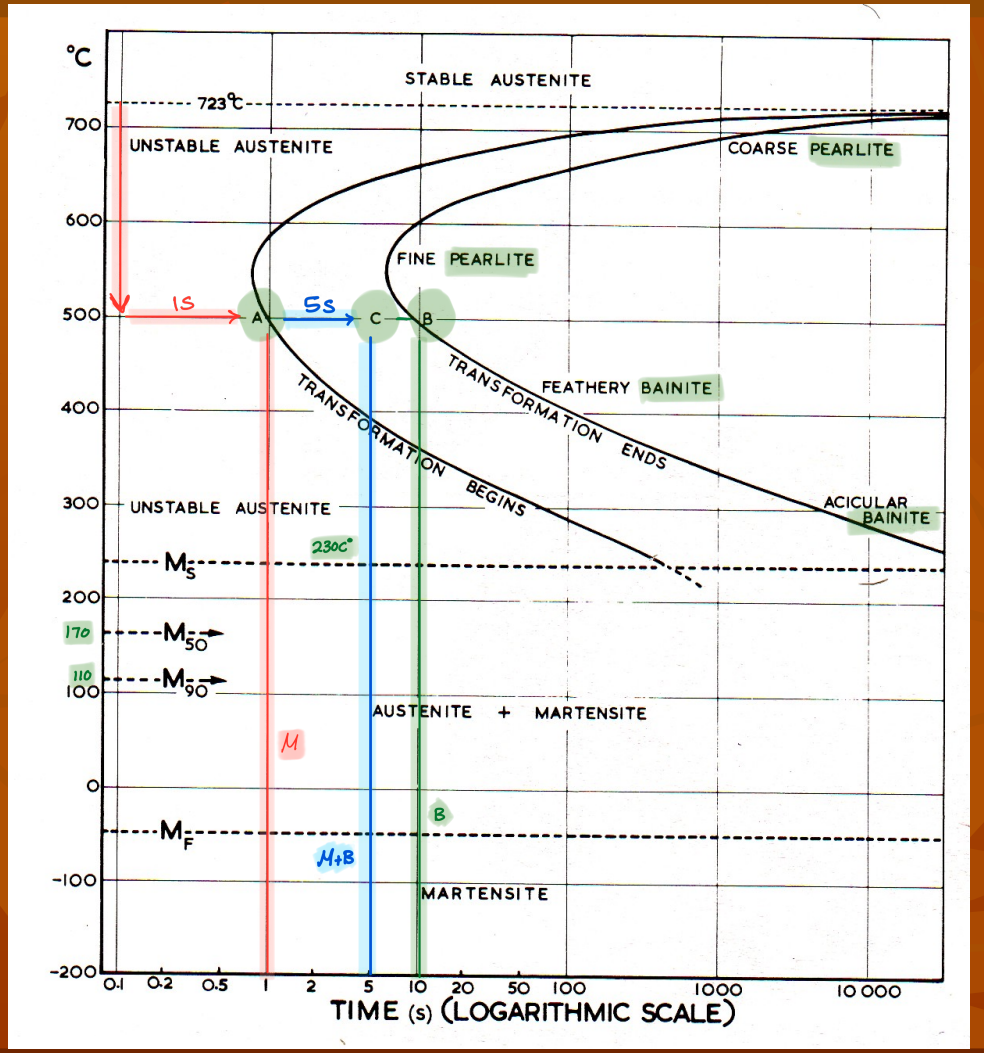


bainite

B

water bath (room temp.)

مثلاً الرسمة
95% Mart.
5% retained δ



• no 100% Martensit at the Line of transformation begins.
↳ From 0%

• Transformation for pearlite & Bainite
• temp. & time dependent.

but
martensit → temp. dependent
(time → Fast cooling).

From M_S to M_F, the structure is unstable austenite + martensite (retained austenite).
↳ didn't reach a low enough temp. to transform

below M_F → totally martensite.
↳ below zero; if the quenching at room temp → no 100% Martensite.

- This type of heat treatment is normally carried out using molten salt or metal "baths" which offer a protection against oxidization.

- Chloride baths consisting of mixtures of NaCl and KCl provide working range of 700 to 900 ºC and can be used in austenitizing treatments.

- Nitrate baths provide a working range of 250 to 600 ºC and can be used in subcritical treatments.

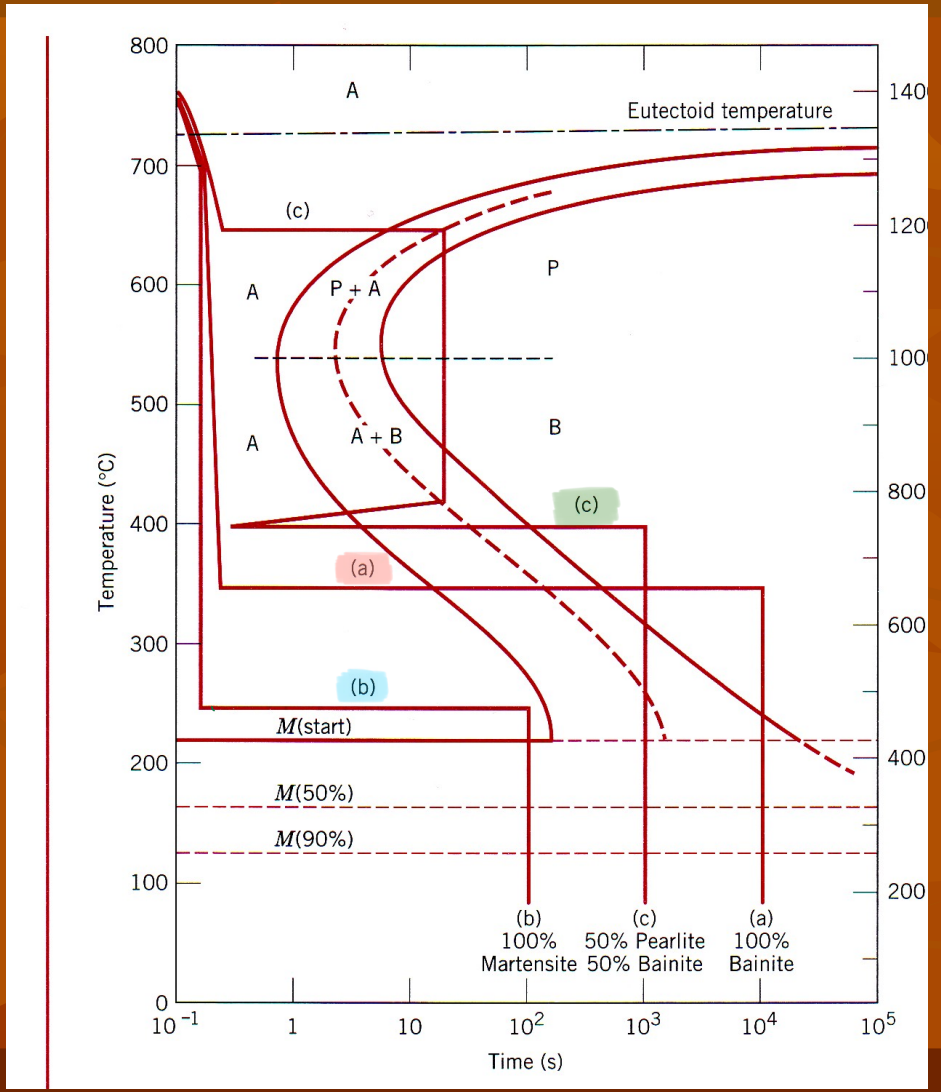
carborization:
(C) to the steel
Decarborization:
(C) out of the steel.
↳ high temp, long time.
·(C) on the surface reacts with (O2)
↳ so use molten salt.
↳ no access for O2

time ↑.

quenching / cooling.

Exercise:

- Sketch the corresponding microstructure for resulting from heat treatments a, b and c, for each step and explain the resulting microstructure.



For curve (a):

start ⟶ completed

100% Bainite.

For (b):

no start transformation.

100% martensite.

بردو بس ما بكون هيك وقت بتغير.

but there is a percentage of retained (γ)

For (c): **

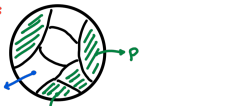
temp. decreased to 650°

50% transformed to pearlite.

then temp. decreased to 400°

(Back in time)!

before it:



unstable (γ).

50% transformation

γ ⟶ Pearlite.

* not transformed yet.

after decreasing the temp.

it should wait to transform again.

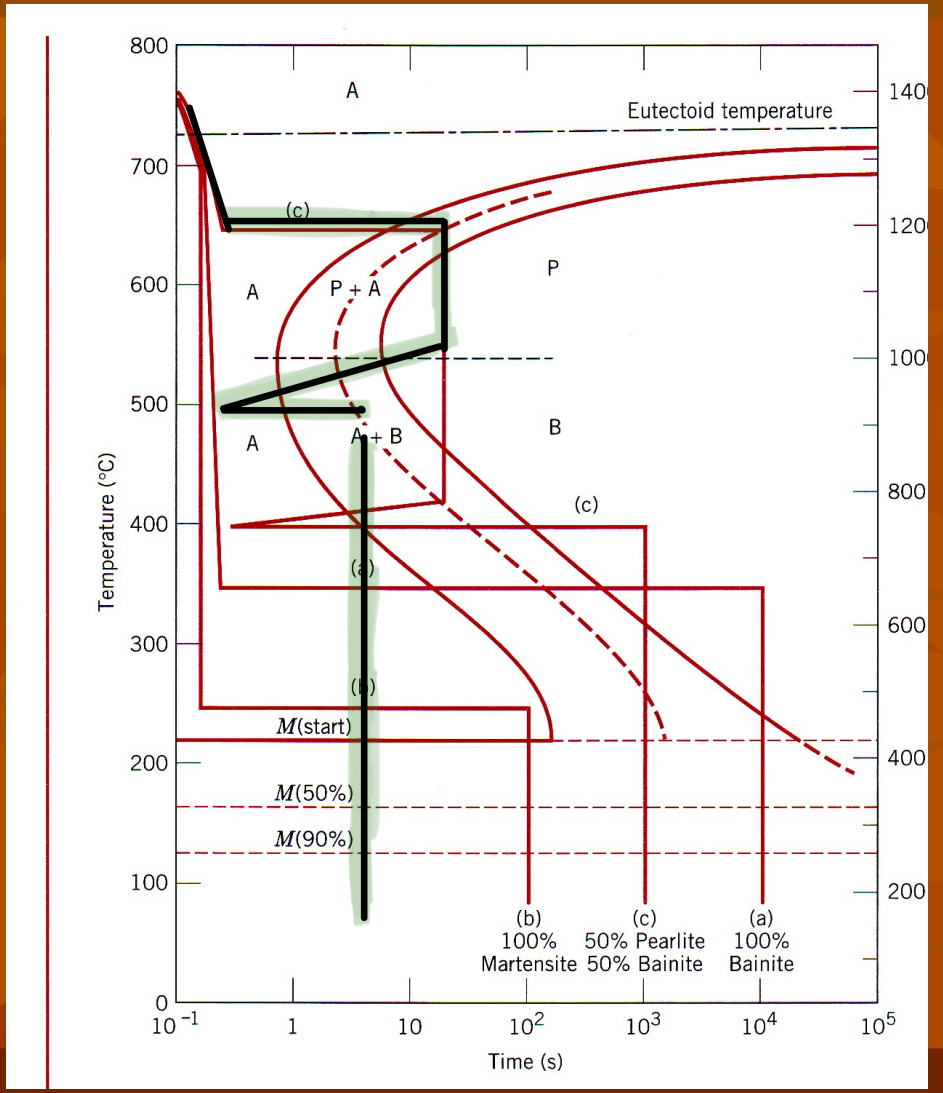
then (γ unstable) start ⟶ complete.

γ ⟶ Bainite.

but 50% Pearlite already existing.



γ unstable ⟶ Bainite.



1. temp. decreas to 650C°

50% transformation

γ ⟶ Pearlite.



2. temp. decreas to 500C°

more time needed.

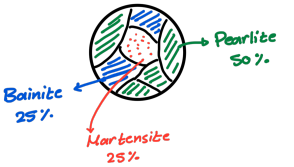
transformation started & 50% completed.

the 50% unstable (γ) transformed 50% to bainit & the remaining untransformed become Martensite.

50% Pearlite

50% (γ) → 50% bainite 25%

50% Martensit. 25%.



ای باشی فاتحون γ ⟶ M.

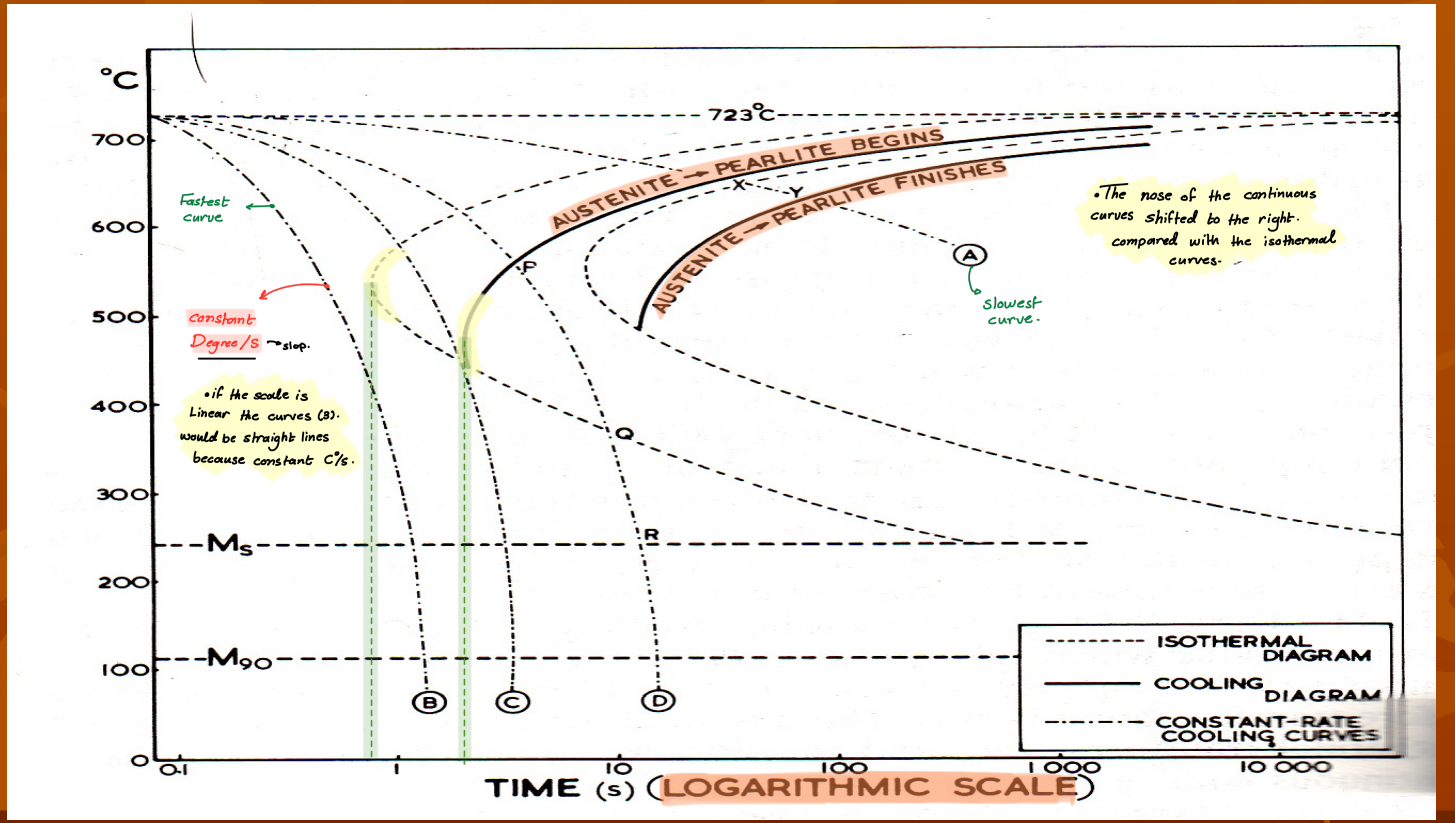
Continuous cooling curves

- Another type of cooling curves relating the resulting structure of quenched steel to the rate of cooling are the continuous cooling curves or the "***modified***" TTT curves.
- These curves, however, indicate transformations which take place under continuous cooling conditions, i.e., the steel does not have to be held in a bath at constant temperature.

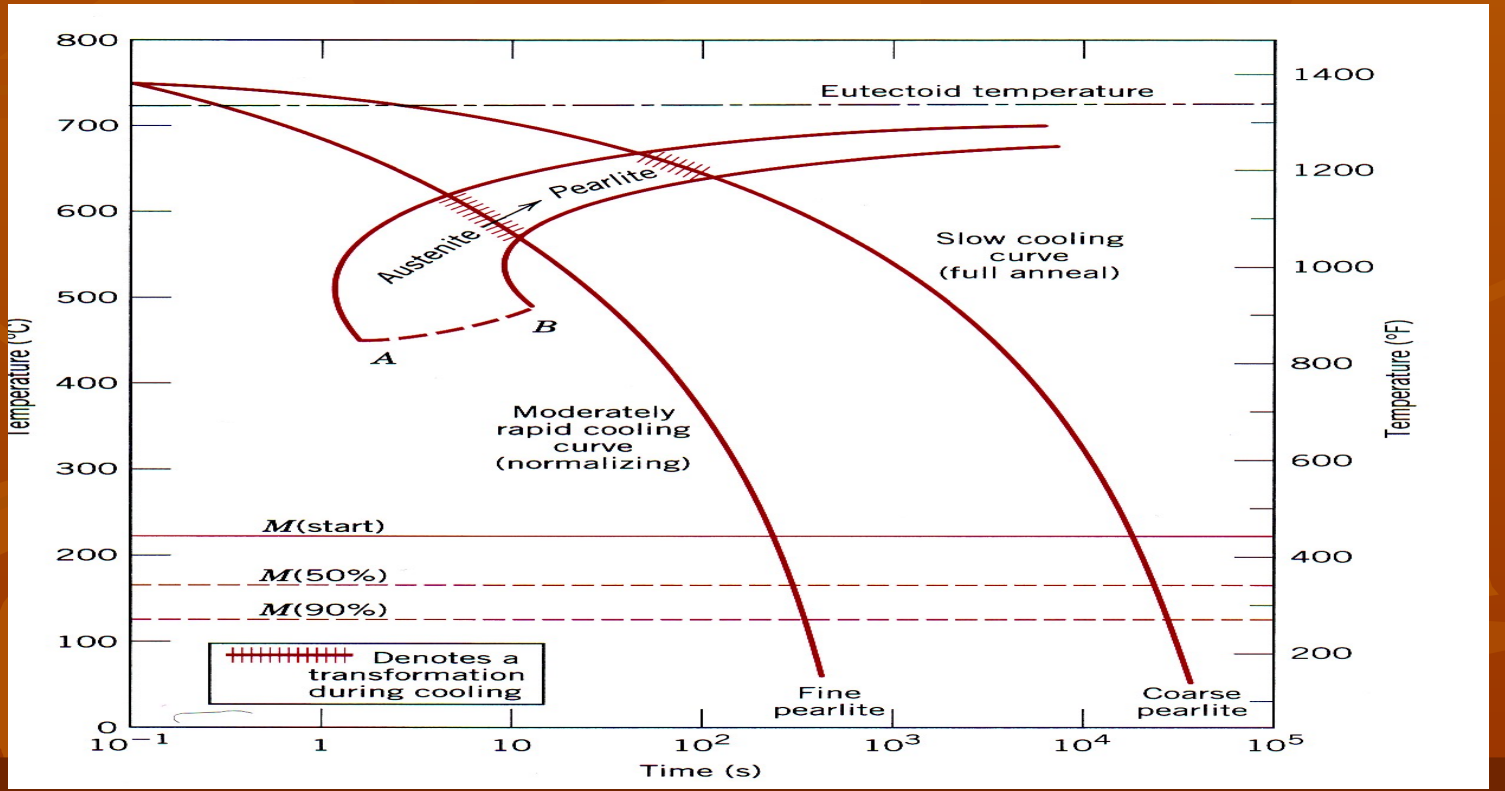
. in the Large masses,
Fast cooling at constant temp. is hard

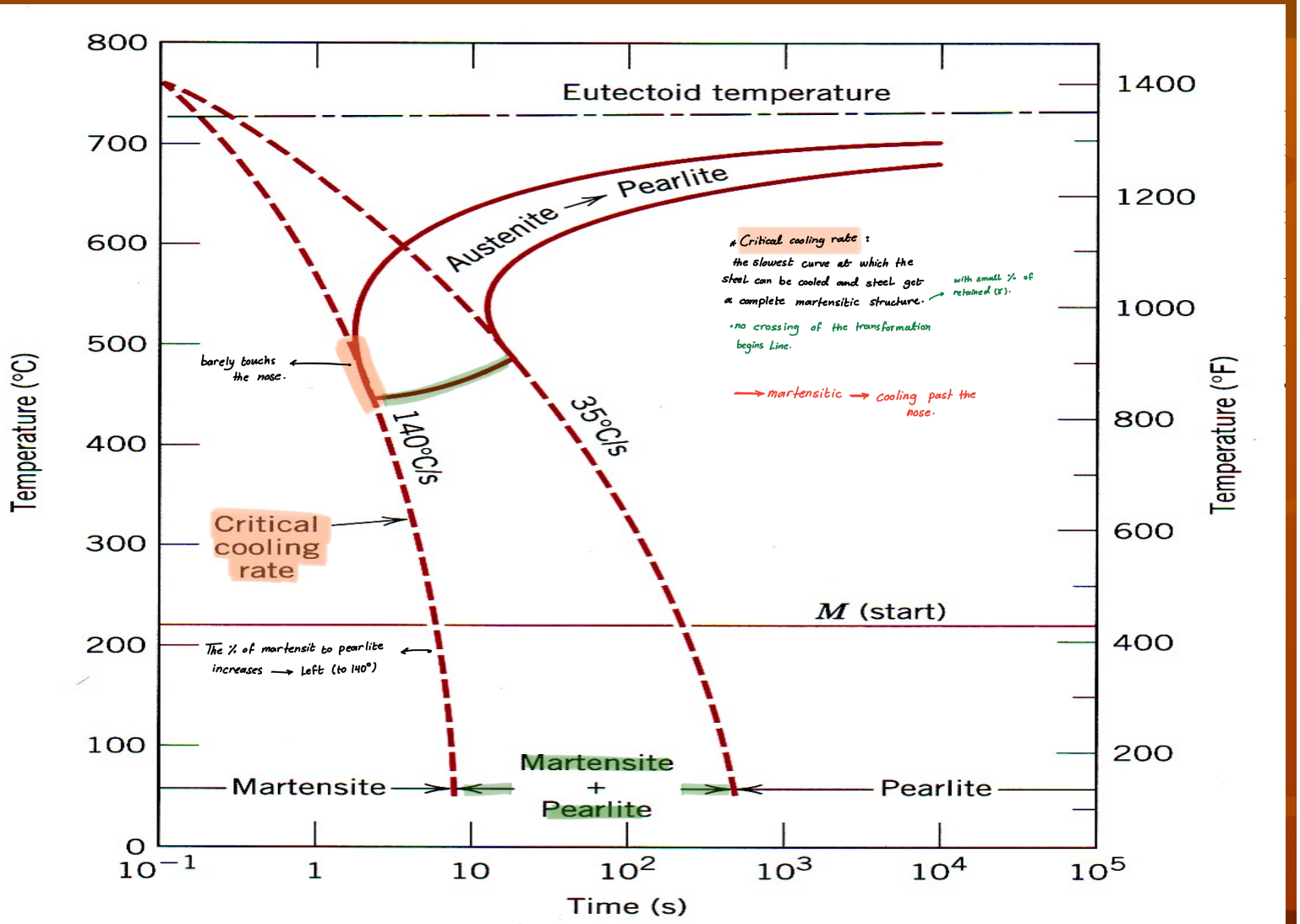
easier → continuous cooling.
using (TTT) curves

These curves are shifted to the right (relative to the TTT curves)



- The "***critical cooling rate for the steel***" is the slowest cooling rate that would result in a completely martensitic structure.

