

Superalloys:-Introduction:-

- Nickel-based superalloys possess good combinations of high-temperature mechanical properties and oxidation resistance up to approximately 550°C .
 - High temperature heat-resistance alloys, which can retain high strengths at elevated temperatures.
 - Alloying increases the strength and temperature capability but reduces the processability.
- [Note: Ni Melting point :- 1455°C
 4946°F]

Properties:-

- Heat resistant and high strength at high temperature ($760-980^{\circ}\text{C}$)
- Good corrosion ~~resist~~ resistance.
- Good oxidation resistance.
- High toughness and ductility
- Excellent cryogenic temperature properties.

Classification:-

- There are three types of Ni-based superalloys
 - Nickel base
 - Nickel-Iron base
 - Cobalt-base

→ The alloys contain high Cr with Ti, Al to form precipitates and addition of Mo, Co, Nb, Zr, B, Fe

Microstructure:-

→ The Major phases present in the nickel-base

Superalloys:

→ γ (gamma) phase - the continuous matrix of FCC austenite.

→ γ' (gamma prime) phase - the major precipitate phase (more cubic shape)

→ Carbides - various types, mainly $M_{23}C_6$ and MC ($M = \text{Metal}$)

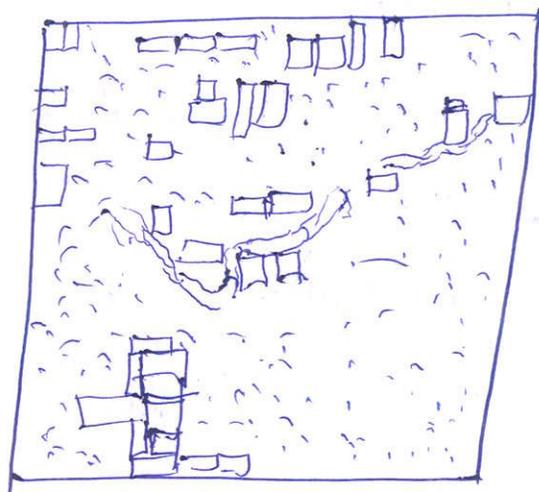
Strengthening Mechanisms:-

three Strengthening Mechanisms are used in Ni-Superalloys

→ Solid solution hardening

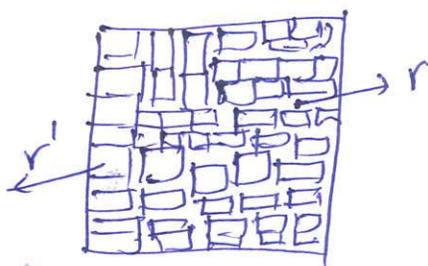
→ Coherent precipitate hardening

→ Carbide phase on grain boundaries



Strengthening Mechanism:-

- solid solution strengthening
 - Cr, Mo, Al, Nb, Ti and others.
- precipitation strengthening.
 - Mostly due to Al and Ti
 - Ni₃(Al, Ti), gamma prime.
- Carbide phases
 - M₂₃C₆, M₆C or MC

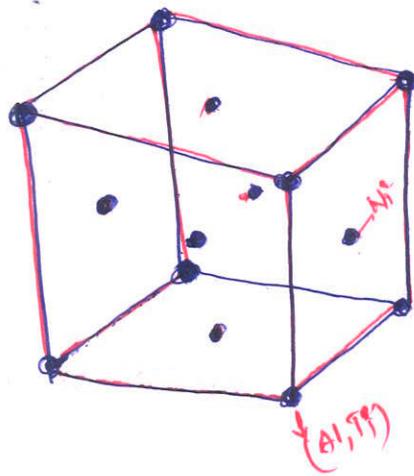


Microstructure:-

- A two phase equilibrium microstructure is generated, consisting of gamma Γ and gamma prime (γ')
- Both phases are face-centered-cubic, have almost identical lattice dimensions and also similar orientation. Consequently the two phases are almost coherent.
- the lattice sites in the γ -phase are totally equivalent and the atoms constituting the solid solution being distributed randomly.

Microstructure :-

- In the γ' -phase ($\text{Ni}_3(\text{Al,Ti})$) the nickel atoms are at the face-centers and the aluminium or titanium atoms at the cube corners.
- The close match in Matrix/precipitate lattice parameter combined with the chemical compatibility allows the γ' to precipitate homogeneously throughout the matrix and has a long-time stability.



Carbides.

- The added content of Carbon is approximately 0.02-0.2%.
- In combination with reactive and refractory elements such as titanium, tantalum, and hafnium it forms carbides (TiC , or HfC).
- During heat treatment these carbides begin to decompose and form lower carbides such as M_{23}C_6 and M_6C which tend to generate on the grain boundaries.

→ the mainly M elements in $M_{23}C_6$ $M_{23}C_6$ are 30 3
 Chromium, Iron, tungsten and molybdenum.

EFFECT OF ALLOYING ELEMENTS

Element	Matrix Strengthening	Increase in r' Volume fraction	Grain boundary phase	Other effects
Cr	Moderate	Moderate	$M_{23}C_6$ and M_7C_3	Improve corrosion resistance
Mo	High	Moderate	M_6C and MC	Increase density
W	High	Moderate		
Ta	High	Large		
Ti	Moderate	Very Large	TiC	Reduces oxidation resistance
Nb	High	Large	NbC	promotes r' and δ phase
Al	Moderate	Very Large		Improve oxidation resistance
Co	slight	Moderate in some alloys		Raises solidus
C	Moderate		Carbide	

Chemical Composition

- Most nickel-based alloys contain 10-20% Cr, up to 8% Al and Ti, 5-10% Co, and small amounts of B, Zr, and C.
- Chromium and aluminium are necessary for oxidation resistance.
- The elements such as C, Cr, Mo, W, C, Nb, Ta, Ti, and Hf form carbides.

Ni-Iron Superalloys :-

- Fe is added to replace some of Ni as it has lower cost.
- Ni-Fe Superalloys contain 25-45% Ni and 15-60% Fe.
- Microstructure consists of austenitic FCC matrix and can be strengthened by solid solution strengthening (Mo, Cr) and precipitation hardening (Ti, Nb, Al) by forming intermetallic phase.

Superalloys Applications :-

- Aerospace Gas Turbine Engines
- Space Vehicles - Rocket Engines
- Nuclear reactors
- power Generation turbines
- Submarines
- petrochemical equipment
- High-Temperature fasteners
- ~~Gas~~ Combustion Engine Exhaust Valves
- Hot working Tooling and dies

What is heat Treatment

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- Heat treatment is a heating and then cooling process using predefined methods to achieve desired Mechanical properties like hardness, ductility, toughness, strength, etc.
- It is the combination of thermal, industrial and metal working process to alter the mechanical properties and chemical properties of metals.
- In simple words, heat treatment is a process of heating the metal, holding it there for some time and then cooling it back.
- During the whole process, the mechanical properties get changed due to changes in microstructure.
- All Metallic Metals have grains which are nothing but microstructures of crystals.
- The nature of those grains determines the behavior of the mechanical properties of a metal.
- Heat treatment changes that mechanical structure by controlling the rate of diffusion and rate of cooling within that microstructure.

Heat Treatment process steps:-

The properties of heat-treated materials vastly depend on the processes that it has to undergo. Below are those key processes of heat treatment

- Heating.
- Holding
- Cooling.

Heat Treatment of Steel:

The properties of heat-treated materials vastly depend on the processes that it has to undergo. Below are all those key processes to heat treatment.

Heating:-

- The first step in the heat treatment process is heating the metal.
- The temperature depends on the type of metal and the technique used. Sometimes you need to heat that outer surface of the metal, and sometimes you need to heat the whole body.
- That depends on what kind of alteration you want in the mechanical structure.

Below are all different furnaces that are used for heating metal in heat treatment process.

- * Box type furnace
- * Batch furnace
- * Elevator type furnace
- * Bell-type furnace
- * Pit type furnace
- * Salt bath furnace
- * Fluidized bed furnace

Holding :-

- During the holding process the material is kept at the achieved temperature for some period of time. The time required depends on the type of metals and the types of mechanical properties expected.
- the holding time also depends on the part size. If the part is large it is kept in a holding state for more time than the same type of Metals having a small part size.

Cooling :-

- After the holding process, cooling starts, the cooling must be done in a prescribed manner. During cooling, there are some structural changes occur.
- Different media such as water, oil, or forced air is used to aid in cooling. You can also use furnaces for cooling purposes as the control environments help inefficient cooling.
- ~~After the holding process, cooling starts,~~
the cooling must be done in a prescribed manner.

→ During cooling, there are some structural changes occur.

→ Different media such as water, oil, or forced air is used to

Heat Treatment Techniques

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→ following are few common heat treatment technique used in industries.

- * Annealing
- * Normalizing
- * Hardening
- * Tempering
- * Carburization
- * Quenching

Annealing :-

- Annealing is a heat treatment process that is used to soften the metal.
- In other words, annealing helps to improve ductility, machinability, and toughness.
- Annealing does this by changing the microstructure of metals.
- Annealing is done by heating the metals at the above critical temperature, hold them there for some time and then cool it at a very slow rate in the furnace.
- Annealing is also done to enhance the electric conductivity of the metal.

Types of Annealing

→ process Annealing

→ full Annealing

process Annealing:-

→ process annealing is done when metal is heated below the critical temperature, keep it for a suitable time, and then cool it slowly.

→ This process is suitable for low carbon steel, like sheet metal and wires.

→ No phase transformation occurs during process annealing, and it's considerably cheaper than full annealing.

Full Annealing:-

→ full annealing is done when metal is heated above the critical temperature. This process is suitable for low and high carbon steel.

→ phase transformation occurs during the full annealing process and it is a costly operation than process annealing.

Why Annealing is Done:

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- * To relieve internal stress.
- * To reduce the hardness of a metal, to increase ductility, maintainability and toughness of metal.
- * Refine the grain structure of metals

Normalizing :-

- Normalizing is also similar to annealing, but the metal is air-cooled. Instead, if other mediums used is the furnace.
- The metal is heated above the critical temperature kept in there for some time, and allowed to cool down under open air. Normalizing is usually done for low carbon to high carbon steel.
- Please note that normalizing does not make metals that much softer as is the case with annealing, but it allows to convert uniform grain structure, and internal stress are also relieved. Normalizing is usually done on carbon steel.

Why Normalizing is Done :-

- To get a uniform grain structure in carbon steel.