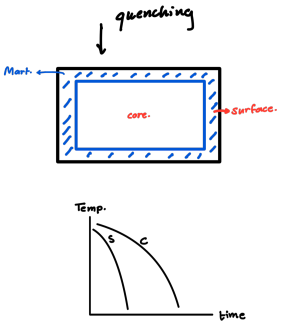


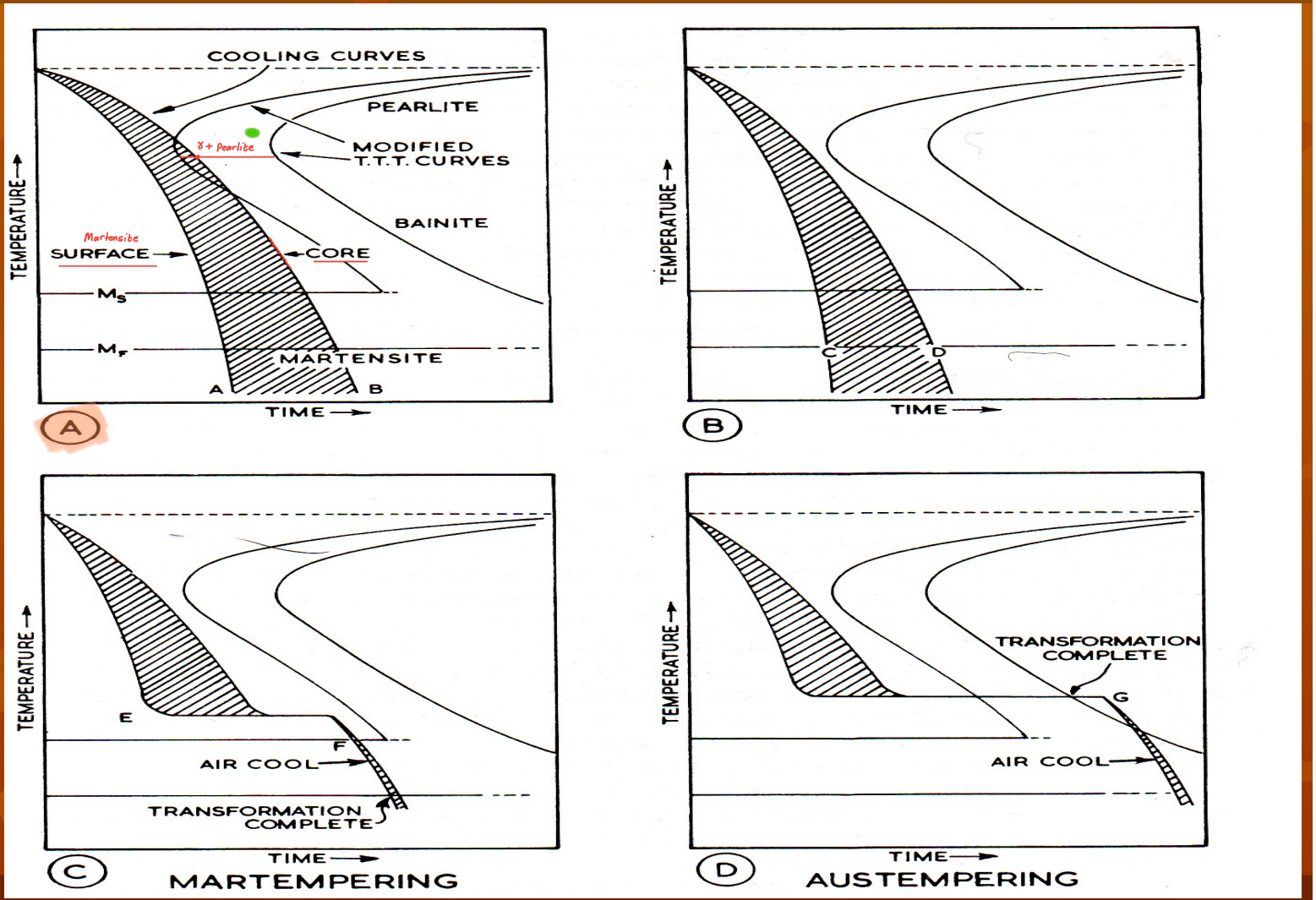


• no bainit → the steel at the continuous cooling doesn't form bainite.

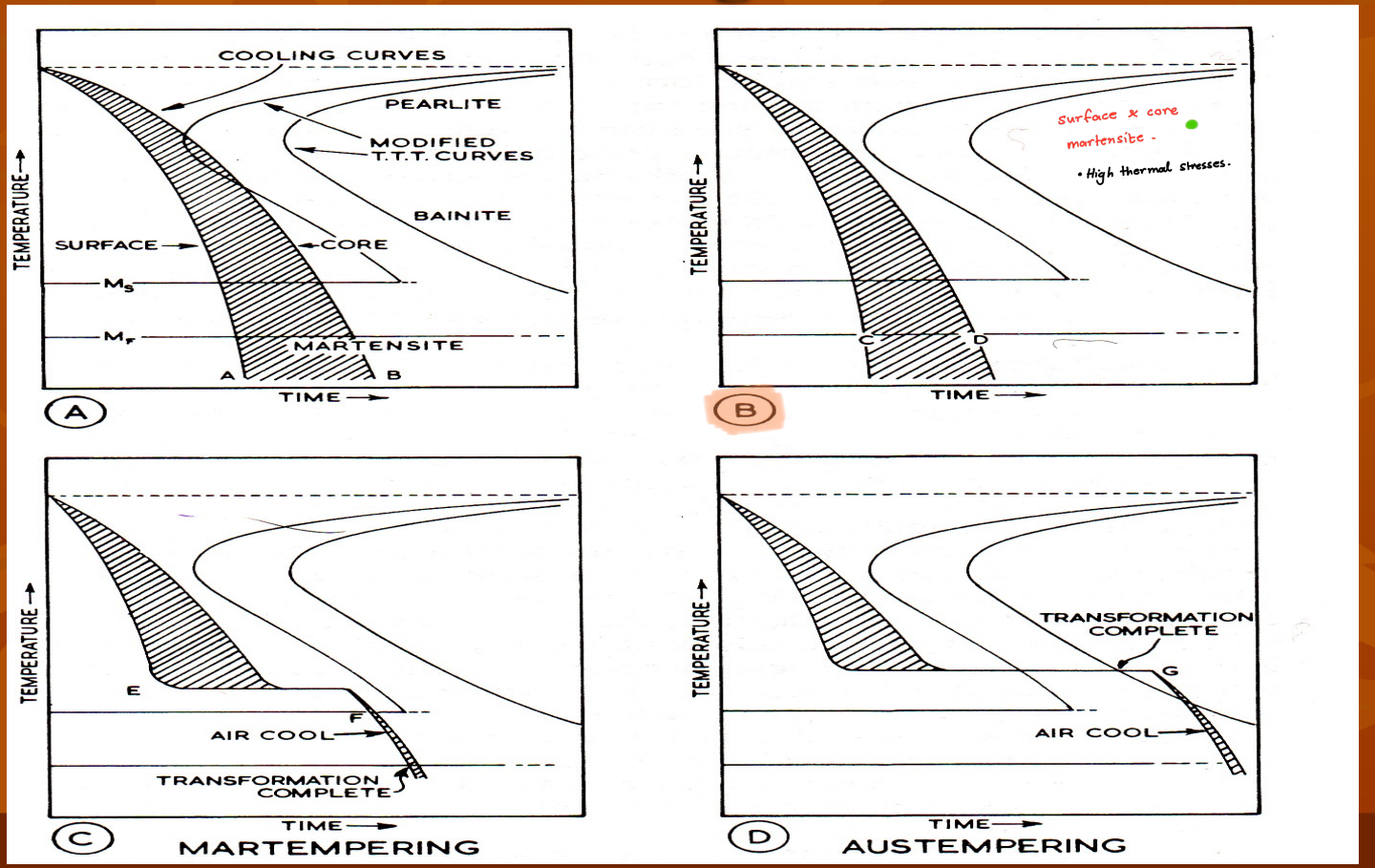
The mass effect

- In quite large and thick parts the mass effect exists during the quenching process.
- This means that the surface of the part will cool faster than the core of the part. This may result in that while the surface has a martensitic structure, the core will have a bainitic or possibly pearlitic structure.

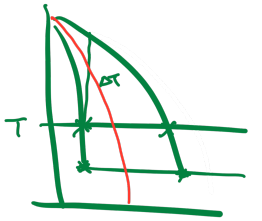


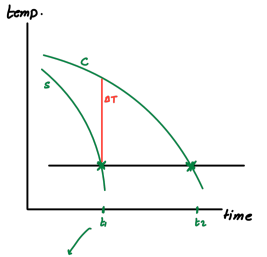

COOLING CURVES
PEARLITE
MODIFIED
T.T.T. CURVES
γ + Pearlite
BAINITE
Martensite
SURFACE
CORE
M_S
M_F
MARTENSITE
A
B
TEMPERATURE
TIME
A
C
D
B
E
F
AIR COOL
TRANSFORMATION
COMPLETE
C
MARTEMPERING
TRANSFORMATION
COMPLETE
G
AIR COOL
D
AUSTEMPERING

This can be avoided by using a higher cooling rate



· martensite → brittle.





time needed to reach the same temp.

• ΔT over time.

(B)

from the non-uniform cooling.

منطقة ساخنة و منطقة باردة وهافي بينهم فاصل.

- But this is likely to result in high thermal stresses causing distortion and possibly cracking.

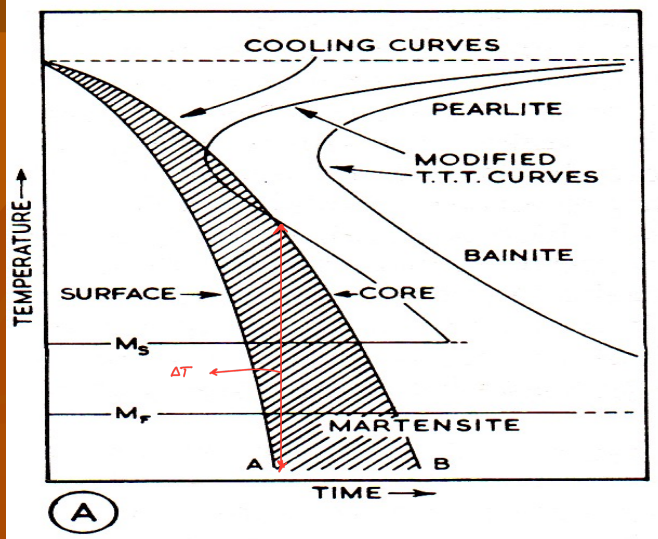
For the surface.

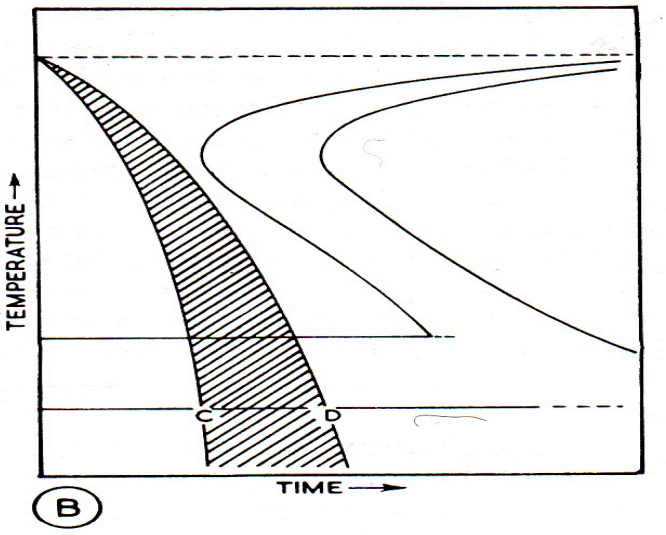
tensil stresses.

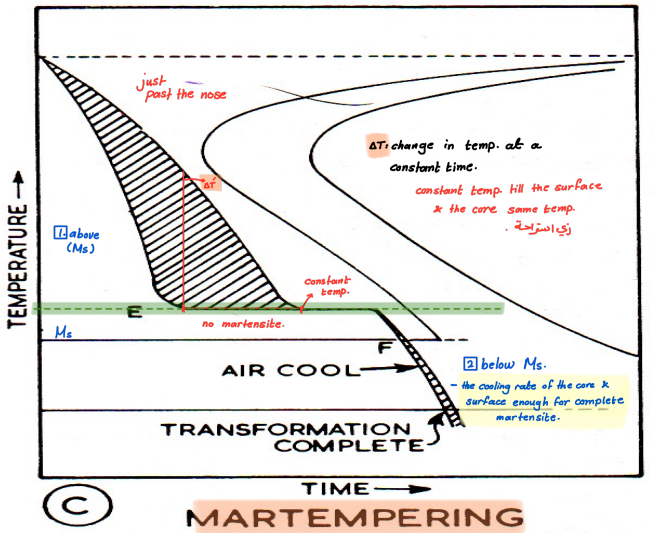
- A means of avoiding this "mass effect" is to apply a process known as "***Martempering***" or "***Marquenching***",

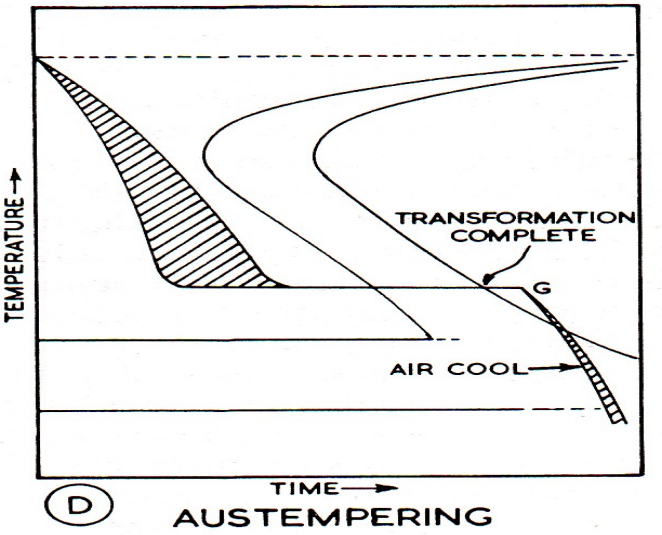
Fast cooling without reaching the martensite (M_F).

(C)


COOLING CURVES
PEARLITE
MODIFIED T.T.T. CURVES
BAINITE
SURFACE
CORE
M_s
ΔT
M_f
MARTENSITE
A
B
TEMPERATURE
TIME
A


TEMPERATURE
C
D
TIME
B


just past the nose
ΔT: change in temp. at a constant time.
constant temp. till the surface & the core same temp.
زي استراحة.
1 above (Ms)
ΔT
constant temp.
E
no martensite.
Ms
F
AIR COOL
2 below Ms.
- the cooling rate of the core & surface enough for complete martensite.
TRANSFORMATION COMPLETE
TEMPERATURE
TIME
C
MARTEMPERING


TRANSFORMATION COMPLETE
G
AIR COOL
TEMPERATURE
TIME
D
AUSTEMPERING

(C)

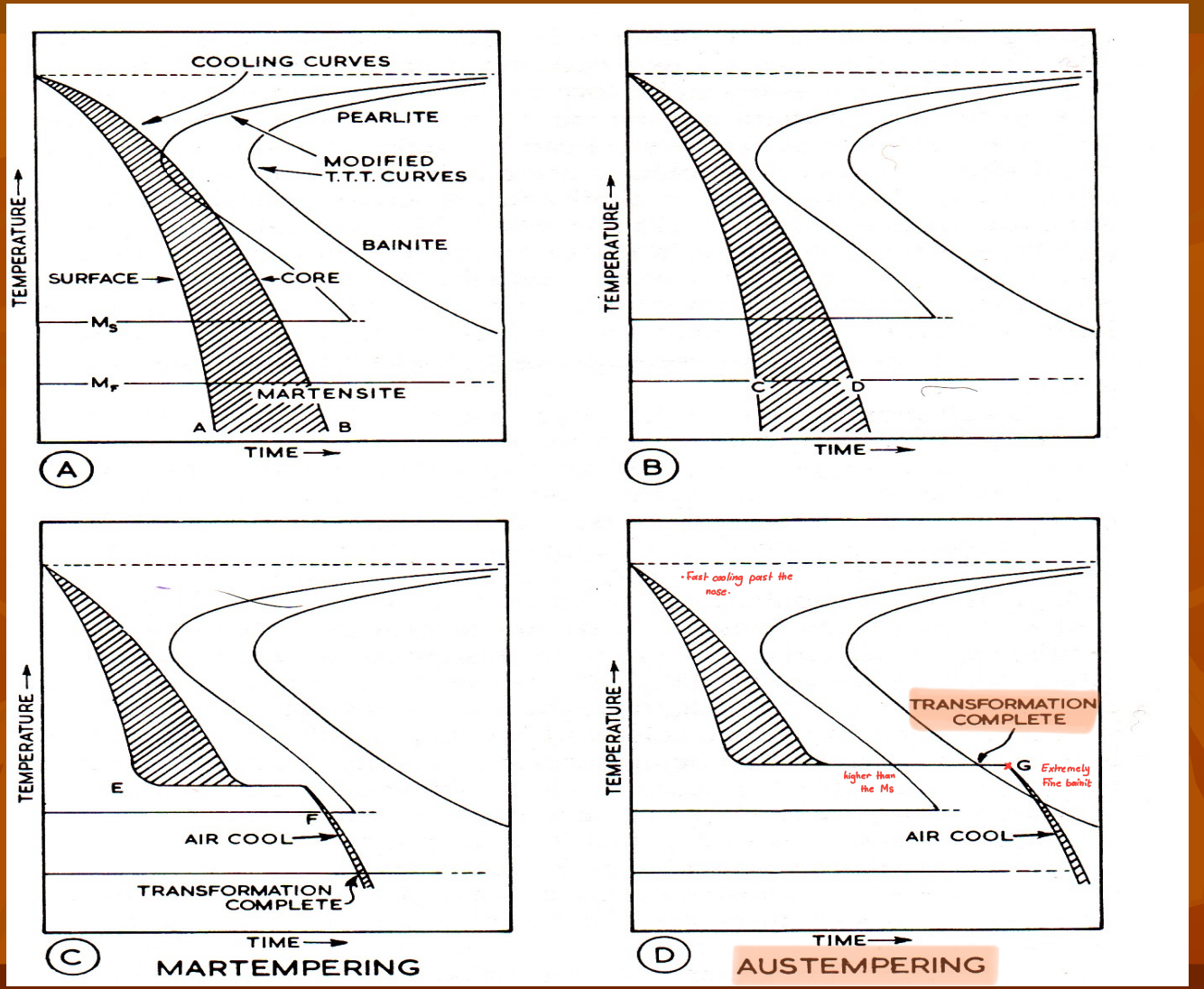
- In this process the part is cooled quickly past the noze of the transformation begins curve and then hold enough until the whole part attains a uniform temperature.

- At this point any rate of cooling will result in a martensitic structure and the difference in subsequent cooling rates between the core and surface will not be large enough to cause and appreciable amount of thermal stresses.

- An alternative process known as "***Austempering***" can be applied.

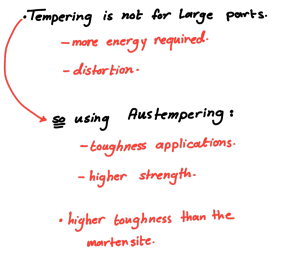
(D)

tempering after the martensite.

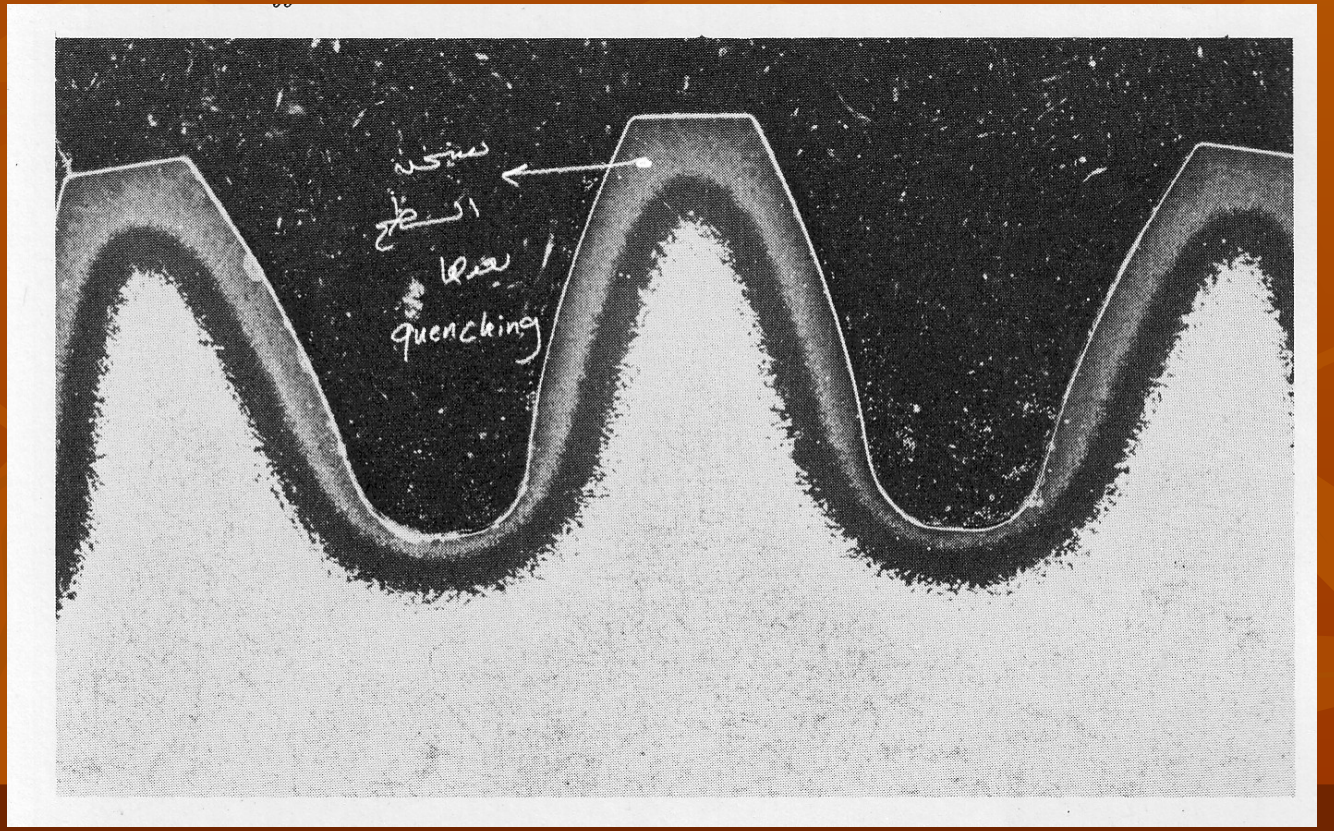

COOLING CURVES
PEARLITE
MODIFIED
T.T.T. CURVES
BAINITE
TEMPERATURE
SURFACE
CORE
M_S
M_F
MARTENSITE
A
B
TIME
A
TEMPERATURE
C
D
TIME
B
TEMPERATURE
E
F
AIR COOL
TRANSFORMATION
COMPLETE
TIME
C
MARTEMPERING
Fast cooling past the nose.
TRANSFORMATION
COMPLETE
G
Extremely
Fine bainit
higher than
the Ms
AIR COOL
TEMPERATURE
TIME
D
AUSTEMPERING

(D)

- In this process the steel is allowed to go through full transformation to acicular Bainite (both core and surface). This will give properties similar to those of tempered martensite but without having to apply a drastic quench and the subsequent tempering operations.