- To relieve internal stress
- To improve the machinability and strength of Carbon Steel

Tempering :-

- Tempering is done on Metals that are already hardened. we all know that sometimes our application needs metal to be hardened, as well as tough.
- Tempering helps to achieve the required toughness by ~~star~~ sacrificing the hardness.
- Tempering a very common process for Machine tools, Knives, etc.
- Tempering is usually done by heating the metal at a relatively low temperature.
- The temperature depends on the required Mechanical properties of Metals. if you want high ductility, then you need to heat it at a high temperature. But if you need low ductility, then the low temperature is sufficient.

Why Tempering is Done :-

- To improve ductility
- To reduce hardness
- To relieve internal stress
- To reduce brittleness

Hardening:-

As the name suggests, hardening is used to increase the hardness of a metal. This is usually done by heating the metal above normalization temperature, keeping it at normalization temperature, and then rapidly quenching (cooling) in water, oil, or brine solution.

→ The heat required depends on the size and the required mechanical properties of the metal. Often after hardening, tempering is done to increase the ductility and toughness of metals.

Why Hardening is Done:-

- To increase the hardness of metals.
- To improve the magnetizing properties.
- To reduce ductility and toughness.
- To reduce grain size.

Types of Hardening:-

- Case Hardening / Surface Hardening
- Differential Hardening
- Flame Hardening.

Case Hardening / Surface Hardening:-

- Case Hardening or surface hardening is a hardening heat-treatment process.
- In the case of hardening, the complete metal piece is heated.

But in the case of Case hardening, only the outer surface is heat-treated to make it hardened.

→ the inner metal is still soft and ductile. Case hardening is widely used for the tool and die industry where the tool surface needs to be hardened but the inner metal piece has to remain ductile.

Types of Case Hardening.

→ Nitriding

→ Cyaniding

Nitriding:-

→ Nitriding is a case hardening process in which nitrogen gas is used to harden the outer surface of the metal. The metal is heated in an ammonia (NH_3) atmosphere, and then it is cooled.

→ During the whole process, ammonia decomposes into nascent hydrogen and nascent nitrogen.

→ This nascent nitrogen diffuses on the outer layer of metal to form nitride which increases the surface hardness.

Cyaniding:-

Cyaniding is a case hardening process in which the metal piece is immersed in a bath of molten sodium or potassium cyanide.

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After that, the metal piece is cooled into lime water so that cyanide salt is sticking to the outer surface of the metal.

→ this cyanide salt is responsible for hardening the outer surface of the metal.

Differential Hardening:-

→ Differential hardening is kind of a hardening process in which different area of the metal piece gets a different heat-treatment process. This is a very popular hardening process for high-end cutting tool.

Carburization:-

→ In carburization, the hardness of the metal piece is increased by increasing the carbon content.

→ The metal piece is heated below the melting point with high carbon materials such as charcoal.

→ The heated metal piece then absorbs carbon to make it more hard and brittle.

Quenching:-

- Quenching is a process of cooling a metal piece quickly after it was heated.
- Quenching helps metals to become harder or softer depending upon whether it is a ferrous or non-ferrous alloy.
- In the case of ferrous alloy, quenching helps to make it harder, but it becomes softer in the case of non-ferrous.
- For quenching, the metal needs to be heated above the upper critical temperature and then cool rapidly under forced air, water, oil, nitrogen depending upon the type of alloy and the desired mechanical properties.
- Some-times when you do quenching too quickly, metal forms crack due to excessive internal stress.

Advantages of Heat Treatment:-

- Heat Treatment assist in improving the ductility of metal in the annealing process.
- Heat treatment helps in hardening metals and hardening helps in hardening only the outer surface of the metal piece keeping the rest of the portion soft and ductile.
- Machinability of metals gets improved.

- Resistance to Corrosion Capability gets enhanced.
- Electrical and magnetic properties get improved
- Internal stress are relieved
- The grain structure of Metal get refined.

Need For High Temperature Alloys:

- Conversion of thermal energy into mechanical (or) other forms of energy is more efficient at elevated temperatures.
- The gas turbine engine employing this principle in jet engine aircraft laid the foundation for the development of high temperature alloys superalloys.

Basic Criteria for High Temperature Materials.

- High Melting point
- Structural stability over very long periods.
- Retention of Mechanical properties at service temperature.
- Resistance to oxidation and corrosion.
- Ability to be fabricated into desired shapes.

Superalloys:-

Superalloys as a class constitute the currently reigning aristocrats of the metallurgical world.

They are the alloys which have made jet flight possible, and they show what can be achieved by drawing together and exploiting all the resources of Modern physical and process metallurgy in the pursuit of very challenging objectives.

Broad classification of Superalloys:-

1). Based on chemical composition

(a) Iron base Superalloy

(b) Cobalt base

(c) Nickel base

2). Based on processing Method.

(a) Wrought alloys

(b) Cast alloys

Nickel based Superalloys:-

→ Nickel-base Superalloys are defined as those alloys that have nickel as the Major constituent with significant amount of Chromium.