Case Hardening



* Case hardening :
- hardening for the external surface.
hardness
soft.
- core remain strong x tough.
* case hardening → High wear resistance.
(hardness).

- In case hardening the surface of steel is made hard and wear resistant but the core remains soft and tough.
- Such a combination is desired in applications such as gears and some shaft applications.
- Increasing surface hardness can be achieved in two ways:

If the carbon content is more than 0.35 % preferential hardening of the surface can be achieved by ***heat treatment***.

This could be done in two ways:

Induction hardening.

In induction hardening an alternating current (AC) of high frequency passes through an induction coil enclosing the part to be heat treated.

1. Fast
2. Uniform temp heating depth.

• increase surface hardness:

1. Heat treatment. (carbon content)

→ before case hardening (plane carbon steel)

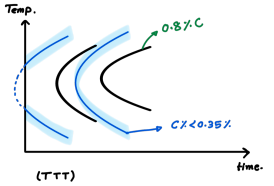
• if C% > 0.35 %. then the steel is hardenable.
(can be hardened by heating & quenching).

• if C% < 0.35 % then the steel is non-responsive hardening.
(can't form martensite even if heat increased & then quenching).

---

if carbon content ↑ → curve shifted to the Right (time ↑).

if carbon content ↓ → curve shifted to the left (time ↓).



• no martensite at any temp. & time.
(any cooling rate).

• any cooling rate will give a pearlite.

كلشي رح يتغير.
(transformation begin line).

* heating the surface till the austenitization temp, then quenching.
1. Martensite on the surface

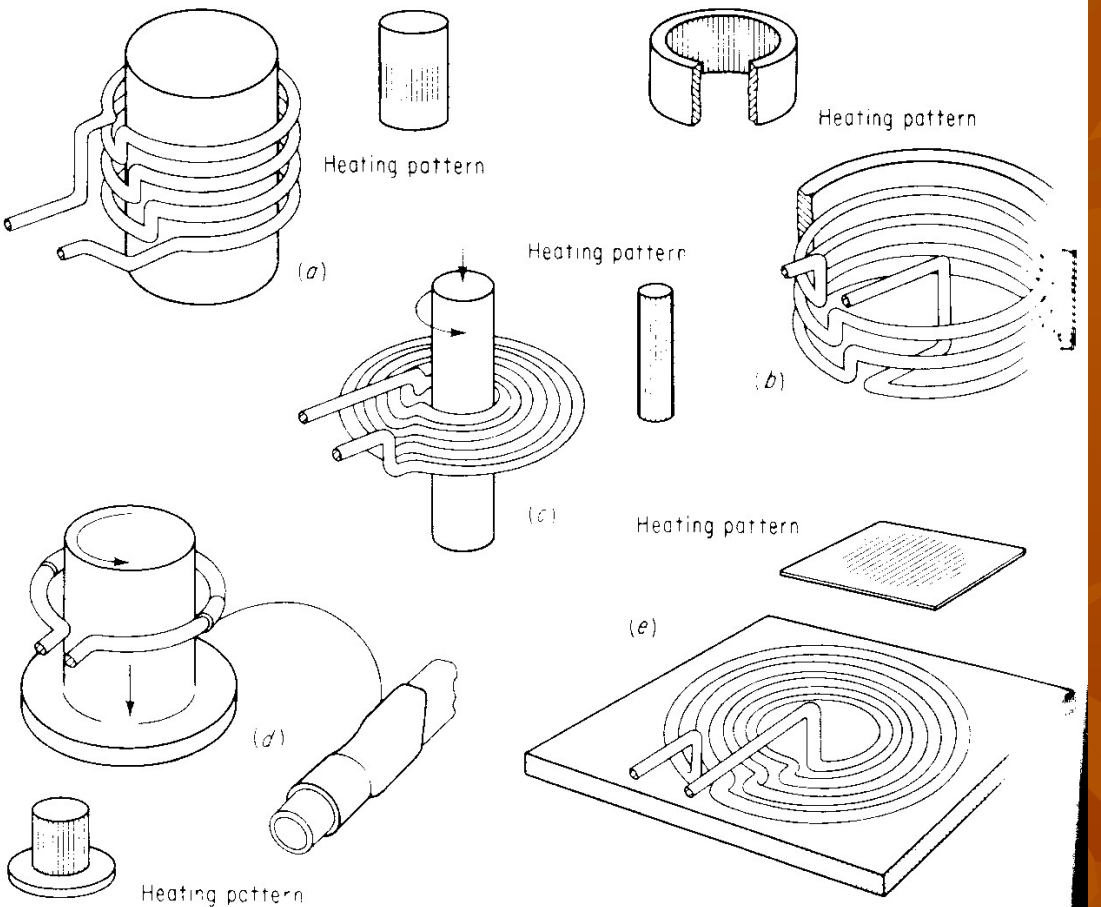


Fig. 8·81 Typical works coils for high-frequency units and the heat patterns developed by each. (From "Metals Handbook," vol. 2, American Society for Metals, Metals Park, Ohio, 1964.)

adv.
- uniform heating depth.
- Fast

Disadv.
- for Simple shapes.

- The induced electro-motive force (emf) causes heating of part to above A3.

  → upper critical temp. → Austenitization.

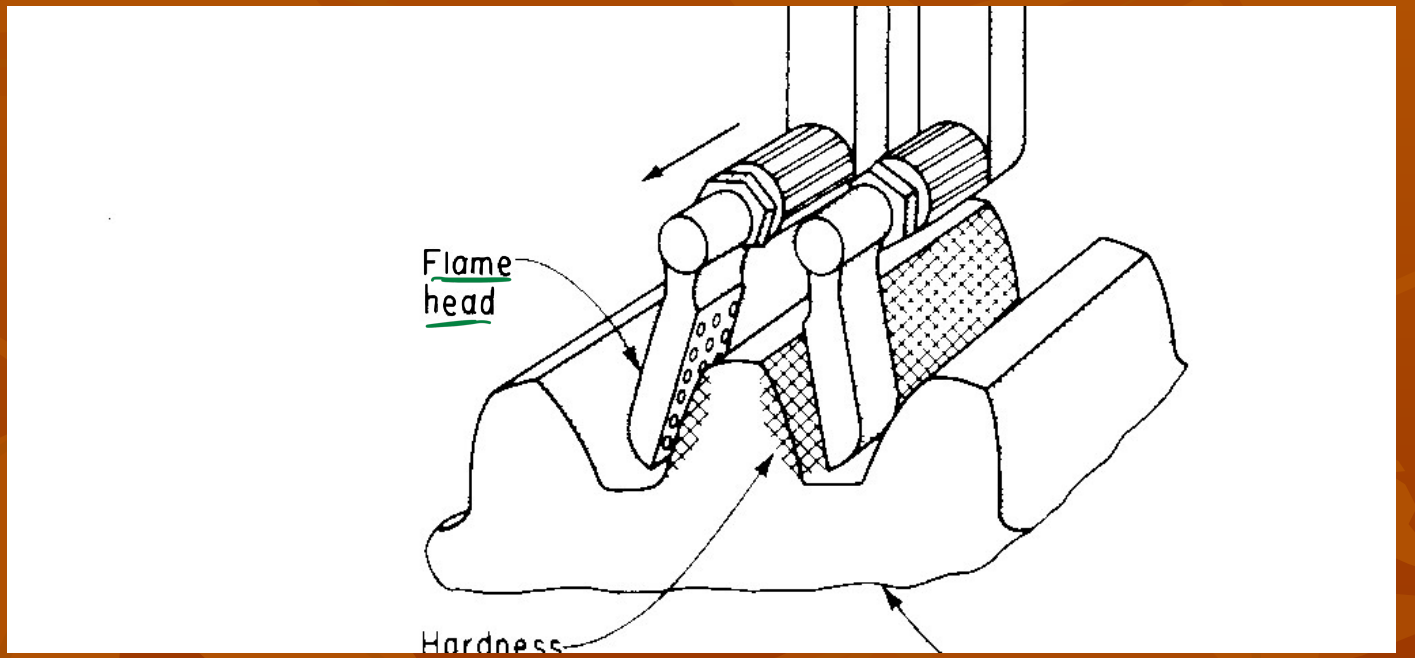
- The depth to which the temperature is raised is inversely proportional to the square root of the frequency. Therefore the depth of heated zone decrease with increasing frequencies used.

  frequance ↑ → temp. ↑ → depth ↓ → time ↑

- Heating is usually done in a matter of a few seconds. Immediately after heating water jets are activated to quench the surface.

- Martensite is produced within the surface layer making it hard and wear resistant while the structure of the core is unaltered.

Flame hardening.



Method (2):
- non-uniform shaps.

- In flame hardening, heat may be applied by a single oxyacetylene torch, or it may be a part of an advanced apparatus which automatically heats and quenches part. ——→ in case C% > 0·35%.

- If the carbon content is lower than 0.35 % (0.15 to 0.2%) preferential hardening of the surface can be achieved by changing the chemistry of the surface.

- This can be achieved through the following:

Carburizing.

- In this treatment, the surface layer of low carbon steel is enriched with carbon up to (0.8 – 1.0 %).
- The source of carbon may be a solid medium, a liquid or a gas.
- In any case the carbon enters (diffuses) into the steel as a function of time and the high temperature (920 – 950 ºC).

• Carburizing:
increasing the carbon content.
only in the surface.
→ Diffusion, steel in high carbon medium.
× heating to certain temp.
heat ↑ × time ↑ → depth ↑
* no change in the core
because it's a low carbon steel.
no respon for hardening.

* High temp. 1.
* Long time 2.
→ Large Grain Size
· low strength
· brittle.

- In gas carburizing a mixture consisting of 5 -15 % methane (or propane) in a neutral carrier gas is used.
- The methane decomposes according to the following reaction:

$$CH_4 + Fe \rightarrow 2H_2 + Fe(C)$$

- Due to the high temperatures involved in carburizing, the grain size is quite large.

→ Same as annealing for Large casting. (less).

- In order to optimize the properties a two step post-carburizing heat treatment is used:

carburizing not for hardening;
only to increase the carbon content in the surface.

* hardening:
- heating then quenching with high enough carbon content to produce martensite.

- The steel is first heated above A3 and air cooled to refine the grain size in the core. * refining

For the surface of steel.

- The steel is then heated above A_3. This produces fine austenite grain size in the surface and upon quenching austenite transforms to martensite in the surface layer. As the carbon content in the core is low, ~~is~~ it has low hardenability and the core remains soft and tough.

refining grain size :

Grain size ↑ → toughness ↓

Similar to annealing for large casting.

Fine austenit.

cooling : Fine pearlite.

no hardening yet.

---

two steps heat treatment :

1. refining Grain size for the core

2. hardening the surface

Nitriding.

- In contrast to carburising, nitriding is carried out within the ferritic range (500 – 590 ºC).

- As such, no phase changes take place during nitriding.

•Nitriding :
– below the critical temp.
– no change from (α/Fe_3C) to (δ).

–hypoeutectoid reaction.
•mostly (α) x the primary phase (α).
(Ferritic steel x small amount of pearlite).
→ temp below 600°
•no δ
•no transformation.

•will be no change in core properties.
(no heat treatment after nitriding).

- Prior to nitriding the part should have the required core properties and, if necessary, a prior heat treatment should be applied.

- In this process pure ammonia decomposes to yield nitrogen which enters the steel:

$$2\,NH_3 \rightarrow 2\,N + 3\,H_2$$

react on the surface.

- The solubility of nitrogen in ferrite is very small and most of this nitrogen entering the steel forms hard nitrides (for example Fe3N).

- Typical nitriding steel contains 1 % Al, 1.5 % Cr and 0.2 % Mo, as these elements form very hard and wear resistant nitrides.

* Nitriding steel ,
Low carbon steel intended to be surface hardened by nitride.

فادة المبيد

. Plain carbon steel only contain carbon.
+ small amount of Mg.
to remove the sulfur.

. عناصر سبائكية .

Effect of alloying elements on the Fe-C phase diagram and transformation rates

- For equilibrium (Phase diagram).
- x non-equ.
  - transformation.
    - isothermal. (constant temp.)
    - continuous cooling.

- The main two reasons for addition of alloying elements to plain carbon steels (i.e., formation of alloy steels) are:

  ↳ contain elements other than the carbon.

- To improve and extend the existing properties of plain carbon steels;

- To introduce new properties not available in plain carbon steels.

- To determine the effects of alloying elements on the Fe-C phase diagram it is advisable to clarify some points:

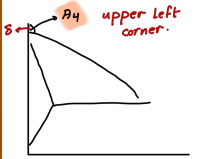
  → Fe_3C phase diagram.

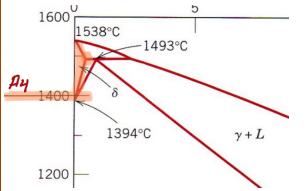
- The temperature at which $\gamma \leftrightarrow \delta$ occurs is called A4

  → in the upper left corner.

- The temperature at which $\gamma \leftrightarrow \alpha$ occurs is called A3

  → upper critical temp.





- The temperature at which austenite ⇔ pearlite occurs (lower critical temperature) is called A1

  → lower critical temp.

- Some elements, notably nickel, manganese, cobalt and copper raise the A4 temperature and lower the A3.

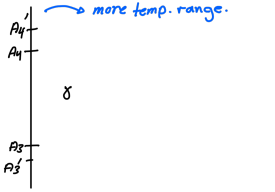
→ increasing the range which the (γ) is stable

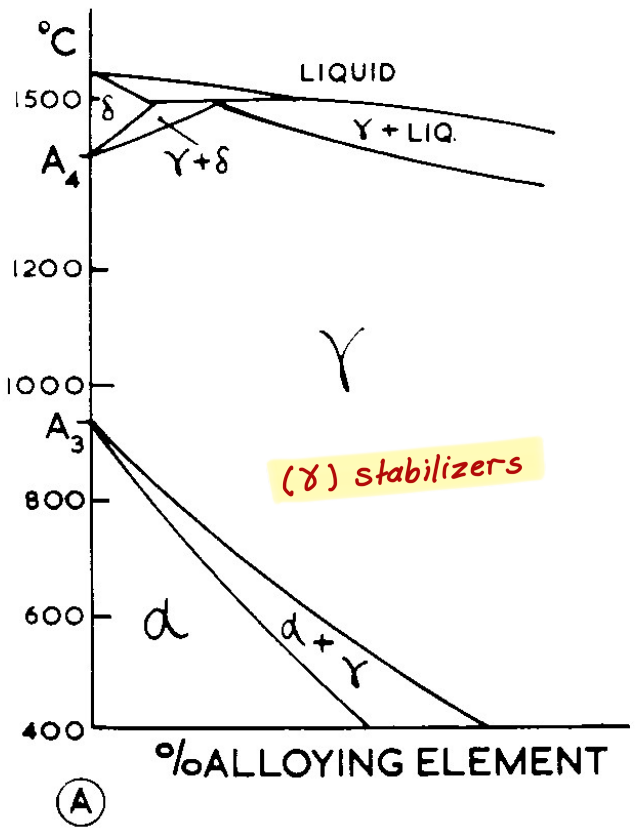
above A4 $\gamma \rightarrow \delta_{Fe}$.

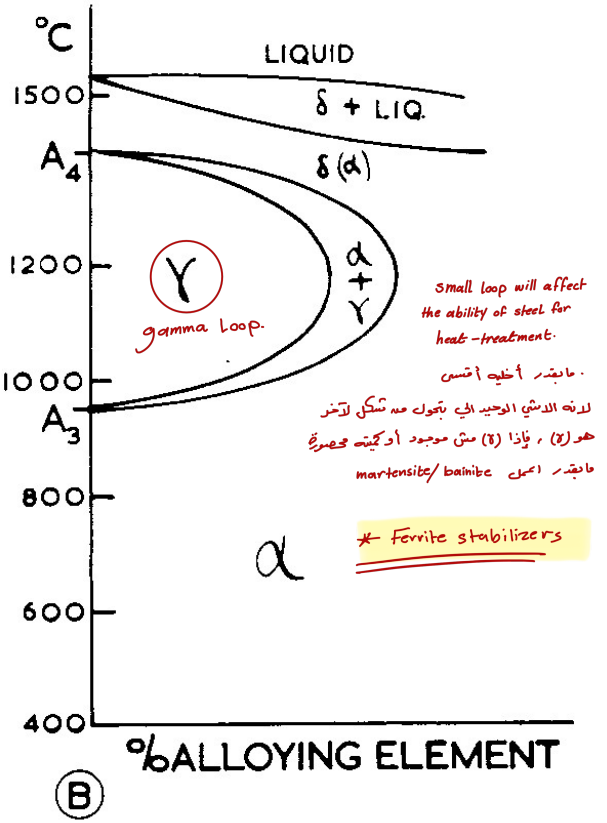
below A3 $\gamma \rightarrow \alpha_{Fe}$.

highering A4 & lowering A3.

→ Higher range. for (γ).




°C
1500
A4
1200
1000
A3
800
600
400
LIQUID
δ
γ + LIQ.
γ+δ
γ
(γ) stabilizers
α
α + γ
%ALLOYING ELEMENT
A


°C
1500
A4
1200
1000
A3
800
600
400
LIQUID
δ + LIQ.
δ (α)
γ
gamma Loop.
α + γ
α
small loop will affect the ability of steel for heat-treatment.
* Ferrite stabilizers
%ALLOYING ELEMENT
B

- Therefore these elements when added to a carbon steel tend to stabilize austenite (γ) and extend the range of temperature over which austenite exists as a stable phase.

The reason is :

- Most of these elements have an FCC crystal structure like that of the austenite, therefore, dissolve substantially with ease in the austenite and consequently retard the transformation of austenite back to ferrite.

- Stabilizers have the same crystal structure as (γ).

- These elements are termed "***Austenite stabilizers***"

- On the other hand, other elements such as chromium, tungsten, vanadium, molybdenum aluminum and silicon tend to stabilize ferrite by lowering the A4 temperature and raising the A3

decreasing the temp. range.

- Such elements restrict the field over which austenite may exist and, thus, form what is known as "gamma (γ) loop".

→ increase the amount of (α) stabilizer → the (γ) only exist in a small loop.

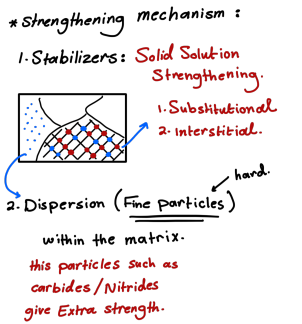
- "***Ferrite stabilizers***" are principally elements with a BCC crystal structure like that of α-ferrite.

* will reduce the existance of (γ).

- Ferrite exist below A3, so increasing A3 will increase the area where (α_{Fe}) exist.

- Suppressing the austenitic range would definitely affect the ability of steels for heat treatment.

- Another important effect alloying elements may have is their effect on the **formation and stability of carbides within the steel**.



- Carbides have a significant hardening effect when present in steels especially when the carbides are harder that the iron carbide (cementite).

That's why some elements are added.

ELEMENT	PROPORTION DISSOLVED IN FERRITE ←	PROPORTION PRESENT AS CARBIDE →	ALSO PRESENT IN STEEL AS—
NICKEL	Solid Solution		$NiAl_3$ Also can produce intermetallic.
SILICON			—
ALUMINIUM			NITRIDES (19.41) to increase the hardness.
MANGANESE	90% S.S	10% as carbids + remove Su.	MnS INCLUSIONS (6.63)
CHROMIUM			—
TUNGSTEN (W)		هاد سه أقوى النواتج..	—
MOLYBDENUM			—
VANADIUM			NITRIDES (19.41)
TITANIUM	strong carbid formers.	90% carbid.	
NIOBIUM			—
COPPER	SOL. 0.3% max.		Cu GLOBULES IF > 0.3%
LEAD	increase the machinability.		Pb GLOBULES (6.64)

not strengthening, just improve machinability.

Start to produce carbid forming element.

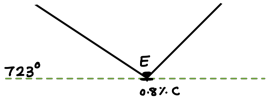
Exist as impurities

هاي العناصر ذائبيتهم بالحديد قليلة. So it's in Globules form. Practically zero solubility.

effects of alloying element on the equilibrium behaviour: [phase diagram.]

Displacement of the eutectoid point

- In this respect, all allying elements will lower the eutectoid carbon content



To determain the hypo. & hyper.