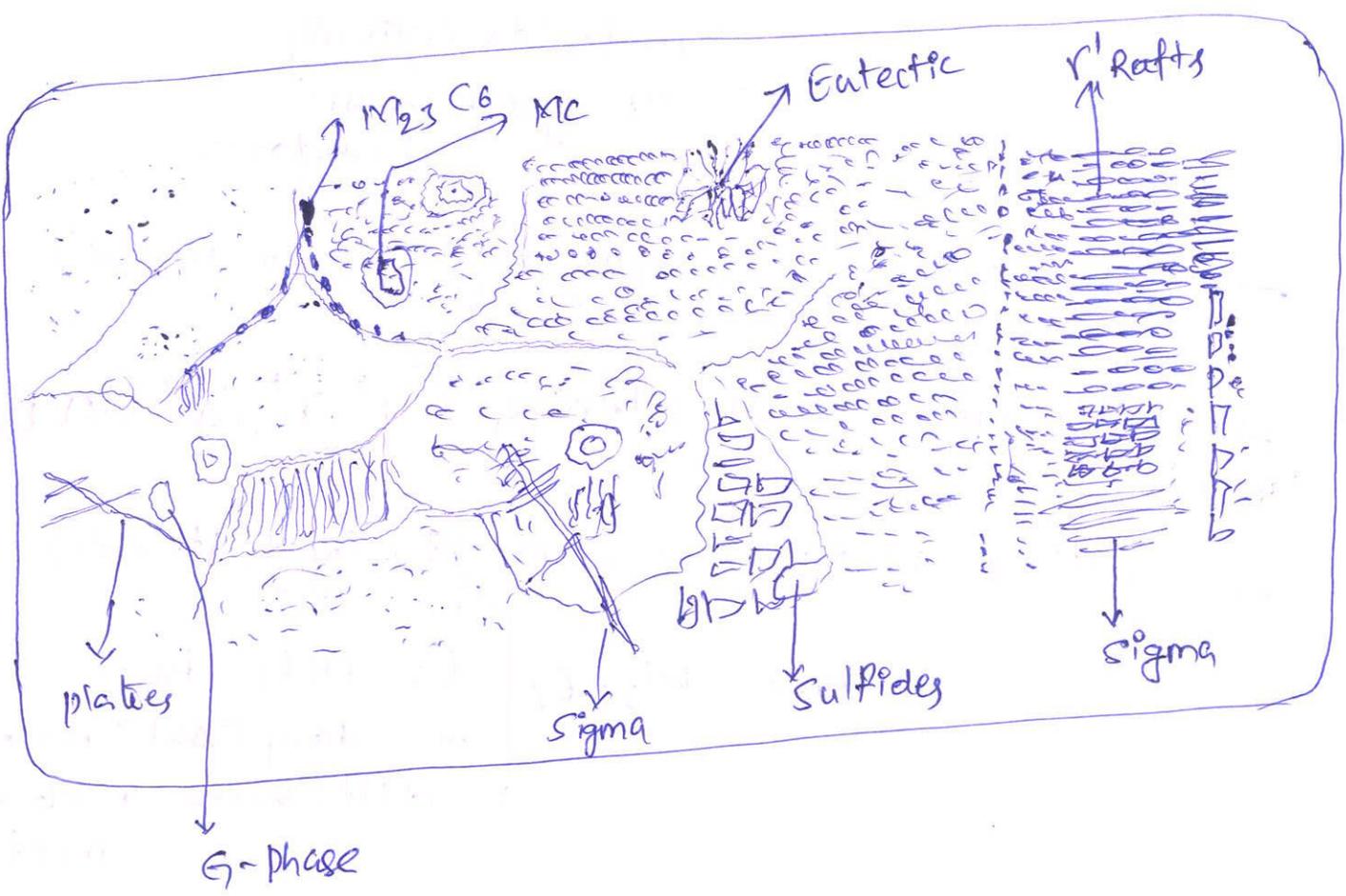
→ They also contain Cobalt, Iron, molybdenum, tungsten, and tantalum, as major alloying additions.

→ They are strengthened by solid-solution and second-phase intermetallic precipitation. The intermetallic forming elements are Al, Al₂O₃, Aluminides, titanium and niobium.