E: completely (pearlite) structure.
strongest structure

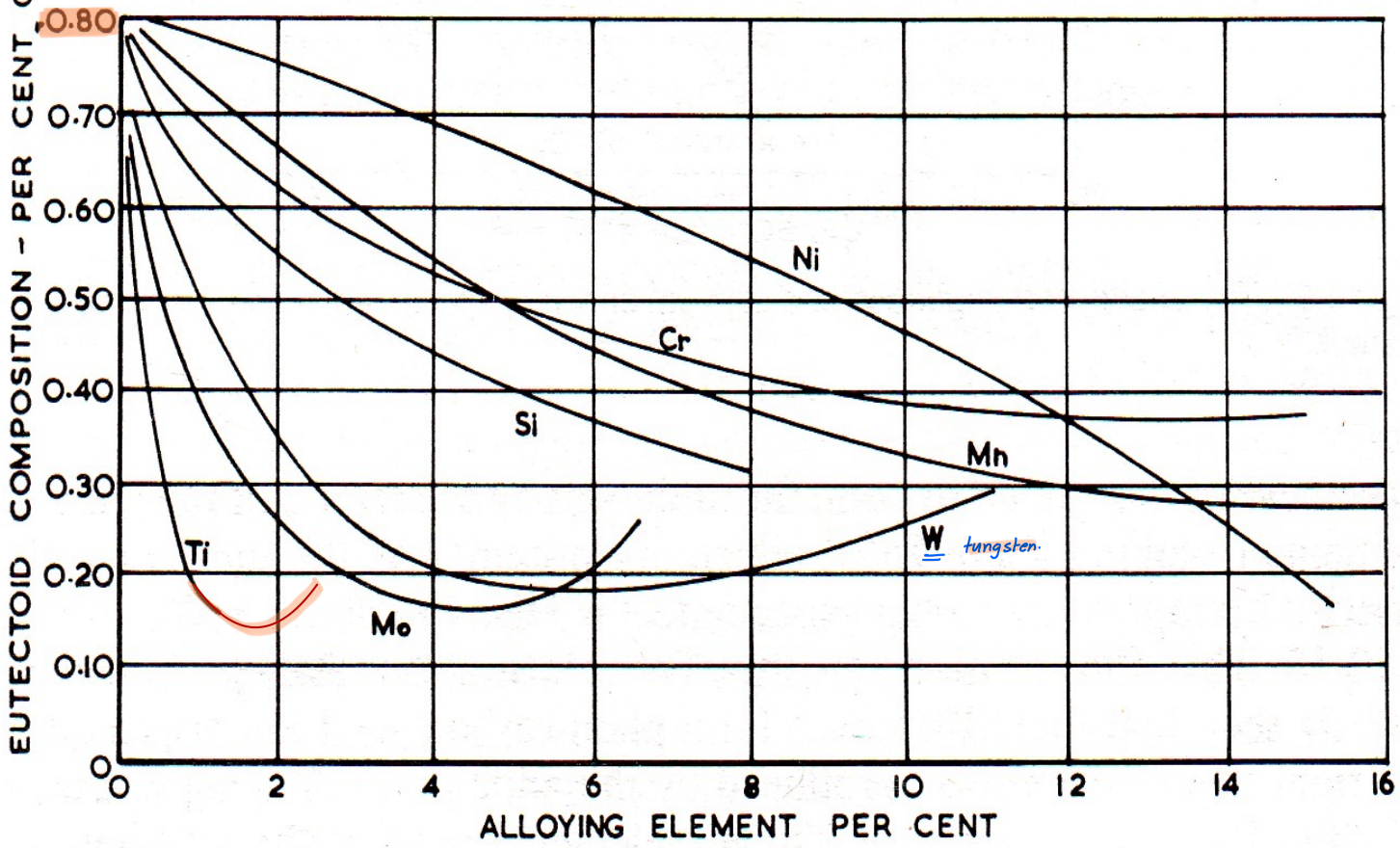
* all alloying element the carbon comp. will be Less than 0.8% C because the alloying elements will take some of the solubility.

→ decreasing the eutectoid comp.
less than 0.8% C.

* increasing alloying percent will decrease the carbon %.

- Strong carbid forming elements leads to fast decreasing of (C%).

* Strong carbid forming element decrease until reaching a specific point (min. point) then start increasing of (C%).



- when we first add an alloying element (Ferrite) هاي العناصر بتروح عند as a solid solution.

Ex: Ni → not forming any carbids
so increasing Ni will decrease C%

min. point يعني عنده —

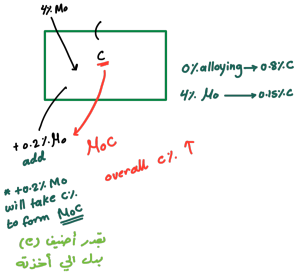
but for (Mo), Ferrite will use the Mo at the beginning → C% will decrease.

* After reaching the min. Point the increasing of (Mo) will be form as carbids outside the (Fe).

So will use the carbon to form the carbid.

So part of the carbon in the solid solution as carbids so there is an ability to add more C.

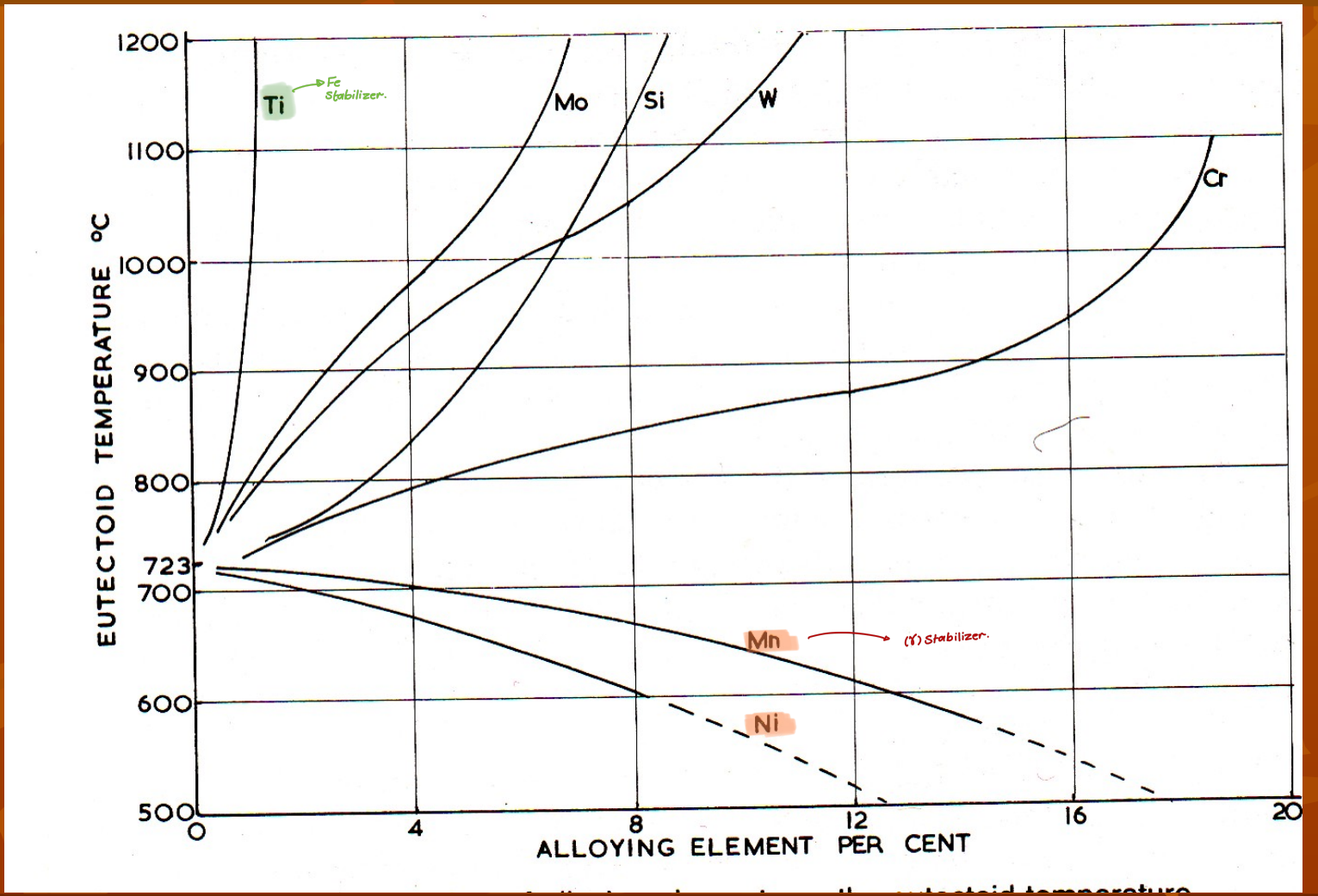
increase the overall carbon.

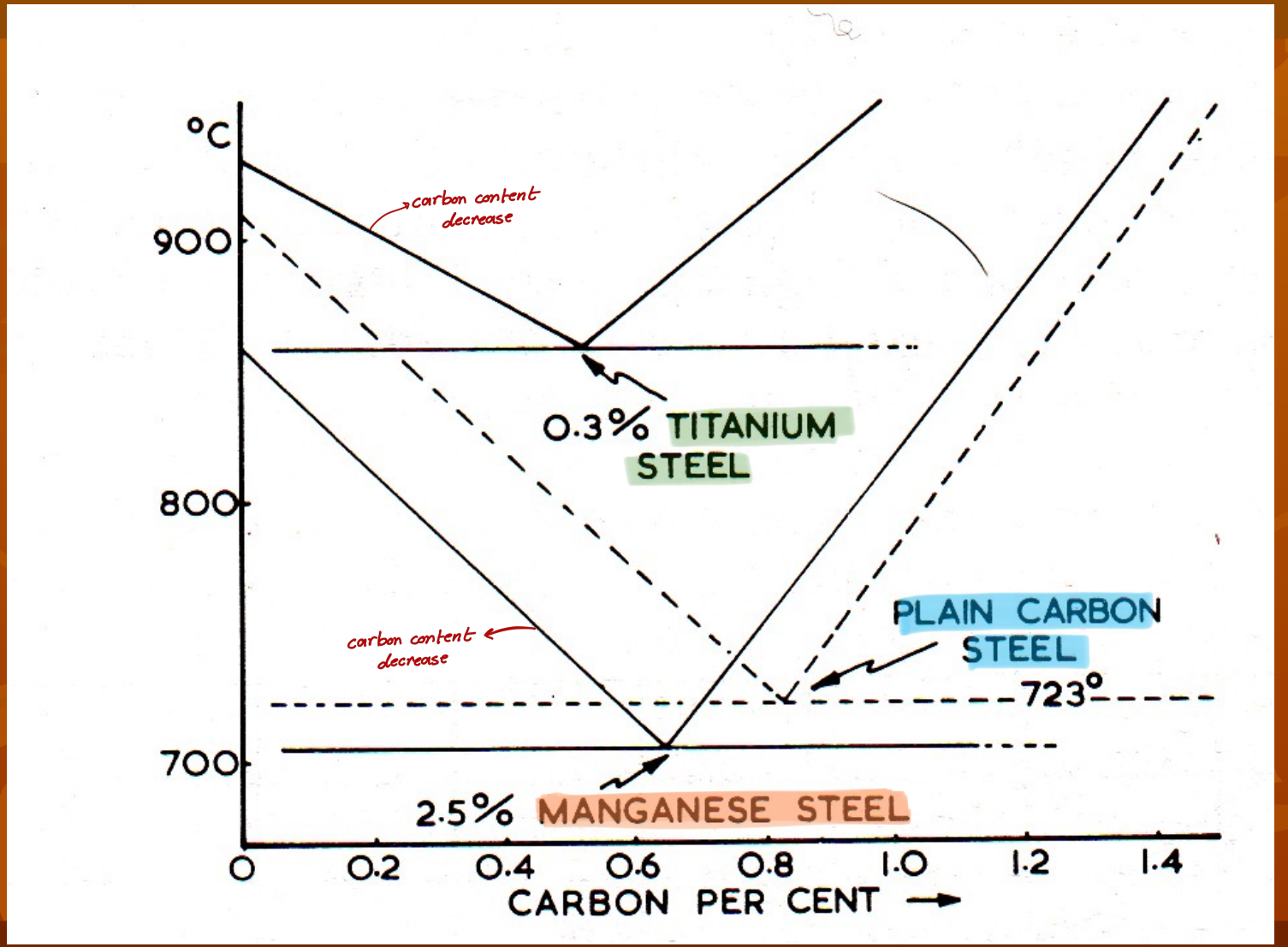


* +0.2% Mo will take C% to form MoC

(C) بتقدر أعطيك بدك اني أخذتك صان

- Austenite stabilizers tend to lower the eutectoid temperature while ferrite stabilizers tend to raise eutectoid temperature


EUTECTOID TEMPERATURE °C
1200
1100
1000
900
800
723
700
600
500
0
4
8
12
16
20
ALLOYING ELEMENT PER CENT
Ti
Fe Stabilizer.
Mo
Si
W
Cr
Mn
(γ) Stabilizer.
Ni


°C
900
800
700
carbon content decrease
0.3% TITANIUM STEEL
carbon content decrease
PLAIN CARBON STEEL
723°
2.5% MANGANESE STEEL
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
CARBON PER CENT →

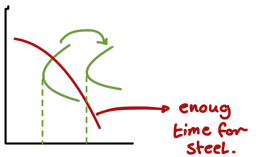
Effect on Transformation rates

- Additions of alloying elements especially nickel and chromium tend to retard transformation rates, i.e., shift the TTT and modified TTT curves to the right.

تثبط / تقادم.

more time.
- Good feature

of unstable (γ) to other phases such as pearlite & bainite.



- يعني ببك ما يبلش على (1s) جهاز ممكن يبلش على (1min).

could have a completely martensitic structure with slow cooling.

- This has a great beneficial effect in that slower cooling rates (such as oil quenching or air cooling) may be used and still get a completely martensitic structure.

- A minor disadvantage introduced by alloying elements (except cobalt) is the lowering of the MF temperature.

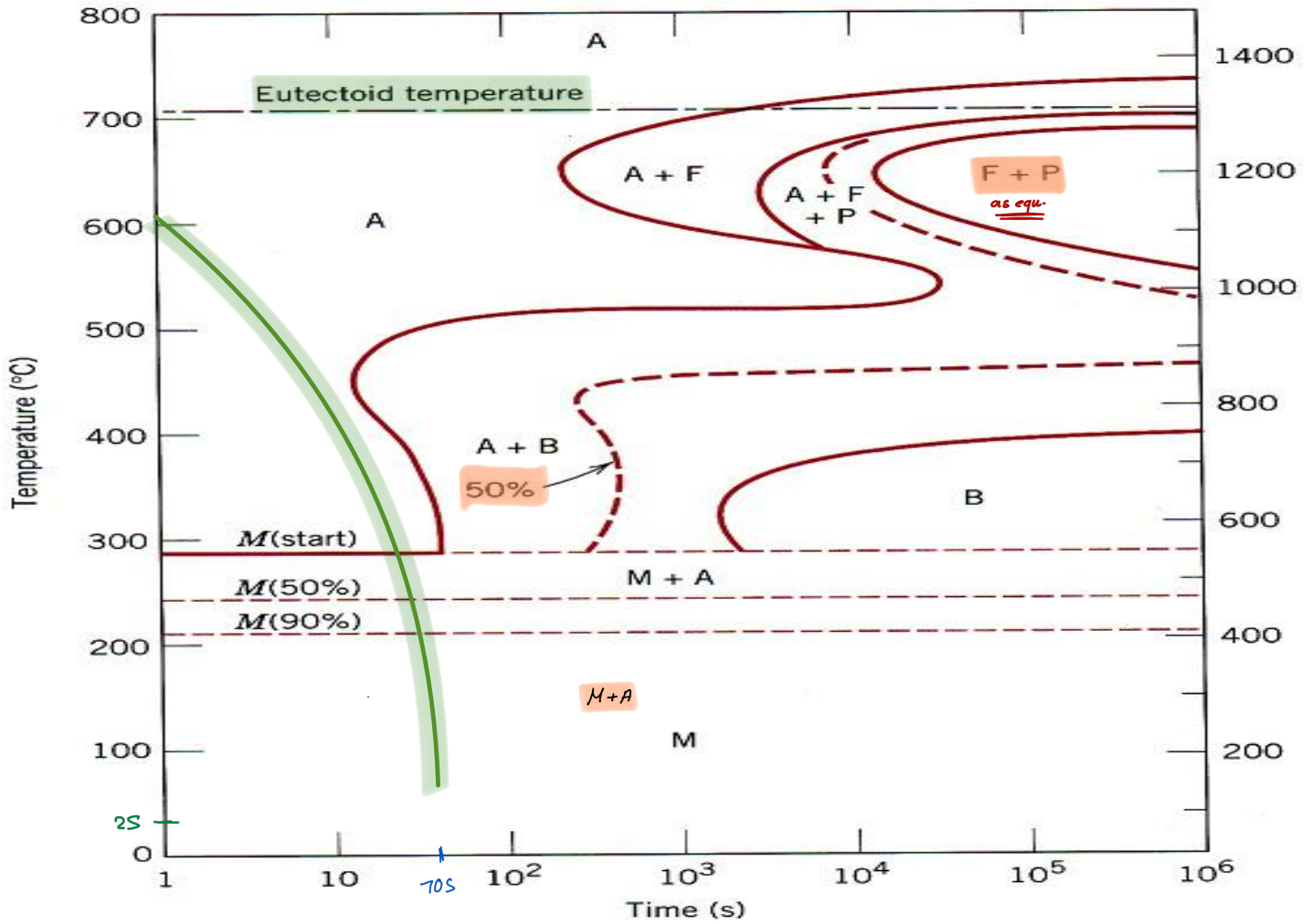
→ increase the amount of retained (γ).

more unstability

- can get rid of it by tempering.

↳ (retained (γ) → bainite).

Final structure : · tempered (γ)
· bainite.



2 noses
— 2 ranges.
— slow cooling

---

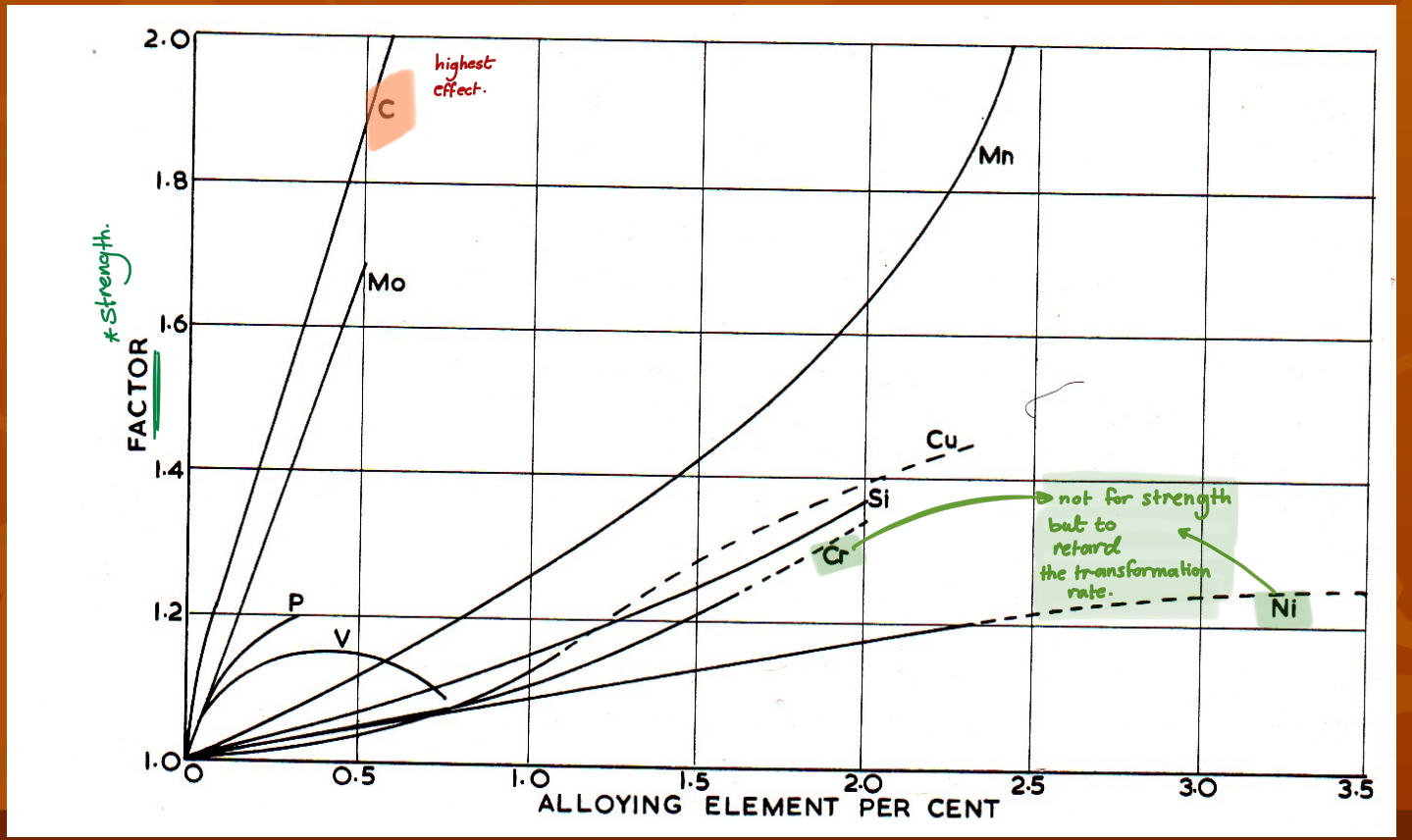
in the determination of quenching temp.
- above (M_F) → Martensite + unstable (γ)
  after tempering & reducing the residual stresses & brittleness.

Ex: after quenching for room temp. & use it in (-)temp. the retained (γ) will be martensite.
will be brettle.
- easily cracked.
- Lowest working temp.

determain the quenching temp. (so Less thermal Stresses).

if the lowest working temp. is lower than quenching temp.
unstable (γ) → martensite

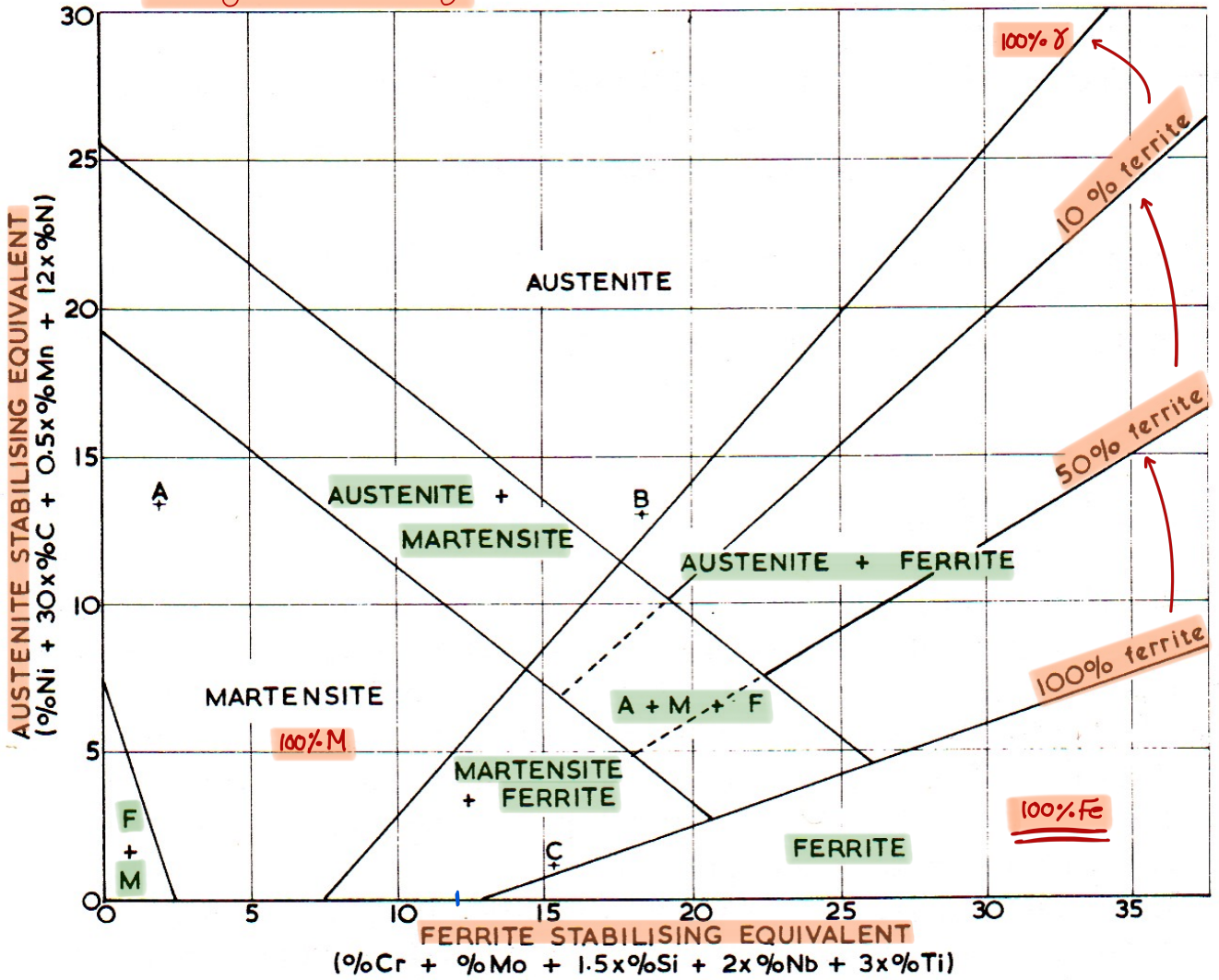
Effect on mechanical properties



- Another important effect of alloying elements on carbon steel is the determination of the final "stable" structure at room temperature.