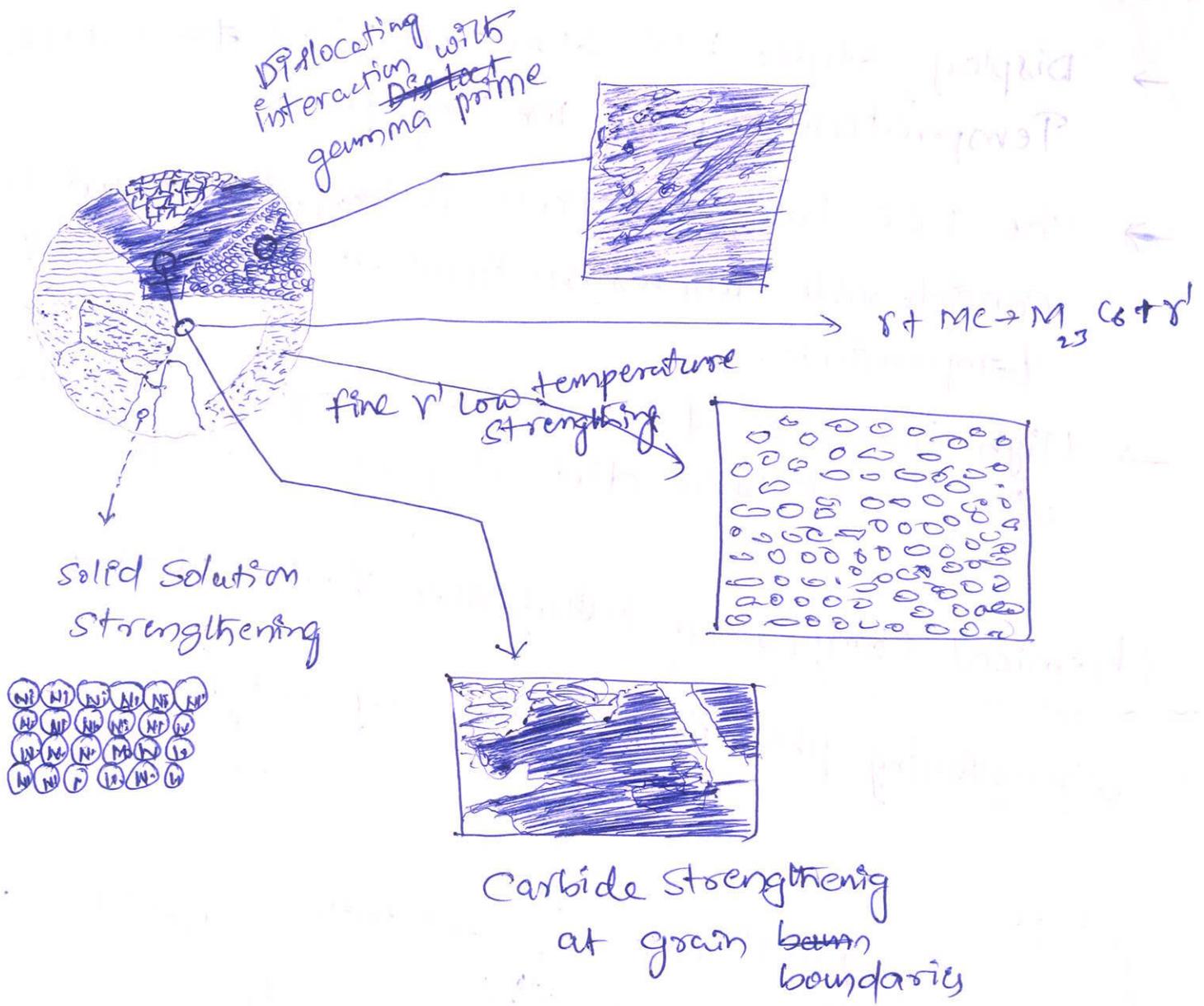
38 Ni-base Superalloys - versatile high Temperature alloys

- Display stable FCC structure right from room Temperature up to melting point
- The FCC base structure is ~~strong~~ ductile and has considerable microstructural stability at elevated temperature.
- High tolerance of Ni to other alloying additions without disturbing phase stability.

Chemical Composition Establishes Various phases:-
 Strengthening phase in Ni-base Superalloys.



Strengthening Mechanisms in Nickel base Superalloys



- Solid solution strengthening (Ti, Cr, Mo, W)
- precipitation hardening (r' , r'' , carbides, borides)
- oxide dispersion strengthening (yttria)

Note $M_{23}C_6$ [Cr-rich fine secondary carbides fully distributed inside the matrix]

Annealing :-

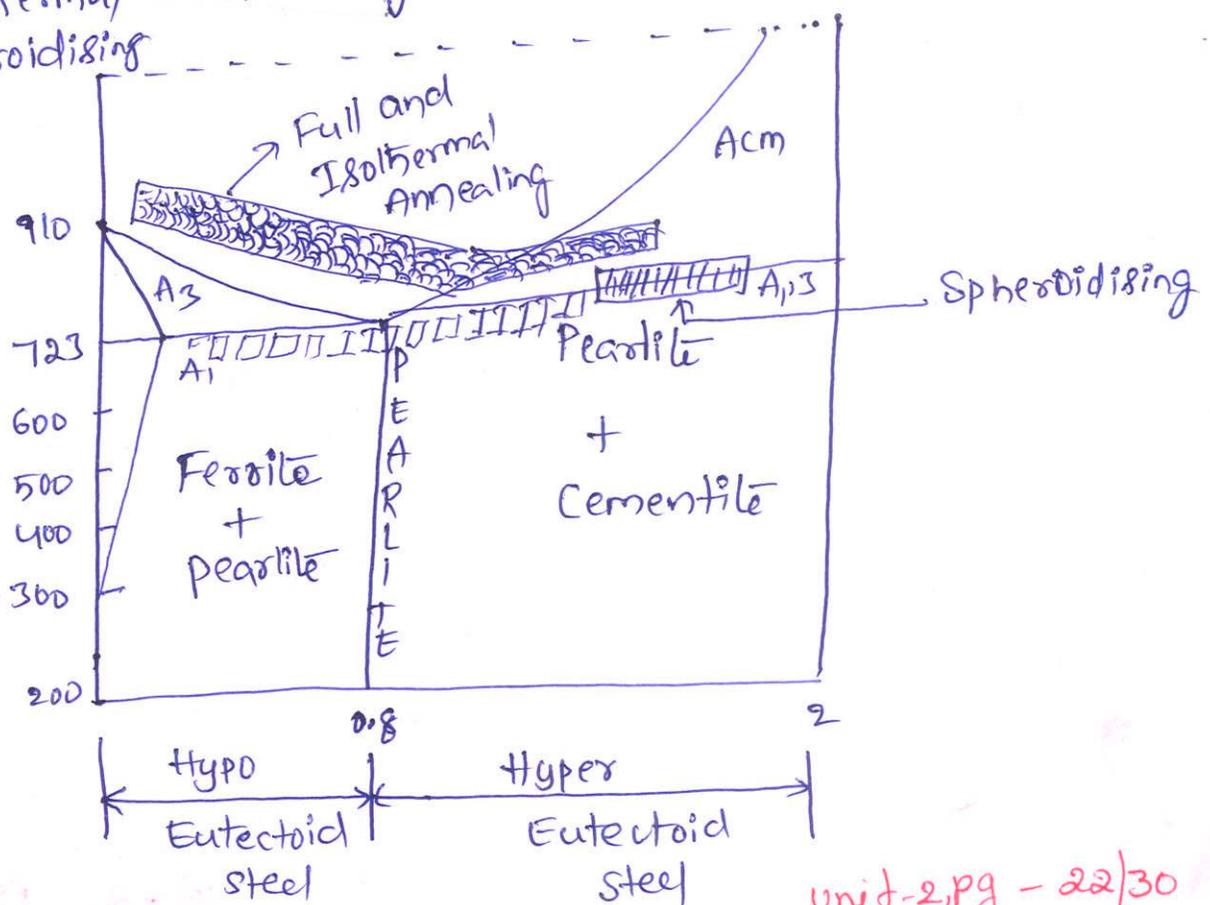
Annealing may be defined as the softening process in which steel are heated to above the transformation range and holding the steel at this temperature for certain time then allow the steel to cool slowly in the furnace

Purposes :-

1. To soften the steel.
2. To improve machinability
3. To refine grain size
4. To remove internal stress
5. To increase ductility and toughness
6. To improve mechanical properties

Classification of Annealing :-

1. full annealing
2. process annealing
3. Isothermal annealing
4. spheroidising

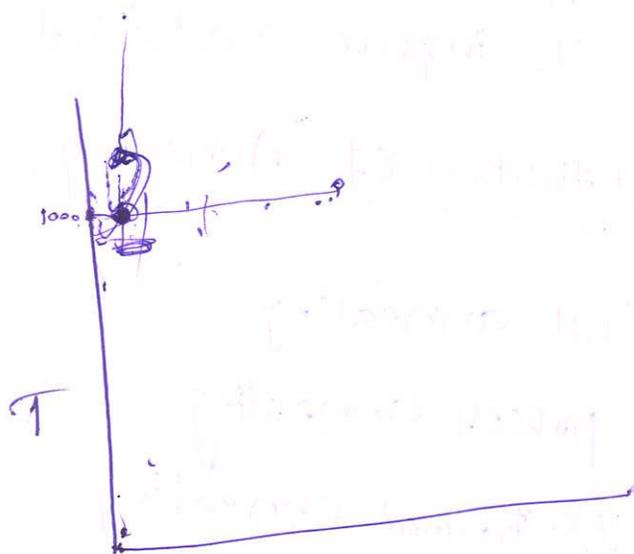


process:-

Full annealing consist of:-

- 1) Heating the hypo eutectoid steel to a temperature of 30 to 50 c above upper critical point 910 c (A_3) and 30 to 50 c above lower critical point 723 c ($A_{1,3}$) in the case of hyper eutectoid steel
- 2) Holding at this temperature for sufficient time so as attain internal structural changes (i.e., to obtain complete austenite structure)
- 3) Slow cooling in the furnace