*At high cooling rates, such as welding or small scale die-casting.

For welding & small scale die-casting.



Stable structure in the room temp. depends on:

- Ferrite stabilizer equivalent.
- Austenite stabilizer equivalent.

with the equ-

(alloy) محسب لنفس الـ على المعادلتين حتى يمكن عشان تحدد مكانه.

الشكل مش موجود ما متطلوب بالمعادلة.

Exercise:

- Determine the final structure of three steels having compositions of:

- 4.25% Ni, 1.25 % Cr, 0.25% Mo, 0.45 % Mn, 0.25% Si and 0.3 C.

الإشارة تشير الى التقاطع الي على الرسمة.

Final structure for steel (A)
100% Martensit
(as welded metal).

As martensitic structure we should use a post heat-treatment (Tempering). to avoid cracks & brittleness.



- 17.5% Cr, 11% Ni, 1.2% Mn, 0.6% Si and 0.05% C.
- 14 % Cr, 0.8% Si, 0.5% Mn and 0.03% C.

Chapter Five

Fatigue

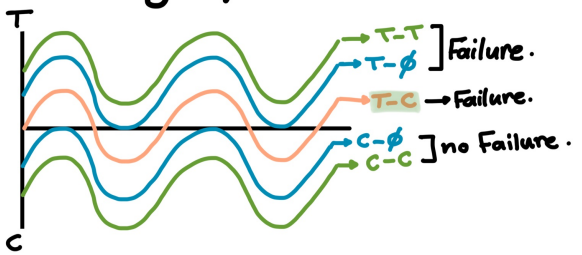
- Fatigue can be defined as "***the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material***"

- Cyclic stresses maybe caused by fluctuating mechanical loads, or by thermal stresses.[2]

most cases are less than the yield.
but Dynamic Load.

•Fatigue•

•Loading cycles•

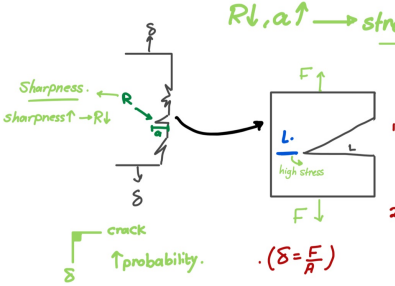


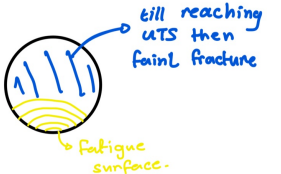
•Fatigue should howe a tensile part.
↳ opening the cracks that leads to the fatigue.

Fatigue : (3stages).
1. crackinitiation (اشتداد)
2. crack propagation
3. Fainal fracture.

Surfaces: (2 type)
1. Smooth → no cracks → cracinitiation , time ↑.
2. notched. → already cracked.

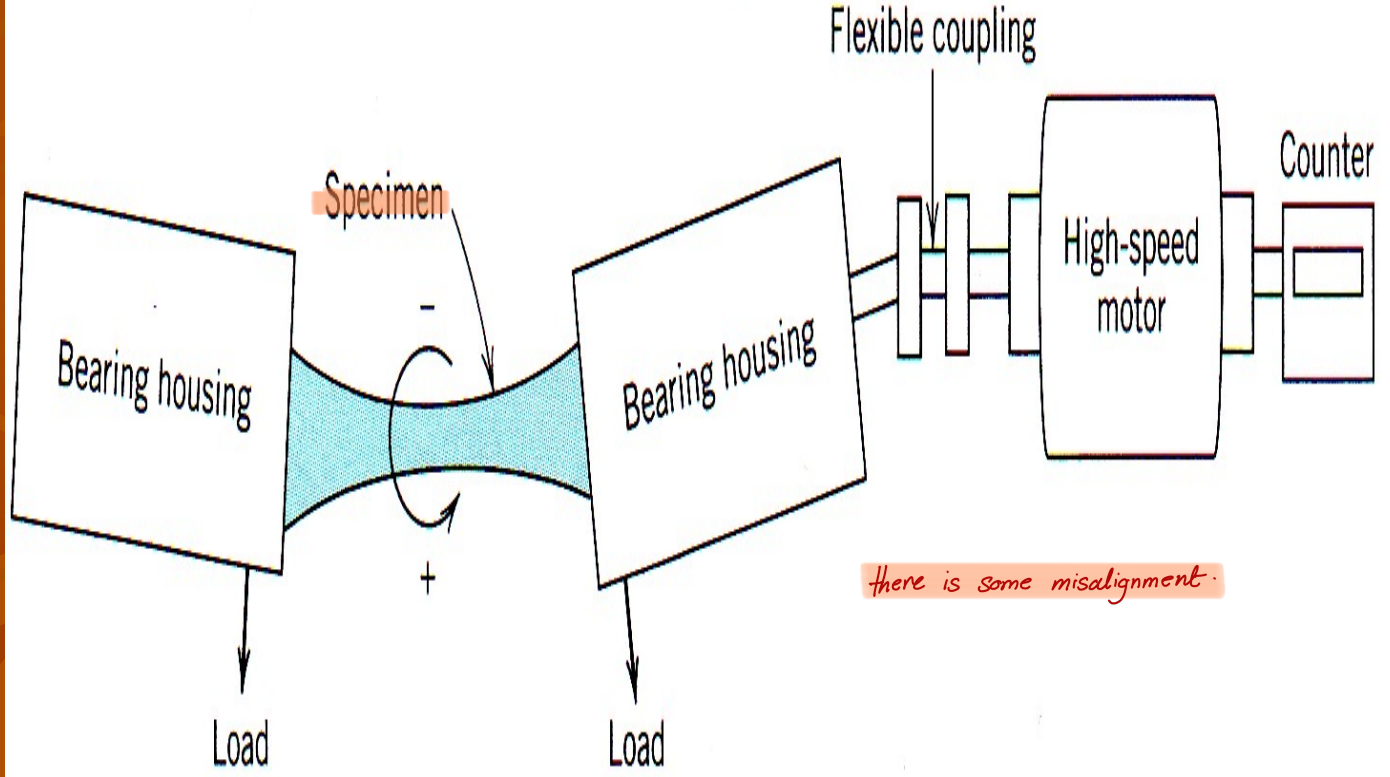
R↓, a↑ → stress concentration.



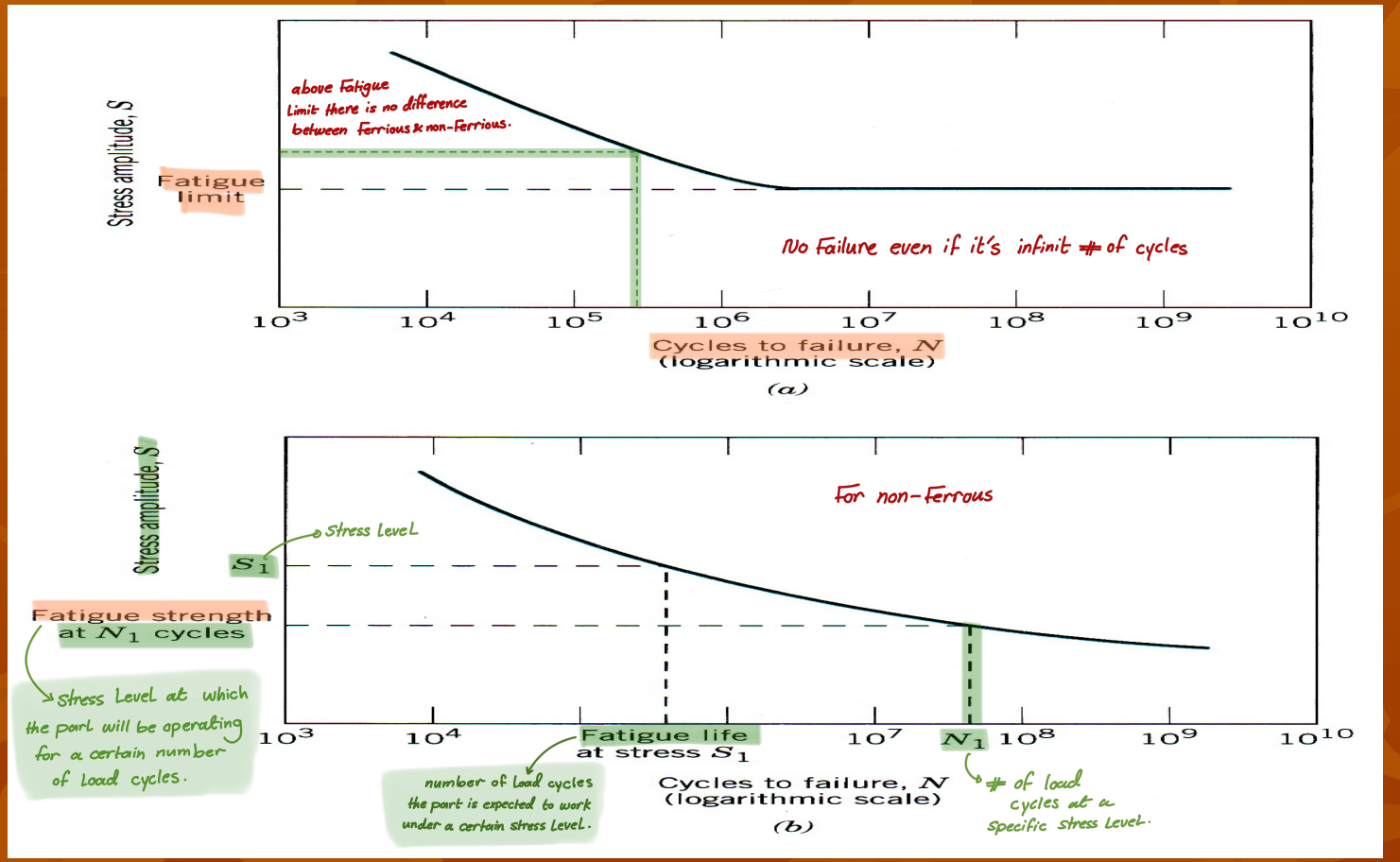


- Fatigue tests involve subjecting a part (or specimen) to repeated cyclic stress (**S**) (such as maximum tensile, maximum compression, maximum tensile and so on) and noting the number of load cycles (**N**) before failure

- "**Fatigue limit**" defined as the stress level under which fatigue failure will not occur under any number of load cycles.


Flexible coupling
Counter
Specimen
High-speed motor
Bearing housing
Bearing housing
there is some misalignment.
Load
Load

* Fatigue Limit → For steels.



at static Load → Creep
Dynamic Load → Fatigue.

Creep

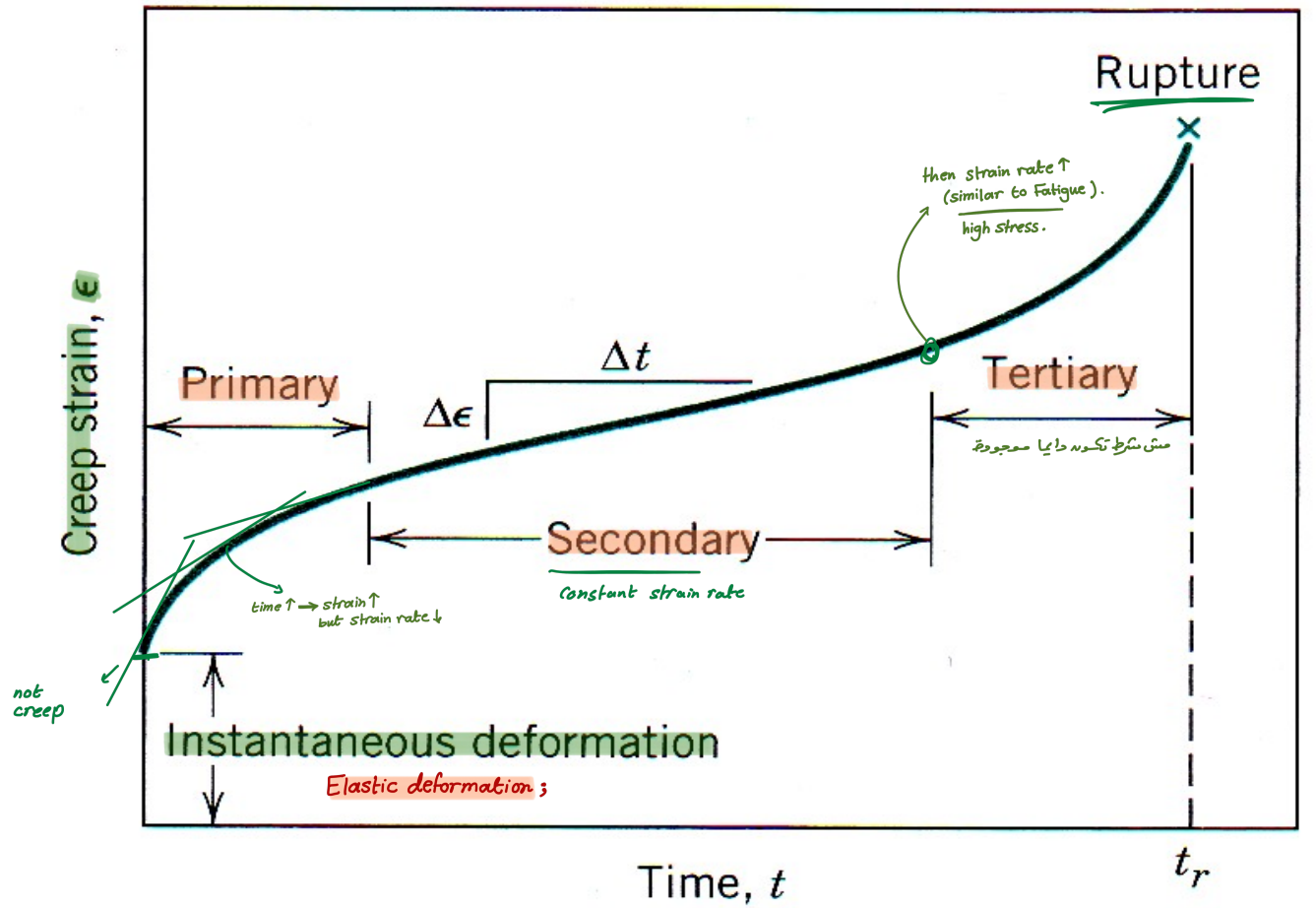
- Creep can be defined as "***time-dependent strain, or gradual change of shape, of a part that is under stress***"

tensile stress.

- Creep is considered to occur in three stages:

Creep↑ depends on
- Stress Level ↑
- Temp. Level ↑

زي كأني فيه load والقطعة بتبدش ترخي وتتراخ.


Rupture
Then strain rate ↑ (similar to Fatigue).
high stress.
Creep strain, ϵ
Primary
Δt
Δϵ
Tertiary
مش شرط تكون دايما موجودة
Secondary
constant strain rate
time ↑ → strain ↑ but strain rate ↓
not creep
Instantaneous deformation
Elastic deformation ;
Time, t
t_r

- After the material undergo an immediate elastic strain due to the application of load, the metal undergoes increasing plastic strain at a decreasing strain rate. This is the primary or first stage of creep which takes place within the first few moments after the load is applied.

- The creep rate usually slows as crystallographic imperfections within the metal undergo realignment leading to secondary creep or stage two. This stage is characterized by continuation of deformation under stress but not as rapid as stage one. The duration of this stage is dependant however on the level of stress and temperature involve.

- Stage three, or tertiary creep, is the gradual increase in strain rate prior to fracture. The presence of the three stages is not always necessary depending on the material involved as well as the temperature and stress levels present.

Recovery, Recrystallization and Grain Growth

- In a cold worked material certain microstructural changes take place including:
- A change in the grain shape
- Strain hardening and → hardness increase.
- An increase in dislocation density → consuming the ductility. no more space for dislocations.

- Certain amount of the energy spent in the deformation process is stored in the material as strain energy.

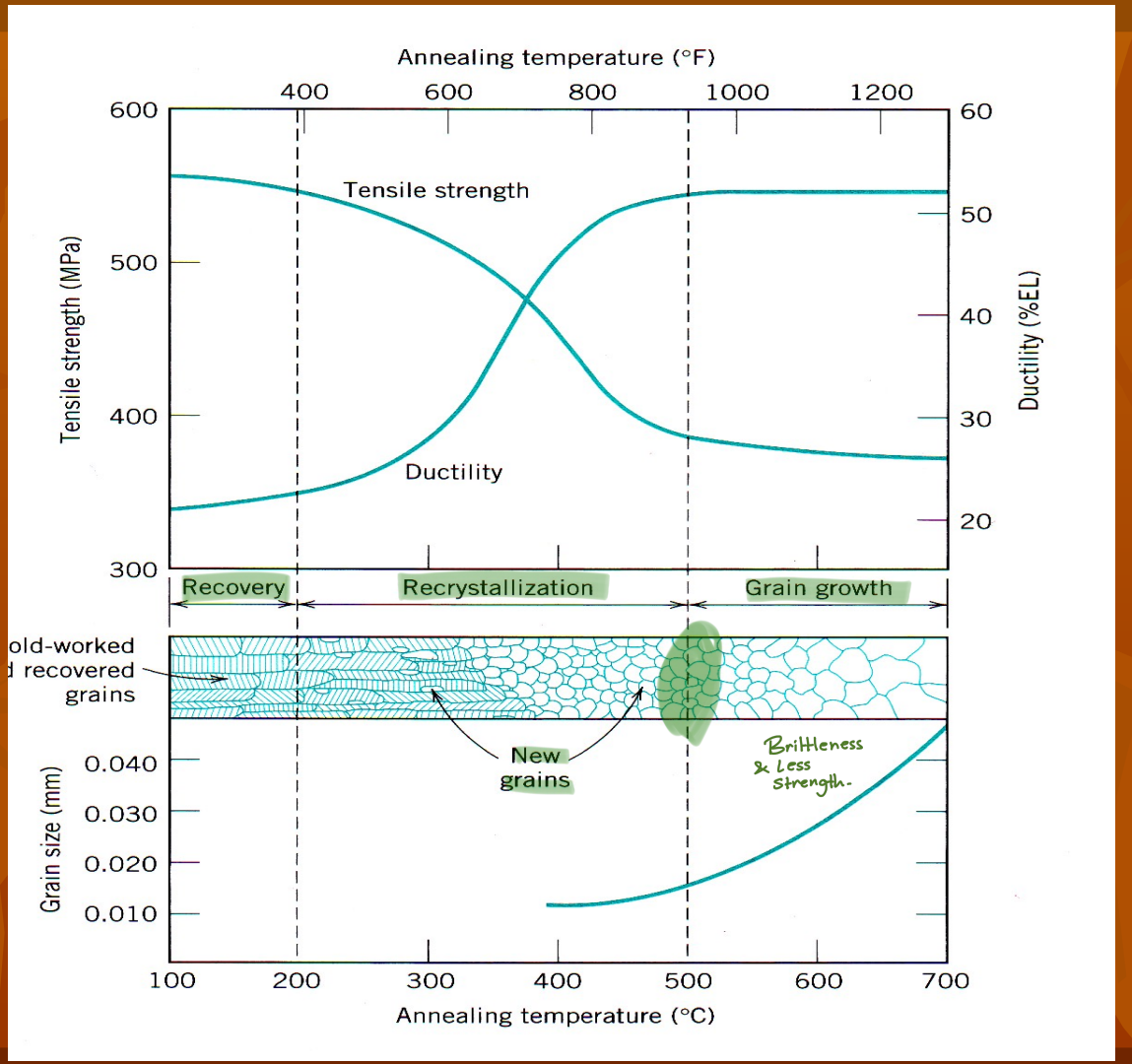
strain hardening.

- In addition to increased level of hardness and strength resulting from plastic deformation at relatively low temperatures, some other properties such as electrical conductivity and corrosion resistance are modified.

- Restoration (استرجاع) of "pre-cold worked" properties could be possible through suitable heat treatment (or annealing).

- This restoration is possible through processes taking place at the elevated temperatures (→ Less than the lower critical temp.) including, recovery and recrystallization which maybe followed by grain growth.

(→ reduce surface energy.)


Annealing temperature (°F)
400
600
800
1000
1200
600
500
400
300
60
50
40
30
20
Tensile strength (MPa)
Ductility (%EL)
Tensile strength
Ductility
Recovery
Recrystallization
Grain growth
old-worked
d recovered
grains
New
grains
Brittleness
& Less
Strength.
Grain size (mm)
0.040
0.030
0.020
0.010
100
200
300
400
500
600
700
Annealing temperature (°C)

Recovery

- This represents slight decrease in the strength level and ***recovery*** of some of the properties such as electrical conductivity to their pe-rcold worked values, which takes place in the first stages of the annealing process.

Recrystallization

- Recrystallization refers to "***the formation of new set of equi-axed grains (grains which have equal dimensions in all directions) with low dislocation density***".

- An important factor to be considered is the "recrystallization temperature".

↳ not constant for all materials.

hot working → working at temp. higher than the recrystallization temp.

Metal	Recrystallization Temperature °C	Recrystallization Temperature °F	Melting Temperature °C	Melting Temperature °F
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

→ at the room temp. we're already above the recrystallization temp. (hot working at the room temp.)

- This would result in a significant reduction in strength and hardness levels.

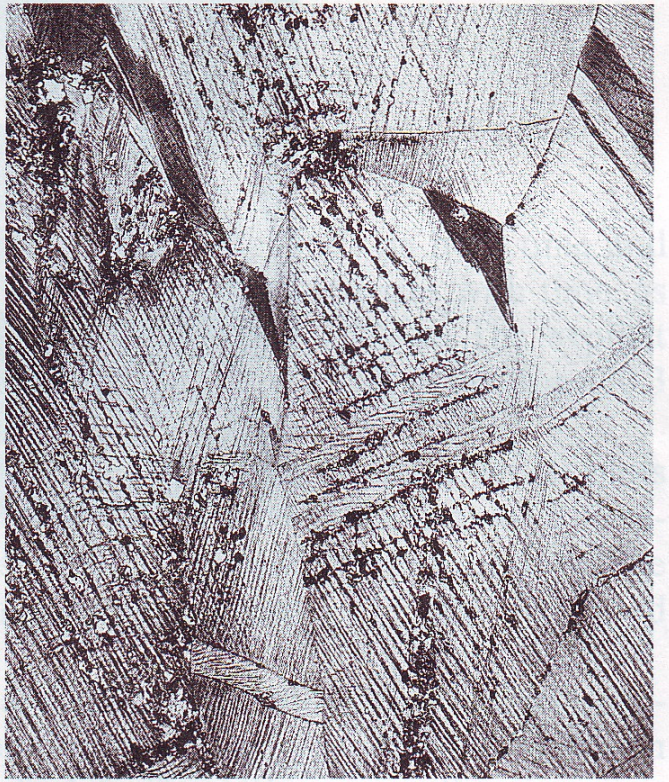
Grain growth

- Upon continued heating, especially at relatively high temperatures, grain growth may take place resulting in large grain size.

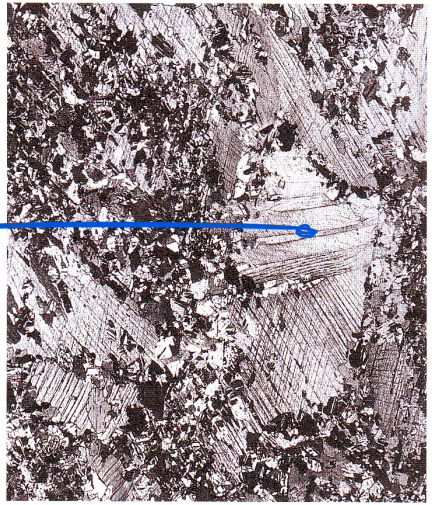


(a)

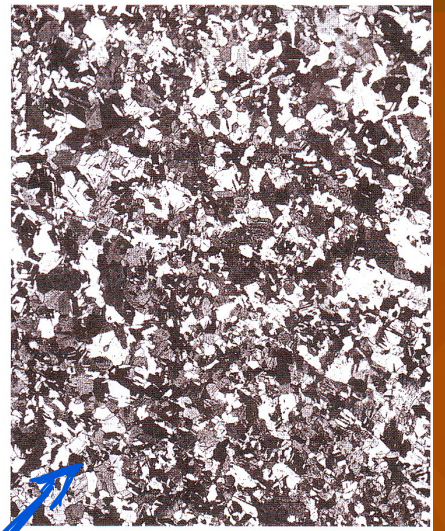
Large dislocation density.



(b)



(c)



(d)



(e)



(f)

Large grains (not fully recrystallized.)

Starting the Grain Growth.

Grain Growth.

Effect of Welding

- In welding two or more metal parts are joined to form a single piece.
- Both similar and dissimilar metals may be welded.
- The "joining bond" is metallurgical rather than just mechanical.

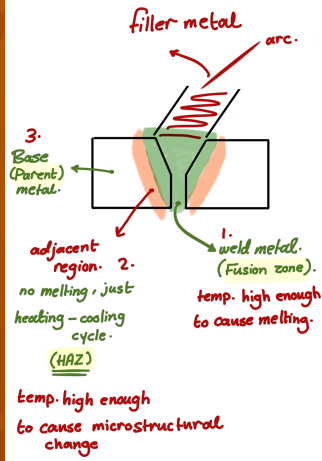
↳ because there are melting, solidification, heating & cooling.

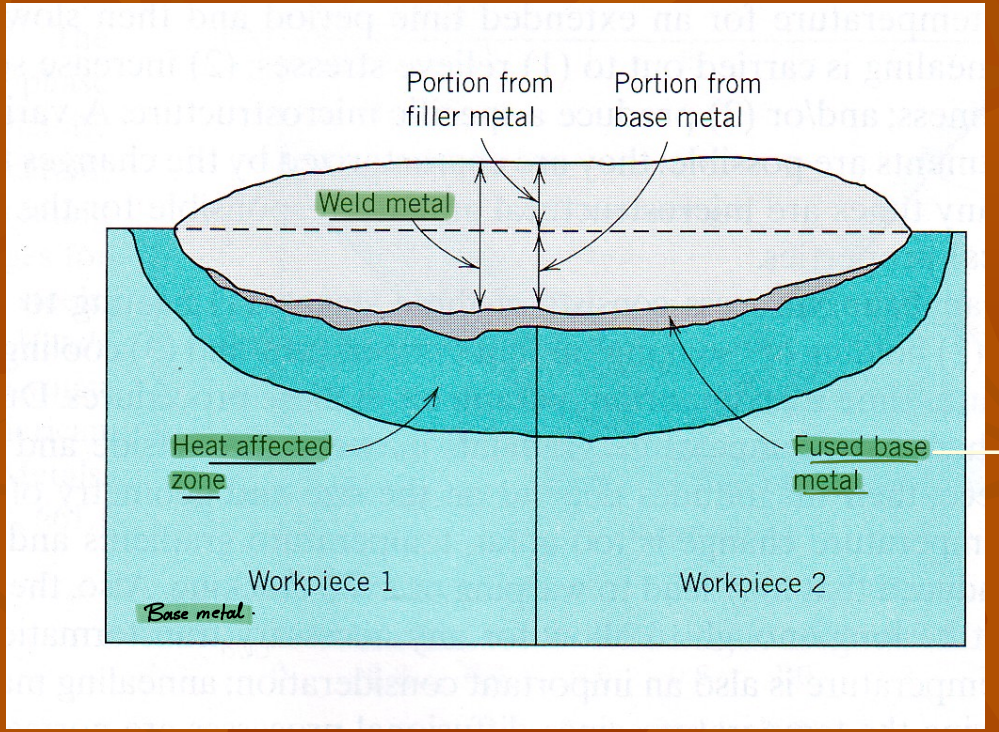
- During arc and gas welding, the work pieces to be joined and the filler metal (welding rod) are heated to a sufficiently high temperature to cause both to melt.

- Upon solidification the filler metal forms a fusion zone to form between the two work pieces.

- Thus the region adjacent to the weld may have experienced microstructural and property changes as a result of the heating-cooling cycle.

- This region is termed the "***Heat Affected Zone***" or **HAZ**,



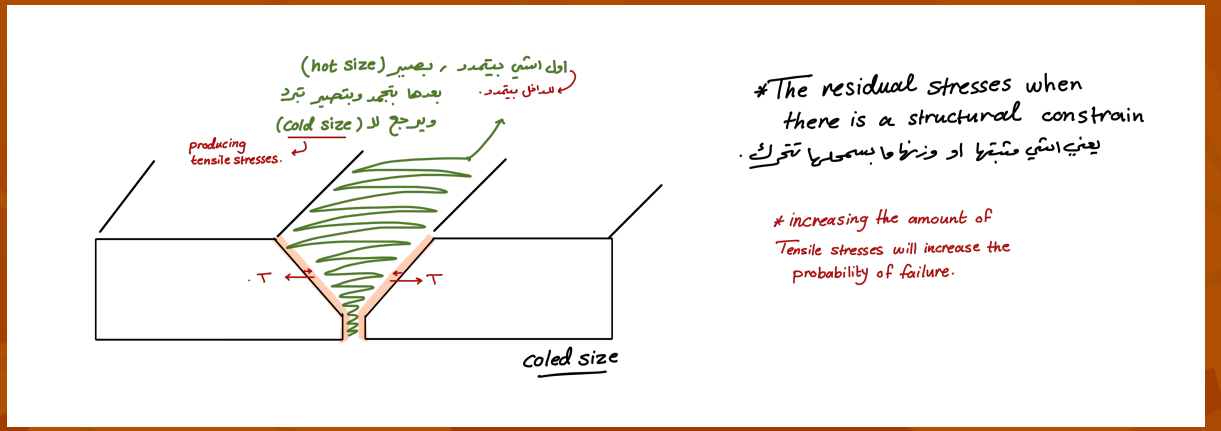


Fusion line (Fusion boundary). partial melting. btw. solidus & Liquidus.

- Possible alterations in the HAZ include the following:

- If the work piece material was previously cold worked the HAZ may experience recrystallization and grain growth with significant reduction in the strength, hardness and toughness levels.

Upon cooling, residual stresses may form within this part which weaken the joint.



*The residual stresses when there is a structural constrain
يعني اشي مثبتها او ومنعها بشكل ما تتحرك .

* increasing the amount of Tensile stresses will increase the probability of failure.

- For steels, the material in this zone may have been heated to temperatures sufficiently high so as to form austenite. Upon cooling to room temperature, the final microstructure will depend on the cooling rate involved. In plain carbon steels, normally pearlite and a pre-eutectoid phase will be present.

higher than the upper critical temp.

high trans. rate.

. chemical comp. (C%)
. cooling rate.

α + Pearlite

For alloy steels however, martensite may result in this zone, which is normally undesired due to its brittleness.

in the HAZ

martensite when the cooling rate is slow.

trans. takes time to start & to end.



alloy steels



plane carbon steel.
no (M).

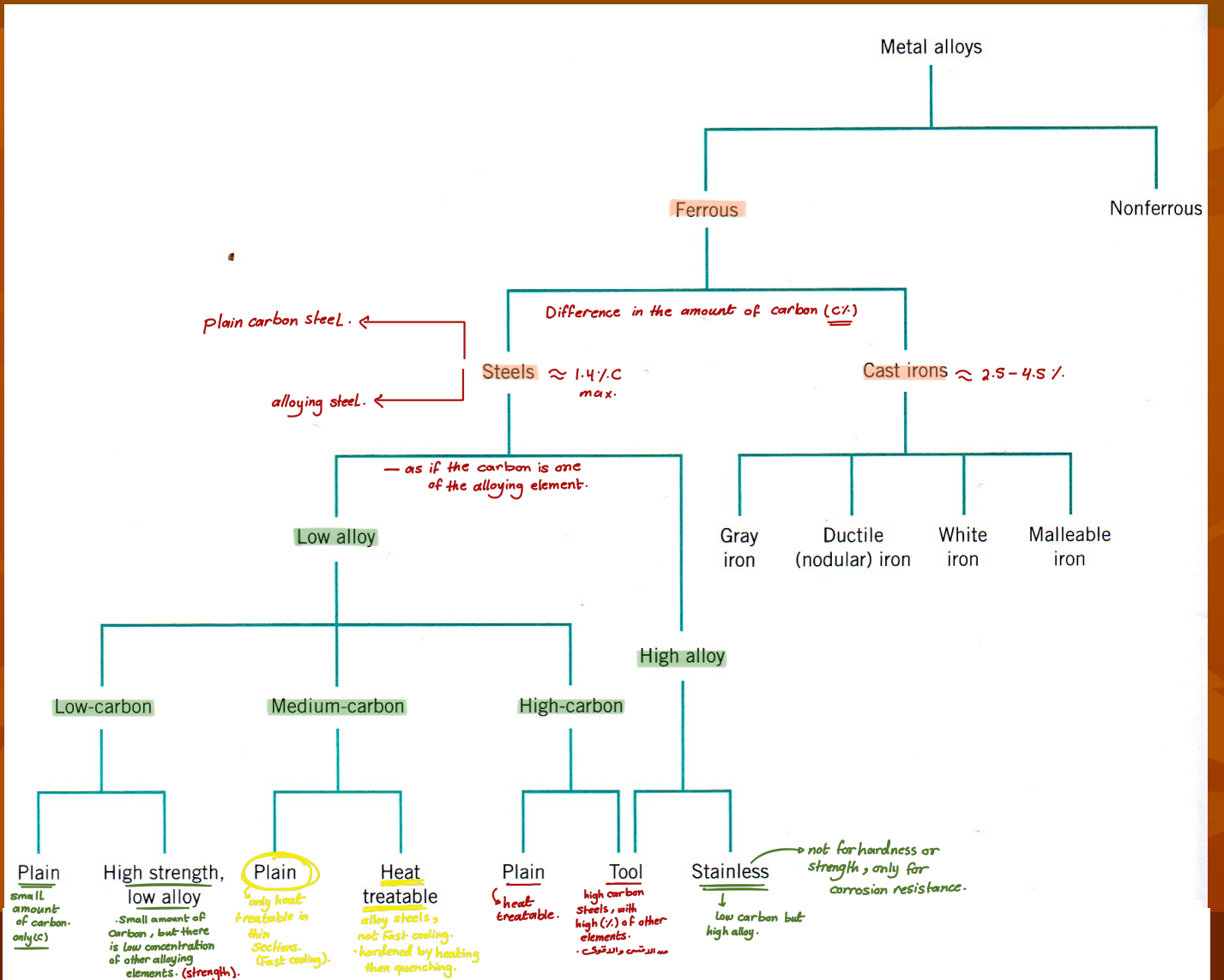
in chapter 7 or 8

Some stainless steels may be sensitized during welding and hence lowering resistance to Intergranular corrosion (as will be discussed later).

Chapter Six

Metallic Alloys

- Metals and metallic alloys are normally grouped into two main classes, i.e., "***ferrous alloys***" and "***non-ferrous alloys***".


Metal alloys
Ferrous
Nonferrous
Difference in the amount of carbon (C%)
plain carbon steel.
alloying steel.
Steels ≈ 1.4%C max.
Cast irons ≈ 2.5 - 4.5 %.
— as if the carbon is one of the alloying element.
Low alloy
High alloy
Gray iron
Ductile (nodular) iron
White iron
Malleable iron
Low-carbon
Medium-carbon
High-carbon
Plain
small amount of carbon. only (C)
High strength, low alloy
.Small amount of carbon, but there is low concentration of other alloying elements. (strength).
Plain
only heat treatable in thin sections. (Fast cooling).
Heat treatable
alloy steels, not Fast cooling.
·hardened by heating then quenching.
Plain
heat treatable.
Tool
high carbon steels, with high (%) of other elements.
Stainless
low carbon but high alloy.
not for hardness or strength, only for corrosion resistance.

- Concentration will be given to ferrous alloys as these are the most widely produced and used types of metallic materials, even though main classes of non-ferrous alloys will be discussed.

Ferrous Alloys

- Ferrous alloys are those of which iron is the prime constituent.

- These are probably the class of most widespread use in engineering due to the following reasons:

- Iron-containing compounds exist in abundant amounts in the earth's crust

- Metallic iron and steel alloys maybe produced using relatively economical extraction, refining, alloying and fabrication techniques

- Ferrous alloys are extremely versatile, i.e., they can be tailored to have a wide range of mechanical and physical properties.

Steels

- Steels are iron-carbon alloys.
- Plain carbon steels contain only residual amounts of impurities other than carbon and a little manganese.
- Alloy steels may contain appreciable amounts of other elements added for specific purposes.

- The mechanical properties are sensitive to the carbon content, which is normally less than 1.0 %.

- Steels are classified according to their carbon concentration, i.e., low-, medium- and high-carbon steels.

- Sub-classes also exist in each group according to the concentration of other alloying elements, i.e., low-alloy and high-alloy-steels.

Low-carbon steels

- These steels can be characterized by the following:
- Carbon content normally less than 0.25 wt.%
  ↳no response for hardening.
- Unresponsive to heat treatments intended to produce martensite
- Strengthened by cold working

- Their microstructure consists of ferrite and pearlite

hypoeutectoid.

- Relatively soft and weak
- Have good properties such as :

- Ductility
- Toughness
- Good machinability
- Good weldability
- Considered inexpensive

Examples of low carbon steels:

Designation[a]		Composition (wt%)[b]		
AISI/SAE or ASTM Number	UNS Number	C	Mn	Other
		Plain Low-Carbon Steels		
1010	G10100	0.10	0.45	
1020	G10200	0.20	0.45	
A36	K02600	0.29	1.00	0.20 Cu (min)
A516 Grade 70	K02700	0.31	1.00	0.25 Si
		High-Strength, Low-Alloy Steels		
A440	K12810	0.28	1.35	0.30 Si (max), 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb
A656 Grade 1	K11804	0.18	1.60	0.60 Si, 0.1 V, 0.20 Al, 0.015 N

added to the steel that intended to case hardening. by nitriding.

AISI/SAE or ASTM Number	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
		Plain Low-Carbon Steels		
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	205 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
		High-Strength, Low-Alloy Steels		
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Grade 1	655 (95)	552 (80)	15	Truck frames and railway cars

*Ductility not strength.

Medium-carbon steels

- These steels can be characterized by the following:
- Carbon content normally between 0.25 and 0.6 wt.%
- May be heat treated by austenitizing, quenching and tempering to improve their mechanical properties

- Mostly used in the tempered condition with a structure of tempered martensite

- Plain medium-carbon steels have low hardenability and can be successfully heat treated only in thin sections and high quenching rates.

* as plain carbon → heat treatable in this section.
because of the high trans. rate.
· no enough time before tran. begin.

- Alloy steels can be heat treated to give rise to a variety of strength-ductility combinations

- Heat treated alloys are stronger than low-carbon steels but generally less ductile.

AISI/SAE Designation[a]	UNS Designation	Composition Ranges (wt% of Alloying Elements in Addition to C)[b]			
		Ni	Cr	Mo	Other
10xx, Plain carbon	G10xx0				
11xx, Free machining	G11xx0				0.08–0.33S
12xx, Free machining	G12xx0				0.10–0.35S, 0.04–0.12P
13xx	G13xx0				1.60–1.90Mn
40xx	G40xx0			0.20–0.30	
41xx	G41xx0		0.80–1.10	0.15–0.25	
43xx	G43xx0	1.65–2.00	0.40–0.90	0.20–0.30	
46xx	G46xx0	0.70–2.00		0.15–0.30	
48xx	G48xx0	3.25–3.75		0.20–0.30	
51xx	G51xx0		0.70–1.10		
61xx	G61xx0		0.50–1.10		0.10–0.15V
86xx	G86xx0	0.40–0.70	0.40–0.60	0.15–0.25	
92xx	G92xx0				1.80–2.20Si

only sulfur.

- Sharp edged
- Weak, brittle
- Low bonding with the matrix.

not for application with tensile stresses.

AISI Number	UNS Number	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
			Plain Low-Carbon Steels		
1040	G10400	605–780 (88–113)	430–585 (62–85)	33–19	Crankshafts, bolts
1080[a]	G10800	800–1310 (116–190)	480–980 (70–142)	24–13	Chisels, hammers
1095[a]	G10950	760–1280 (110–186)	510–830 (74–120)	26–10	Knives, hacksaw blades
			Alloy Steels		
4063	G40630	786–2380 (114–345)	710–1770 (103–257)	24–4	Springs, hand tools
4340	G43400	980–1960 (142–284)	895–1570 (130–228)	21–11	Bushings, aircraft tubing
6150	G61500	815–2170 (118–315)	745–1860 (108–270)	22–7	Shafts, pistons, gears

High-carbon steels

- These steels can be characterized by the following:
- Carbon content normally between 0.6 and 1.4 wt.%
- Almost always used in the quenched and tempered condition

tempered martensitic structure.

used for tools

- Hardest, strongest and least ductile steels

because of the hardness.

- Have high wear resistance

- Tool steels are high-carbon steels with additions of chromium, vanadium, tungsten and molybdenum (carbide forming elements)

AISI Number	UNS Number	Composition (wt%)[a]						Typical Applications
		C	Cr	Ni	Mo	W	V	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lathe and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, woodworking tools

Air hardening.

delaying the trans.

Stainless Steels

- Stainless steels are steels that are highly resistance to corrosion in a number of environments, especially the ambient atmosphere.

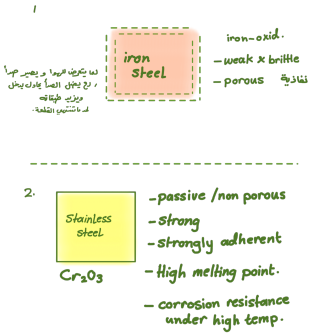
the surrounding.

- ***Chromium*** is the major alloying element where at least 11.0 % is required for corrosion resistance.

- Corrosion resistance may be further enhanced by the addition of elements such as nickel and molybdenum.

primary element is chromium.

- Stainless steels are divided into three main classes:



Fcc : Austenitic structure.

The stable phase at room temp. is (γ) FCC

1.

Austenitic stainless steels.

- These stainless steel have a stable austenitic FCC (γ) crystal structure as a result of high amounts of nickel (austenite stabilizer) added and the most corrosion resistant as a result of high chromium and nickel concentrations.

• corrosion : aqueous environments

• oxidation : dry & high temp.

- They are not heat treatable and, hence can be hardened by cold work.

- Austenitic stainless steels are non-magnetic and especially appropriate for cold work due to their austenitic structure.

FCC → γ

much more ductility than BCC

Austenitic martix = FCC structure.

2.

Ferritic stainless steels.

- These stainless steel have a ferritic BCC (α) crystal structure as a result of high amounts of chromium (ferrite stabilizer).
-
- They are strengthened and hardened by cold work and are magnetic.

not by heat-treatment.

- Due to the high chromium content, these steels are considered to have of high resistance to oxidation

*Chromium .

3.

Martensitic stainless steels.

- These stainless steel have a martensitic structure and, hence can be heat treated and are magnetic.

Less ductility.
but more hardness.

AISI Number	UNS Number	Composition (wt%)[a]	Condition[b]	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
			Ferritic				
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
			Austenitic				
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction
			Martensitic				
410	S41000	0.15 C, 12.5 Cr, 1.0 Mn	Annealed Q & T	485 (70) 825 (120)	275 (40) 620 (90)	20 12	Rifle barrels, cutlery, jet engine parts
440A	S44002	0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed Q & T	725 (105) 1790 (260)	415 (60) 1650 (240)	20 5	Cutlery, bearings, surgical tools
			Precipitation Hardenable				
17-7PH	S17700	0.09 C, 17 Cr, 7 Ni, 1.0 Al, 1.0 Mn	Precipitation hardened	1450 (210)	1310 (190)	1–6	Springs, knives, pressure vessels

[a] The balance of the composition is iron.

Higher carbon than the steel.

Cast Irons

- Cast irons are a class of ferrous alloys containing more than 2 wt. % carbon; in practice they contain between 3 and 4.5 wt. % carbon and other alloying elements. → To control the structure
- Reconsidering the Fe-C phase diagram indicates these alloys to be in the liquid state in the temperature range 1150 to 1300 ºC.

less heat required.

steel max. carbon content. from (γ) with 2%

steel. بعد الـ (2%) ما بصير عندي

- This range is well below that for carbon steels and hence these alloys can be easily melted and cast.

- In addition some irons are brittle (no ductility) and casting becomes the only practical way of processing.

iron-carbid.