Normalising

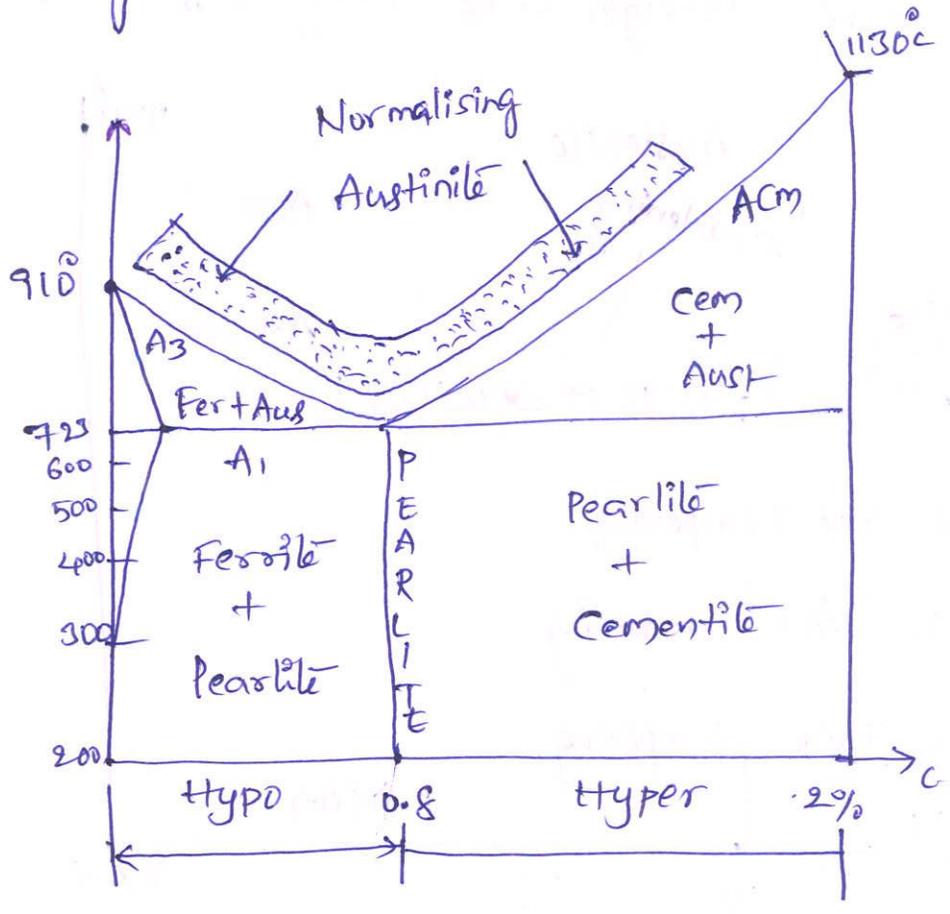


Normalising

Normalising temperature generally varies from 810 to 930°C
Temperature ~~is~~ ~~the~~ ~~same~~ ~~as~~ ~~the~~ ~~range~~ ~~of~~ ~~normalising~~ ~~are~~.

Process:-

- 1) Heating the hypo eutectoid steel to a temperature of 30 to 50°C above Upper Critical Temperature (A_3) and 30 to 50°C above upper critical temperature (A_{cm}) in case of hyper-eutectoid steel.
- 2) Holding at this temperature for a shorter period
- 3) Cooling in still air



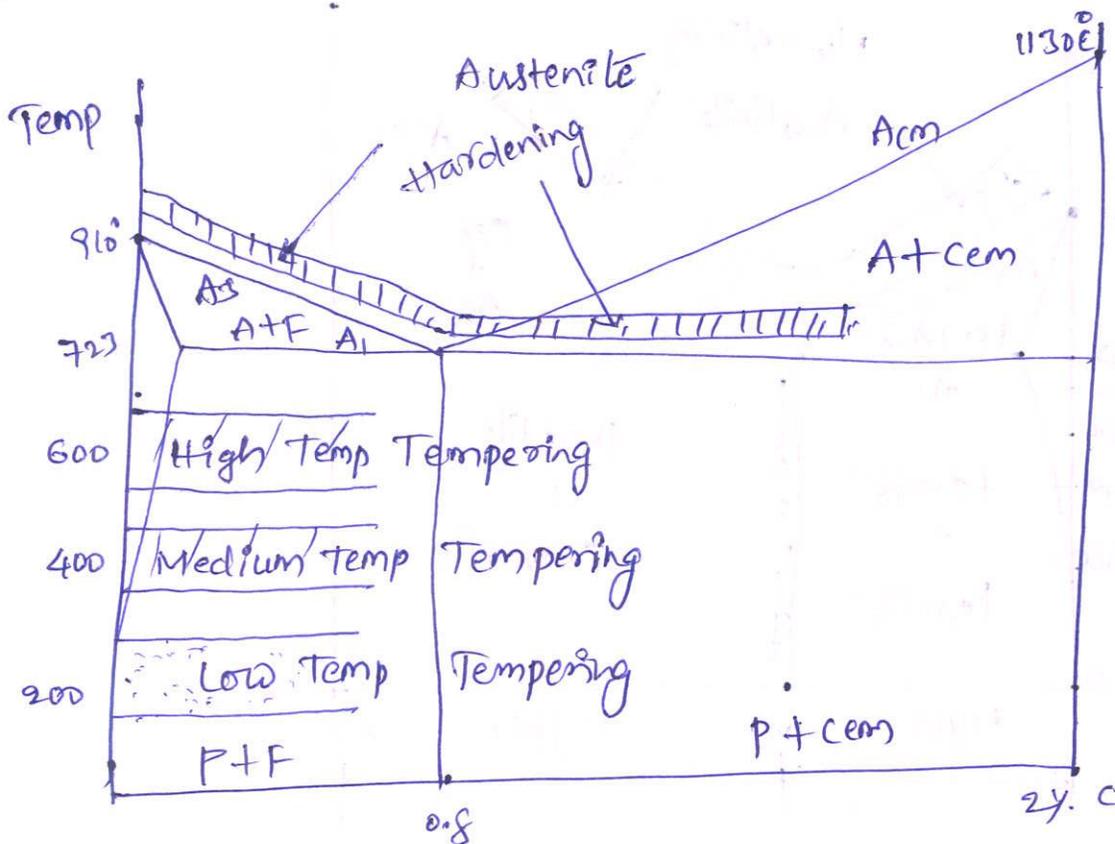
- The micro structures produced by normalising is similar to that of annealing. Normalising produces microstructures consisting of ferrite and pearlite for hypo eutectoid steel. For eutectoid steel, the microstructure is only pearlite and is pearlite and cementite for hyper eutectoid steel
- cooling rate is the major difference b/w normalising and annealing. cooling rate is faster in normalising result in fine grain structure.