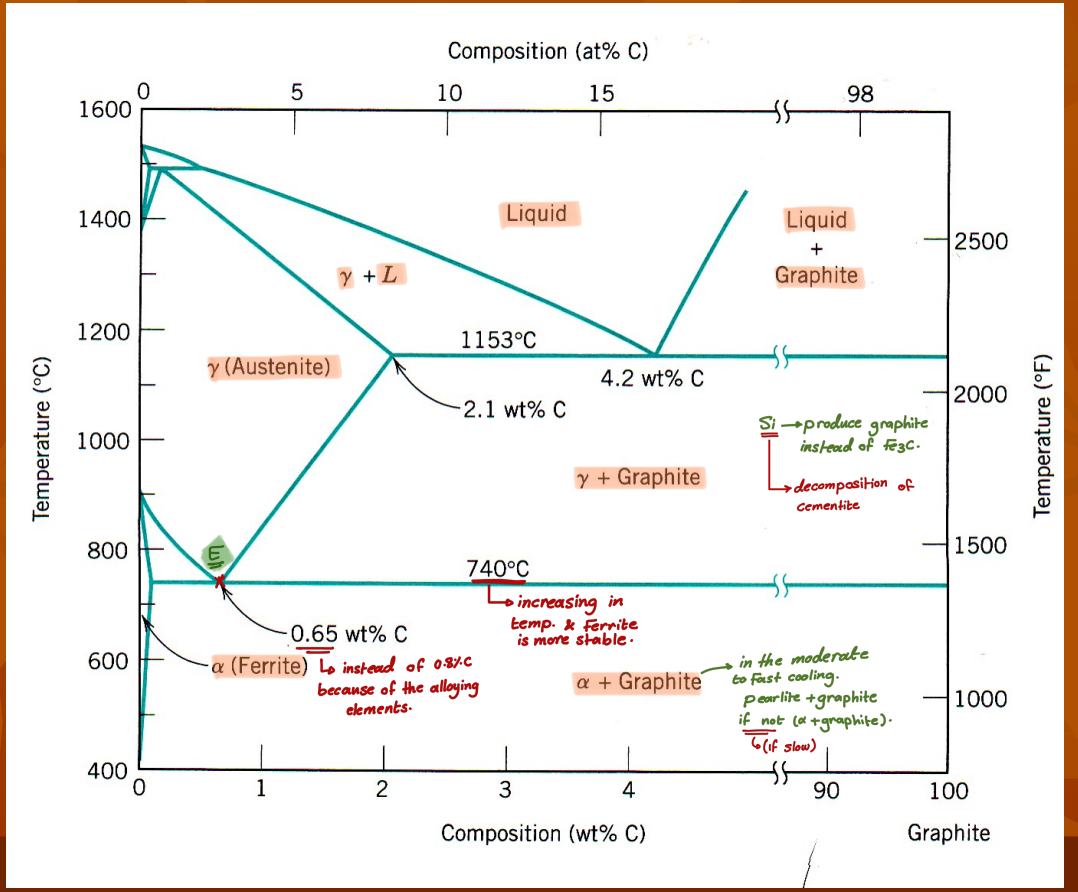
Stable only in specific conditions., and unstable at any change of the conditions.

- Cementite is a metastable compound and under certain circumstances:(presence of more than 1wt.% Si and slow cooling) it can be made to decompose into ferrite and graphite aacording to the reaction:

هاد الشرط الاهم.

$$Fe_3C \rightarrow 3Fe(\alpha) + C\ (\textbf{graphite})$$

Thus the true Fe-C phase diagram becomes



Doesn't apply for steel now.

Si → produce graphite instead of Fe_3C.
↳ decomposition of cementite

increasing in temp. ∴ ferrite is more stable.

↳ instead of 0.8% C because of the alloying elements.

in the moderate to fast cooling. pearlite + graphite if not (α + graphite).
↳ (if slow)

Gray cast iron

no Fe_3C as a separate phase.

- In this class the carbon and silicon concentrations are 2.5 to 4.0% and 1.0 to 3.0 %, respectively.

شرائح

- The graphite exists in the form of flakes normally surrounded by a ferrite or pearlite matrix.



. Gray cast iron :

- Sharp flakes mostly.
- Weak & brittle (Graphite).
  - weak bonding with the matrix.
  - brittleness for the whole alloy.
- easy path for the cracks.
  - not for Tensile stresses applications.

— only for compressive stresses.

يعني لو كسرناها واطلعنا عليها .

- Because of these graphite flakes a fracture surface takes a gray appearance from which the name was derived.

- Gray cast irons are considered to be weak and brittle if loaded in tension.

- The graphite flakes are sharp and may act as stress raisers during tension loading.

نتؤات .

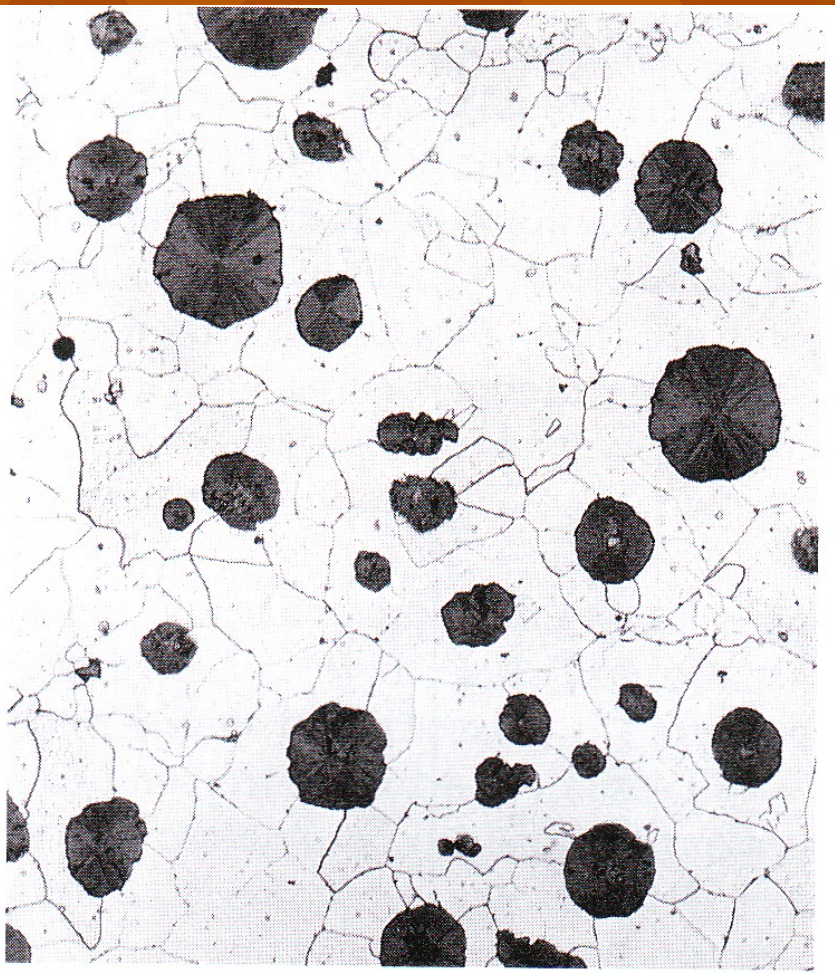
Ductile or nodular iron

- Addition of a small amount of magnesium and/or cerium to the gray cast iron before casting produces a distinctly different microstructure.

- Graphite is still present but in the form of spheres or nodules instead of flakes in a matrix of ferrite or pearlite

– magnesium / cerium.

Graphite as nodules not as Flakes.



(b)

- tough
- Ductily
- less stress raisers.
- Space btw particles
- mostly (α)

- This structure has much better mechanical properties than gray cast iron which accounts for its use in applications such as valves, crankshafts, gears and other automotive parts.

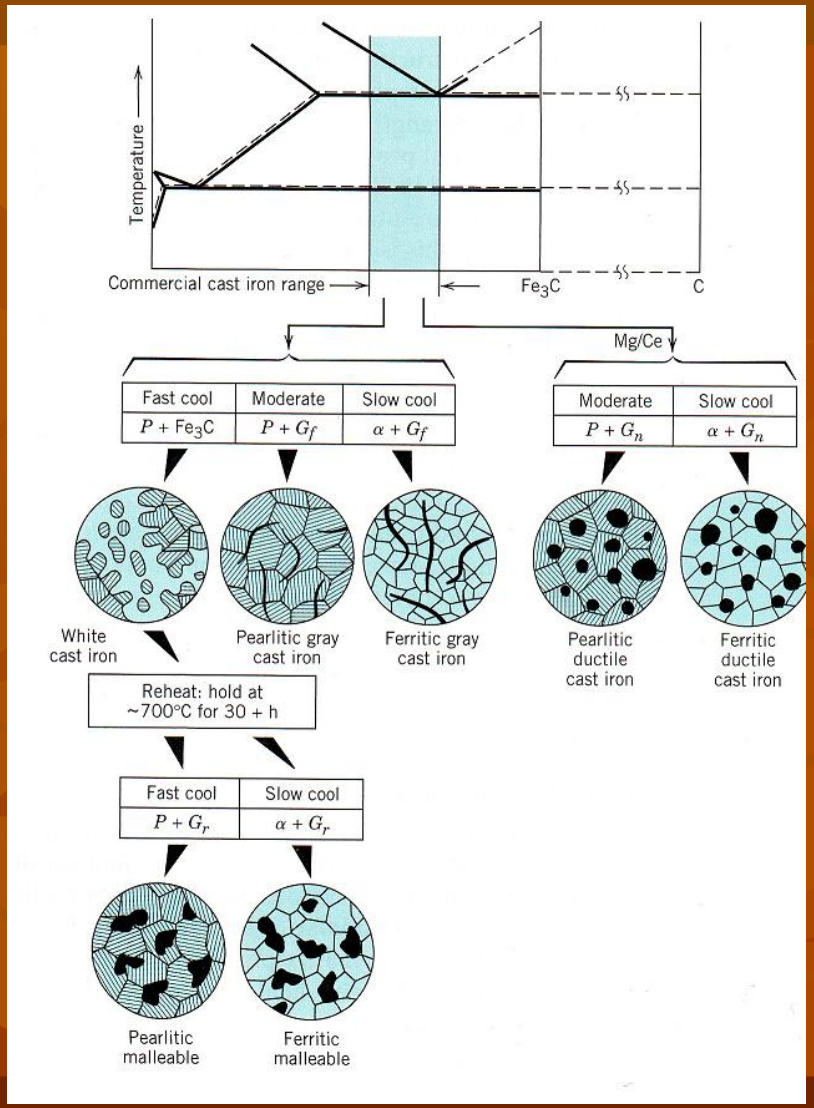
Small amount of stresses.

قابل للتشكيل.

White iron and malleable iron

- For low silicon cast irons (below 1 %) and rapid cooling most of carbon exists as cementite

no enough Si to resist the forming of Fe_3C.


Temperature
Commercial cast iron range
Fe_3C
C
Mg/Ce
Fast cool
$P + Fe_3C$
Moderate
$P + G_f$
Slow cool
$\alpha + G_f$
Moderate
$P + G_n$
Slow cool
$\alpha + G_n$
White cast iron
Pearlitic gray cast iron
Ferritic gray cast iron
Pearlitic ductile cast iron
Ferritic ductile cast iron
Reheat: hold at ~700°C for 30 + h
Fast cool
$P + G_r$
Slow cool
$\alpha + G_r$
Pearlitic malleable
Ferritic malleable

- A fracture surface of this alloy takes a white color, hence the name white iron.



(c)

The original matrix is pearlite

* Fe_3C exist because no enough (Si).

-Extremely hard.

because of the rapid cooling

- In this case it is a very hard and brittle material and limited uses only where extreme hardness and wear resistance with limited ductility is needed such as in rollers in roll mills.

• wear resistance & hardness at high temp.

not a fainal stage.

- White iron is in fact produced as an intermediate step in producing another type of iron; "**malleable iron**".

more ductility.

- This is achieved by heating for prolonged periods in the temperature range 800 to 900 ºC in a neutral atmosphere.

  inert

- This causes a decomposition of cementite and the formation of graphite. Graphite is present in the form of clusters or rosettes in a matrix of ferrite or pearlite depending on the rate of cooling.

rosettes /clusters



(d)

- toughness
- Ductility.

. Ferrite without pearlite or Fe_3C.

- This structure is similar to that of nodular iron and accounts for relatively high strength and appreciable ductility.

Grade	UNS Number	Composition (wt%)[a]	Matrix Structure	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
			Gray Iron				
SAE G1800	F10004	3.40–3.7 C, 2.55 Si, 0.7 Mn	Ferrite + Pearlite	124 (18)	—	—	Miscellaneous soft iron castings in which strength is not a primary consideration
SAE G2500	F10005	3.2–3.5 C, 2.20 Si, 0.8 Mn	Ferrite + Pearlite	173 (25)	—	—	Small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases
SAE G4000	F10008	3.0–3.3 C, 2.0 Si, 0.8 Mn	Pearlite	276 (40)	—	—	Diesel engine castings, liners, cylinders, and pistons
			Ductile (Nodular) Iron				
ASTM A536 60-40-18	F32800	3.5–3.8 C, 2.0–2.8 Si, 0.05 Mg, <0.20 Ni, <0.10 Mo	Ferrite	414 (60)	276 (40)	18	Pressure-containing parts such as valve and pump bodies
100-70-03	F34800		Pearlite	689 (100)	483 (70)	3	High-strength gears and machine components
120-90-02	F36200		Tempered martensite	827 (120)	621 (90)	2	Pinions, gears, rollers, slides
			Malleable Iron				
32510	F22200	2.3–2.7 C, 1.0–1.75 Si, <0.55 Mn	Ferrite	345 (50)	224 (32)	10	General engineering service at normal and elevated temperatures
45006	—	2.4–2.7 C, 1.25–1.55 Si, <0.55 Mn	Ferrite + Pearlite	448 (65)	310 (45)	6	

Strength اشياء ثانوية ما يرها

no stresses

* white iron only for hardness & wear resistance.

Non-Ferrous Alloys

- Ferrous alloys are used in large amounts, as they can offer a wide range of mechanical properties. There are, however, some distinct limitation inherent in these alloys such as:

steel is not good .
لهذا يكون بدي وزنه خفيف .

- Relatively high density
- Relatively low electrical conductivity
- An inherent susceptibility to corrosion.

- Thus, for many applications it is advantageous or even necessary to use other types of alloys. Alloys are normally classified according to the "***base metal***", which is the metal having the highest concentration.

- It is also necessary to distinguish between cast and wrought alloys;

↳ some mechanical processing.

comparing with the wrought alloys.

- ***Cast alloys*** are alloys that are brittle in which forming or shaping by appreciable deformation is not possible and are normally processed by casting.

- ***Wrought alloys*** on the other hand are those alloys amenable to mechanical deformation.

- Two main classes of non-ferrous alloys will be briefly discussed below.

1. Copper and its alloys. → Brasses. / Bronzes.
2. Aluminum and its alloys.

Copper and its alloys

- Unalloyed copper is soft, ductile, corrosion resistant and difficult to machine. Corrosion and mechanical properties can be enhanced by alloying.

FCC

can produce BNE.

- The most common copper alloys are "***brasses***" in which zinc is the major alloying element.

major alloying element.

α: represent the First appearing phase.

→ not same as (α) for iron (BCC)
but (α)-brasse → FCC.

→ solubility of zinc in copper.

- "α-brasses may contain up to 35 % Zn and have an FCC crystal structure and are relatively soft, ductile and easily cold worked.

but stronger than the original copper.
because of the solid solution strengthening.

- Brass alloys having higher zinc content will contain both α and β′.

Zn > 35%
• more than the solubility Limit.

→ as a new phase,
mainly (Zn) with some copper.
(partial solubility in the solid state.).

2 solid solutions : α: Zn in copper.
β′: copper in Zn.

→ the solute atoms are in fixed positions

- β′ has an ordered BCC structure and is harder and stronger than β.

- Consequently α + β′ brasses are hot worked.

→ harder & stronger, less ductily → no cold work.

— because they are 2 phases.

- ***Bronzes*** are another class of copper alloys containing elements such as aluminum, tin, silicon and nickel.

- These are considered to be stronger than brasses but still have good corrosion resistance.

Alloy Name	UNS Number	Composition (wt%)[a]	Condition	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
			Wrought Alloys				
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	690–860 (100–125)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed	300 (44)	75 (11)	68	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
			Cold-worked (H04 hard)	525 (76)	435 (63)	8	
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed	325 (47)	130 (19)	64	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
			Cold-worked (H04 hard)	560 (81)	515 (75)	10	
Copper-nickel, 30%	C71500	30 Ni	Annealed	380 (55)	125 (18)	36	Condenser and heat-exchanger components, saltwater piping
			Cold-worked (H02 hard)	515 (75)	485 (70)	15	
			Cast Alloys				
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

Aluminum and its Alloys

- Aluminum and its alloys are characterized by
- low density (2.7 g/cm3) compared to irons and steels (7.9 cm3) Density (AL) ≈ $\frac{1}{3}$ Density (steels).
- high electrical and thermal conductivities

*used for application with (high strength to weight ratio.)
↳ low weight.

- corrosion resistance
- high ductility even at low temperatures (as a result of the crystal FCC structure)
- One limitation of aluminum is its low melting temperature (660 ºC) which limits the maximum temperature the material can be used at.

high strength but not for high temp.

- Aluminum alloys are versatile and can offer a wide range of engineering properties.

- They exist in both wrought and cas forms and contain both heat-treatable and non- heat-treatable alloys.

numbering system.

- Aluminum alloys are characterized by a 4-digit number as follows:

major alloying element.

- The first digit indicates the alloy group

- The second digit indicates modification of the original alloy or impurity limits

يشو التعديلات الي صارت.

- The third and fourth digits are the same as the two digits to the right of the decimal point in the aluminum percentage.

For 99.6% AL :
the third and Fourth digits are (60)

TABLE 12·5 Designation for Alloy Groups*

	ALUMINUM ASSOCIATION NO.
Aluminum, 99.00% and greater	1xxx
major alloying element	
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and silicon	6xxx
Zinc	7xxx
Other element	8xxx
Unused series	9xxx

*The Aluminum Association.

- In addition to their four-digit number, aluminum alloys are characterized by one or more letters indicating their temper (thermal and/or mechanical treatments) as follows:

- **F**: as fabricated
- **O**: annealed, recrystallized

ready for cold working / hot working

: Ductility exist.

- **H**: strain hardened
  - H1: strain hardened only
  - H2: strain hardened then partially annealed
  - H3: strain hardened and then stabilized
- **W**: solution heat treated

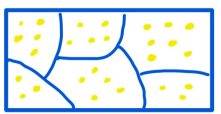
start of recr.

↳ treatment and stabilizing for some phases.

W: Solution heat treated;

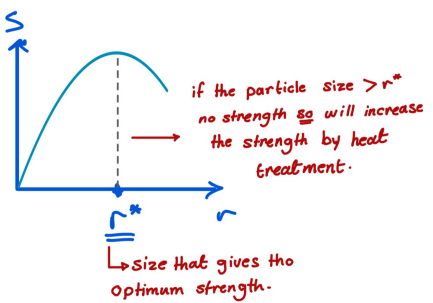
— All Aluminum Except the pure one thier hardening not Like the steel (heating then quenching).
because there is only (γ)

— so hardened by:
(Precipitation hardening).



Precipitation for intermetallic phases.
the small Particles are intermetallic compounds.
Ex: Mg_2Si

the strength:



solution heat-treatment:
heating to a high enough temp.
to cause all the intermetallic phases
to desolve in the matrix, Forming
saturated solid solution.

heating the AL alloy
till it's a saturated solid solution
then Aging ?
↳ same as precipitation hardening.

(intermetallic phases) برجع برسب ال
بكسر بحجم أصغر.

* Strength decrease with the solution heat treatment because of reducing the particle size.

- **T**: thermally treated

  → could also be theromechanically.

  - T2: Annealed (cast products)
  - T3: Solution heat treated and then cold-worked
  - T4: Solution heat treated and then naturally aged

    within the range of room temp. (no need for high temp.).
  - T5: Artificially aged only

    heated to high temp.

Aging:
Subjecting the alloy to a certain temp. (range) for a certain duration of time to allow precipitation of intermetallic compounds for the purpose of hardening./ Strengthening.

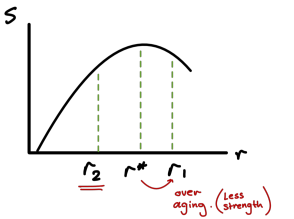
(heat-treatment / solid solution) بتكون بتكسر الـ (Aging)
هاد برجع برسب الي دان قبل بس بخليه يترسب
بالحجم الي انا بدي ايام فت اوصل الـ(ST) الي بتعطيني
الـ(strength) الي بدي اياها.

- T6: solution heat treated and then naturally aged
- T7: Solution heat treated and then artificially aged

Over aged. Less strength.

- T8: Solution heat treated, cold-worked and then artificially aged
- T9: Solution heat treated, artificially aged and then cold-worked
- T10: Artificially aged and then cold-worked

The initial condition is the solution heat treatment.
because the intermetallic particle size Larger than the Optimum.



if the particle size is less than the Optimum : Should have the required grain growth till the optimum, by the artificial aging only.

Chapter Eight

Introduction to Metallic Corrosion and its prevention

for aqueous environment

Corrosion " *The destruction or deterioration of a material because of a reaction with its environment*"

not only for metal.

- Corrosion has a great economical and environmental impact.
- Corrosion is a naturally occurring process that tends to reverse the chemical action of the refining process.
- In their natural, chemically stable state, metals are found primarily either as oxides or sulfides in the ores.

(−ve) change in energy.

→ the material goes from high energy state to lower energy state.

not as pure metal.

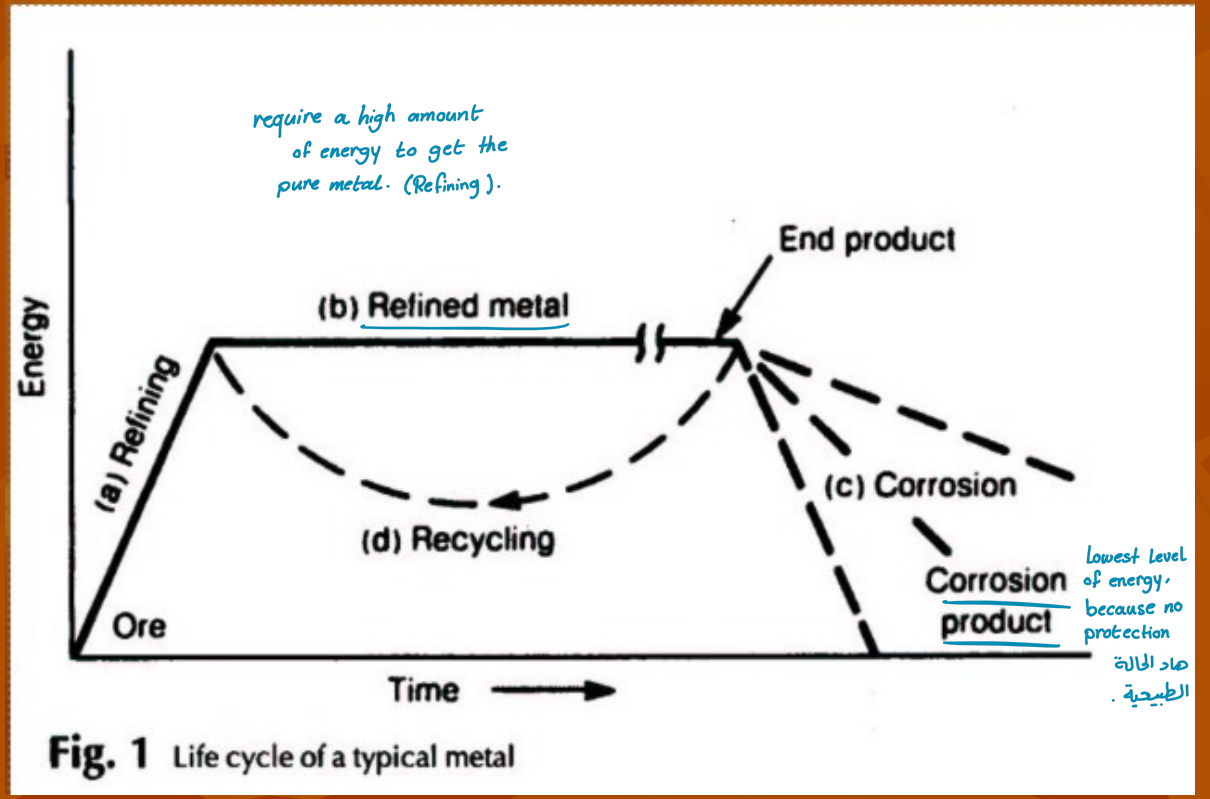


Fig. 1 Life cycle of a typical metal

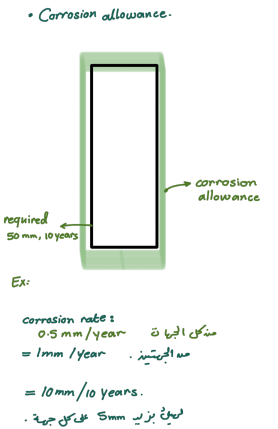
Uniform corrosion or Attack

- Uniform corrosion is the most common type of corrosion
- Greatest economical impact
- Characterized by a "***chemical or electrochemical reaction that takes place uniformly over the entire exposed surface or over a large area***".
- In this case the metal becomes thinner and, eventually fail.

- This type of corrosion is not, however, dangerous, as the life of a part is well predicted under this form of corrosion.

• in case of bad coating.

- A common variety is rust on iron and steel surfaces.



- Prevention of this type of corrosion may achieved by:
- Choosing the right material
- Coating
- Use of inhibitors
- Cathodic protection

→ not the most corrosion resistance material.
→ depends on the right function with the lowest cost.

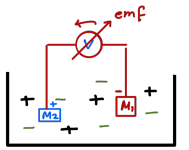
→ difference in the thermal properties from the metal x coating material → Damage

→ مثبطات → used in controlled environment / loops (closed invironment).

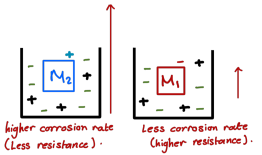
Second type of corrosion.

Galvanic (or two metal) corrosion

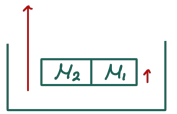
- An electrical potential difference is usually present between two dissimilar metal or alloys when they are placed a corrosive or conductive solution.
- If these metals are brought into contact, this potential difference produces a net electrical current and hence, corrosion.
- Normally corrosion of the less resistant metal is accelerated and attack of the more corrosion-resistant metal is decreased.



$M^+ + Cl^- = MCL$



* both will have a corrosion but in thier own environments.
(with different corrosion rate).



(corrosion rate) اللي مقاومته خفيفة بيضحى اكتر وبزيد الـ
(corrosion rate) واللي مقاومته عالية بتزيد وبيقل الـ

- The less resistant metal becomes ***anodic or active*** and the more corrosion resistant become ***cathodic or noble***.
- Attack of the anodic metal is usually aggravated if the area ratio is great (i.e., if the cathode has a much larger area than the anodic metal).

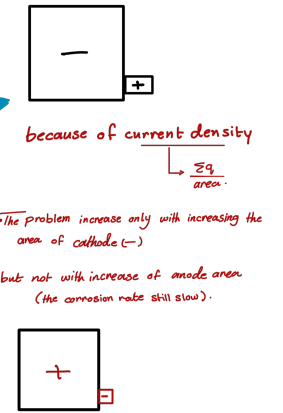


Table 1 Galvanic series in seawater at 25 °C (77 °F)

Anodic end (most easily corroded)

Magnesium
Magnesium alloys
Zinc
Galvanized steel or galvanized wrought iron
Aluminum alloys
5052, 3004, 3003, 1100, 6053, in this order
Cadmium
Aluminum alloys
2117, 2017, 2024, in this order
Low-carbon steel
Wrought iron
Cast iron
Ni-Resist (high-nickel cast iron)
Type 410 stainless steel (active)
50-50 lead-tin solder
Type 304 stainless steel (active)
Type 316 stainless steel (active)
Lead
Tin
Copper alloy 280 (Muntz metal, 60%)
Copper alloy 675 (manganese bronze A)
Copper alloys 464, 465, 466, 467 (naval brass)
Nickel 200 (active)
Inconel alloy 600 (active)
Hastelloy B
Chlorimet 2
Copper alloy 270 (yellow brass, 65%)
Copper alloys 443, 444, 445 (admiralty brass)
Copper alloys 608, 614 (aluminum bronze)
Copper alloy 230 (red brass, 85%)
Copper 110 (ETP copper)
Copper alloys 651, 655 (silicon bronze)
Copper alloy 715 (copper nickel, 30%)
Copper alloy 923, cast (leaded tin bronze G)
Copper alloy 922, cast (leaded tin bronze M)
Nickel 200 (passive)
Inconel alloy 600 (passive)
Monel alloy 400
Type 410 stainless steel (passive)
Type 304 stainless steel (passive)
Type 316 stainless steel (passive)
Incoloy alloy 825
Inconel alloy 625
Hastelloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Platinum

Cathodic end (least easily corroded)

Source: Ref 1

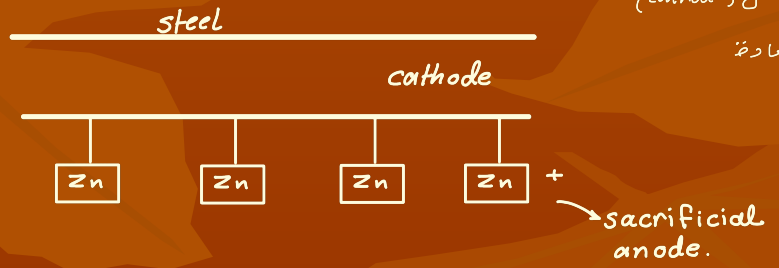
- **Prevention of this type of corrosion may be achieved by:**
- Selection of combinations of metals and alloys that are as close as possible in the galvanic series.

emf ≃ zero.

- Avoid the unfavorable area effect of small anodic parts in contact with large cathodic parts in a possibly corrosive environment.

- Insulate dissimilar metal wherever practical.
- Add inhibitors if possible.
- If welding is necessary then use welding filler metal close or the same as the base metal.

Cathodic protection :



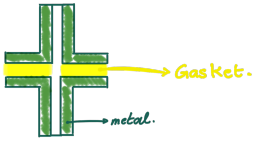
• الفكرة منها انه الي بدي احافظ عليه خليه يكون موجود على شكل (cathod) عن طريق اني اشبك معه مادة تشتغل على انها (anode).

شقة صغير

Crevice corrosion

- Characterized by "***intensive attack*** ***that takes place in crevices and small shielded areas*** ***in metal surfaces exposed to corrosives***".
  - concentrated.
  - with small access for Fluid.
- Normally associated with small volumes of stagnant solutions caused by holes, gasket surfaces, lap joints, surface deposits and crevices under bolts and rivet heads. This is why it is called ***crevice corrosion*** and sometimes ***gasket corrosion***
  - راكد.
  - because there is a fluid but not always a flow → gasket corrosion
    not same as having running fluid.
  - → no flow state → the solution starts drying & the concentration increases
    (From Low concentrated solution → High conce. solution.).
  - High concentrated could be highly acidic
    ⇒ High probability for corrosion.

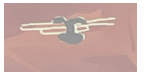
Gasket:
material btw. metal to metal surfaces.

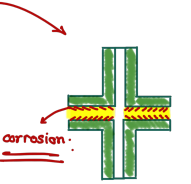


• Lap joint:
will have a small crevice.



• rivet تباسيم.





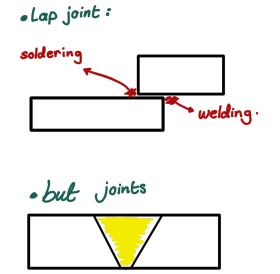

Gasket /
crevice
corrosion

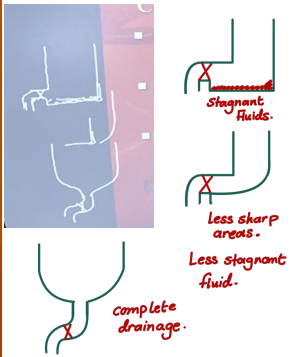
Crevice corrosion may be prevented by:

- Use welded but joints instead of riveted or bolted joints on new equipment.
- Design vessels for complete drainage; avoid sharp areas and stagnant areas.
- Close crevices in existing lap joints by continuous welding or soldering.

to make it Permanent.

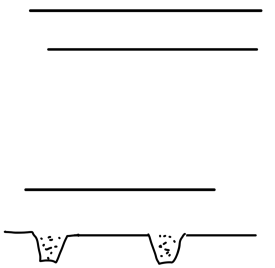
اذا بدي أفكها.
Soldering metal (can't withstand high temp.).
Low melting point.
Ex: Si.





- Inspect equipments and remove deposits frequently.
- Remove solids in suspension early in the process or plant flow if possible.
- Remove wet packing material during long shutdowns. → to avoid high concentration solution phase.
- Provide uniform environment as in the case of backfilling a pipeline trench.

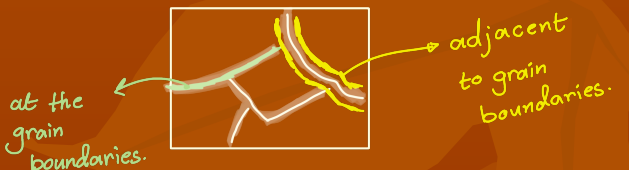
زي لما امرر في تصفية عشان اخفف التركيز .



- Use solid non-absorbent gaskets such as Teflon, wherever possible.

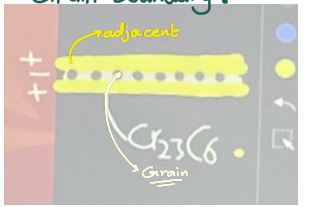
Intergranular corrosion

- Intergranular corrosion is a "***localized attack at or adjacent to grain boundaries with relatively little corrosion of the grains themselves***".



- The consequence is that grains of the metal or alloy fall out and strength is lost.
- The reason for this type of corrosion is the difference in resistance to corrosion between grain-boundary phases (normally carbides) and the grains.

Grain boundary :



the corrosion resistance difference → similar to the galvanic corrosion.

يعني عندك مادتين ، وحدة بتقاوم ووحدة لا ، وتتصلين بعض (cathode) واللي مقاومتها عالية (anode) واللي مقاومتها أقل بتتشبرح

since it's on the grains Level →

(micro-Galvanic cell.).

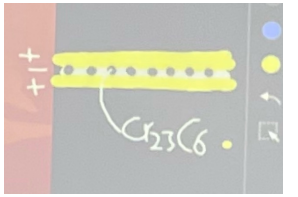
- In the presence of a corrosive media this produces a net potential difference between grains and grain boundaries leading to a localized attack of the less resistant (anodic) areas, and eventually separation of grains.

- Stainless steels are normally subject to this type of attack when exposed to a certain temperature range (normally 650 to 950 ºC) resulting in **sensitization** (***precipitation of chromium carbides at grain boundaries and depletion of chromium in the grains***).

مستنزفة .

sensitization : stainless steel characteristic.

→ most important element in stainless steel is Cr . (راجعي لشرحي بسلايد 326 تبع الرسمات)



$Cr_{23}C_6$: chromium carbides.
↳ cathodic (Graphite.)

1C with 4Cr

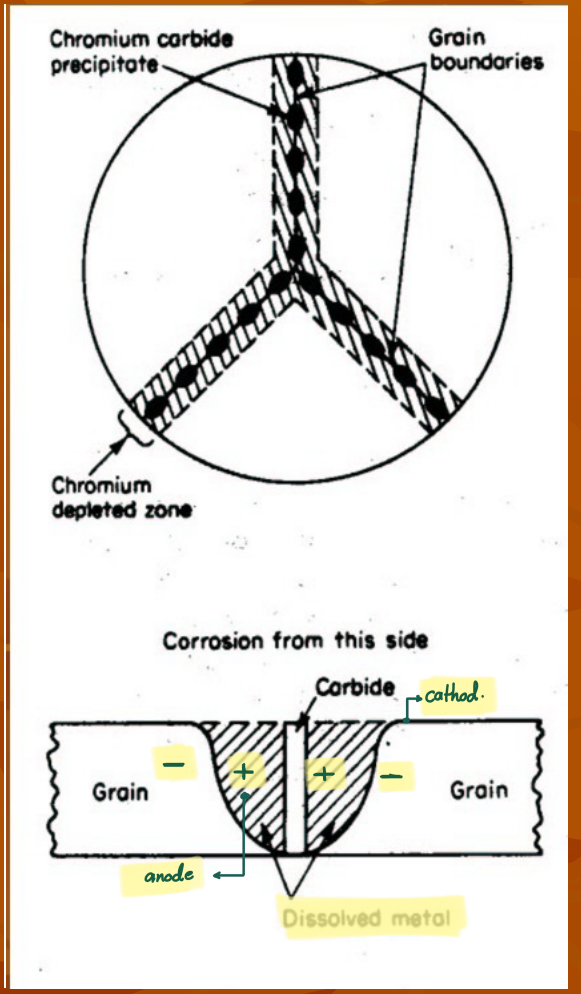
that's why the grains are depleted from Cr.

with (650-950°) temp. range.

the areas that are adjacent to the Grain boundaries → depleted from Cr return to be normal steel with less corrosion resistance.

(micro-Galvanic cell).

37:05
6/5.


Chromium carbide precipitate
Grain boundaries
Chromium depleted zone
Corrosion from this side
Carbide
cathod.
Grain
Grain
anode
Dissolved metal

- As carbides are considered very noble and as corrosion resistance of the grains is reduced as a result of chromium depletion, then this will accelerate the attack of grains at grain boundary sites and may lead to cracking (if a stress is present) or complete failure of the material

Minimizing intergarnular corrosion may be achieved by:

- Using high temperature solution treatment → for small parts.
- Adding strong carbide-forming elements (stabilizers) such as titanium, niobium, and molybdenum. → higher ability to form carbids than the (Cr). → inside the grains.
- Lowering the carbon content to below 0.03%.

316 L → Low carbon content
304 S → Super Low carbon content
→ To reduce the sensitization.

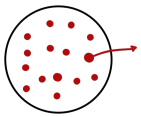
*Super/low carbon → for welding.



→ Highest sensitization. (650-950)

- using solution treatment :
  - increasing the temp. to the complete dissolution for all phases.
  - carbids in the solid solution with uniform concentration for (C) & (Cr) in the matrix.

Stabilizers:



- Stabilize the (Cr) within the Grains.
- not in the Grain boundaries (inside the Grains)
- The carbon content not only in the boundaries.

ماعدل عنصري (C) بتفاعل مع ي لربطه الـ(C) تفاعل مع الـ(stabilizers)

Stress corrosion cracking (SCC)

SCC "***the cracking of a material under combined action of tensile stresses and corrosion***".

→ propagation for the cracks.

→ in most cases → initiation for the cracks.

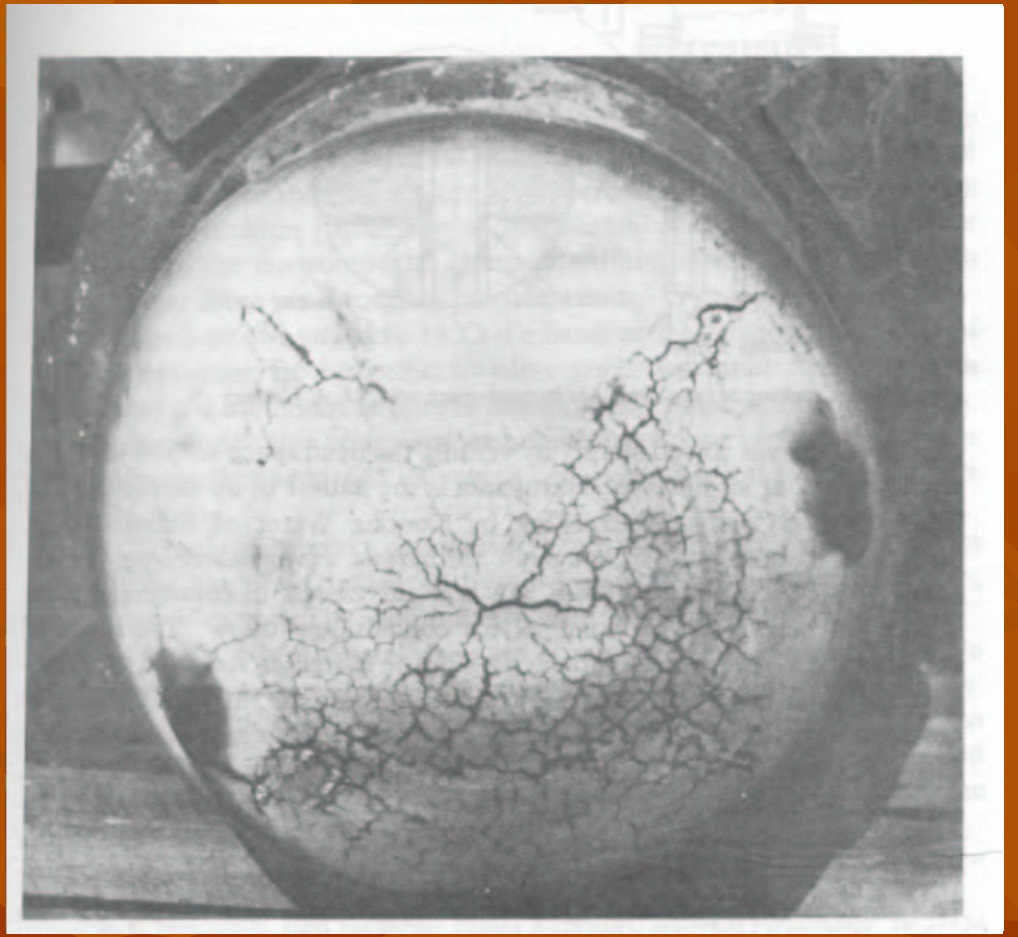
- The tensile stresses may be applied, residual or combination of both.
- The part normally is not attacked on most of its surface, while there are small cracks that are propagating under the mechanism pointed to above.

inside the Grains.

- The cracks may be either intergranular or transgranular depending on the metal-environment (including temperature) combinations.

outside the Grains.

Ex: stainless steel → intergranular.



SCC may be prevented by:

- Lowering the stress level below that of the threshold if possible.
- Eliminating the critical environmental species by, for example, degasification or distillation.

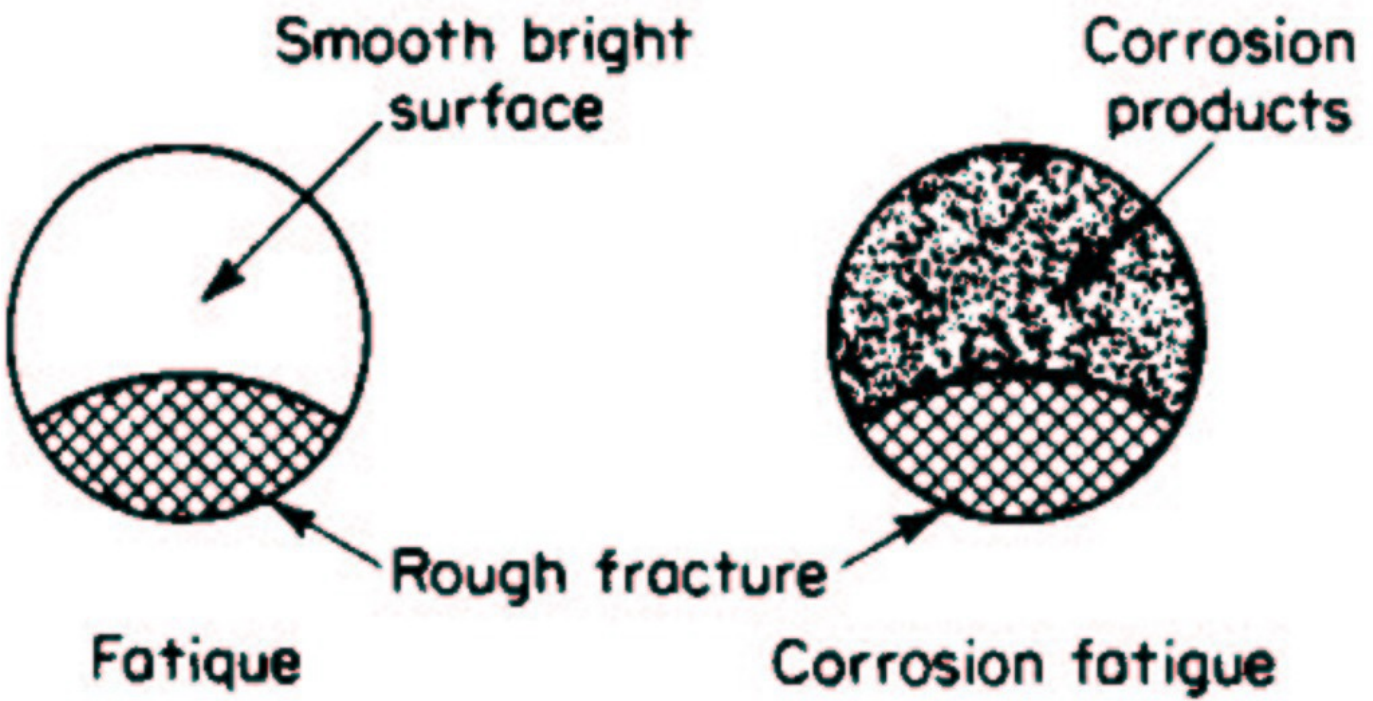
- Changing the alloy to a more resistant one.
- Applying cathodic protection
- Applying coating if possible and practical.
- Introduce compressive residual stresses by means of, for example, shot peening.

residual compressive stresses.

Corrosion fatigue

" The reduction of fatigue resistance due to the presence of a corrosive medium".

because corrosive increases the cracks.


Smooth bright surface
Corrosion products
Rough fracture
Fatique
Corrosion fatigue

Prevention of such attack is a combination of enhancing both fatigue strength and corrosion resistance and measures to be taken are of similar nature to those of SCC.