Hardening

Hardening is the process of heating steel to austenite phase following by rapid cooling in a liquid bath and martensite structure is obtained after cooling

Process :-

- 1) To increase the hardness of steel so that it can resist wear
- 2) ability to cut other materials ^{i.e.} to make it suitable for cutting tools
- 3) to improve strength and toughness



Process :-

- 1) Heating the hypereutectoid steel to a temperature of 30-50°C above upper critical point (A_3) and 30-50°C above lower critical point (A_{1s}) in case of hypereutectoid steel
- 2) Holding at this temperature for sufficient time to complete phase transformation
- 3) Sudden cooling in a (water or oil) suitable medium

Tempering:-

→ Hardened Steel is brittle and highly internally stressed and unsuitable for most applications. These unfavourable characteristics are eliminated by a heat treatment called Tempering

Process:-

- 1) To reduce the thermal stresses ^{Caused by rapid cooling of steel}
- 2) To reduce the brittleness of the hardened steel and thus to increase its ductility.
- 3) To stabilize the structure of metal.
- 4) To increase toughness and ductility.

Process

→ Tempering consists of heating the steel to a temperature of ~~150°~~ ^{150°} - 650° C (i.e, below lower critical temperature) and followed by cooling

→ Tempering an essential operation after hardening to modify the properties of the hardened steel for the purpose of increasing its usefulness.

As the hardness and brittleness may be reduced to the desired point, there is decrease in the tensile strength and an increase in the ductility

Classification of Tempering

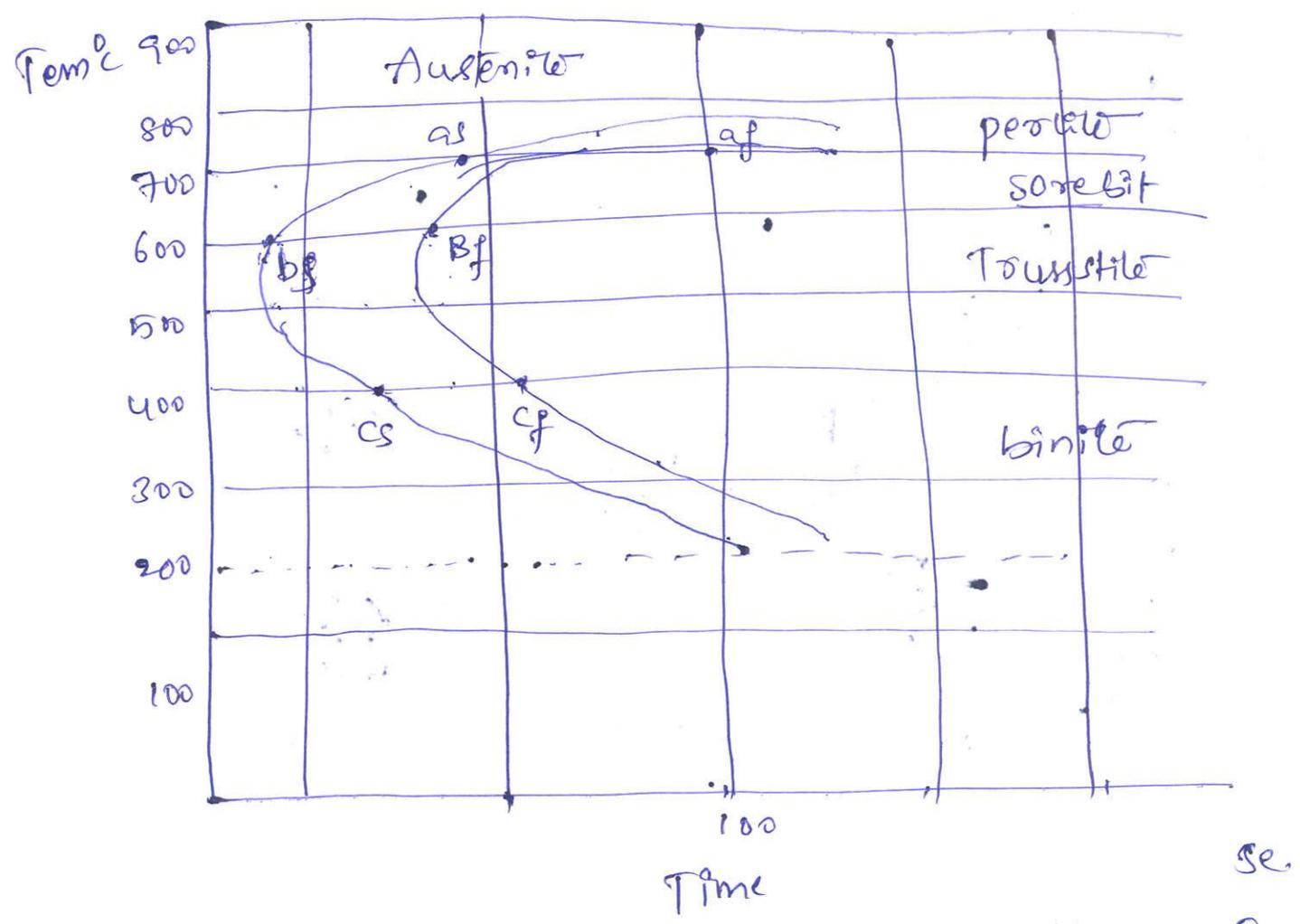
- 1) Low temperature tempering (150 - 250°C)
- 2) Medium Temp Tempering (350 - 450°C)
- 3) High Temp Tempering (500 - 650°C)

A rapid cooling from the hardening temperature causes the austenite to be transformed into another constituent called ~~Martensite~~ to be transformed into Martensite which is very hard and brittle.

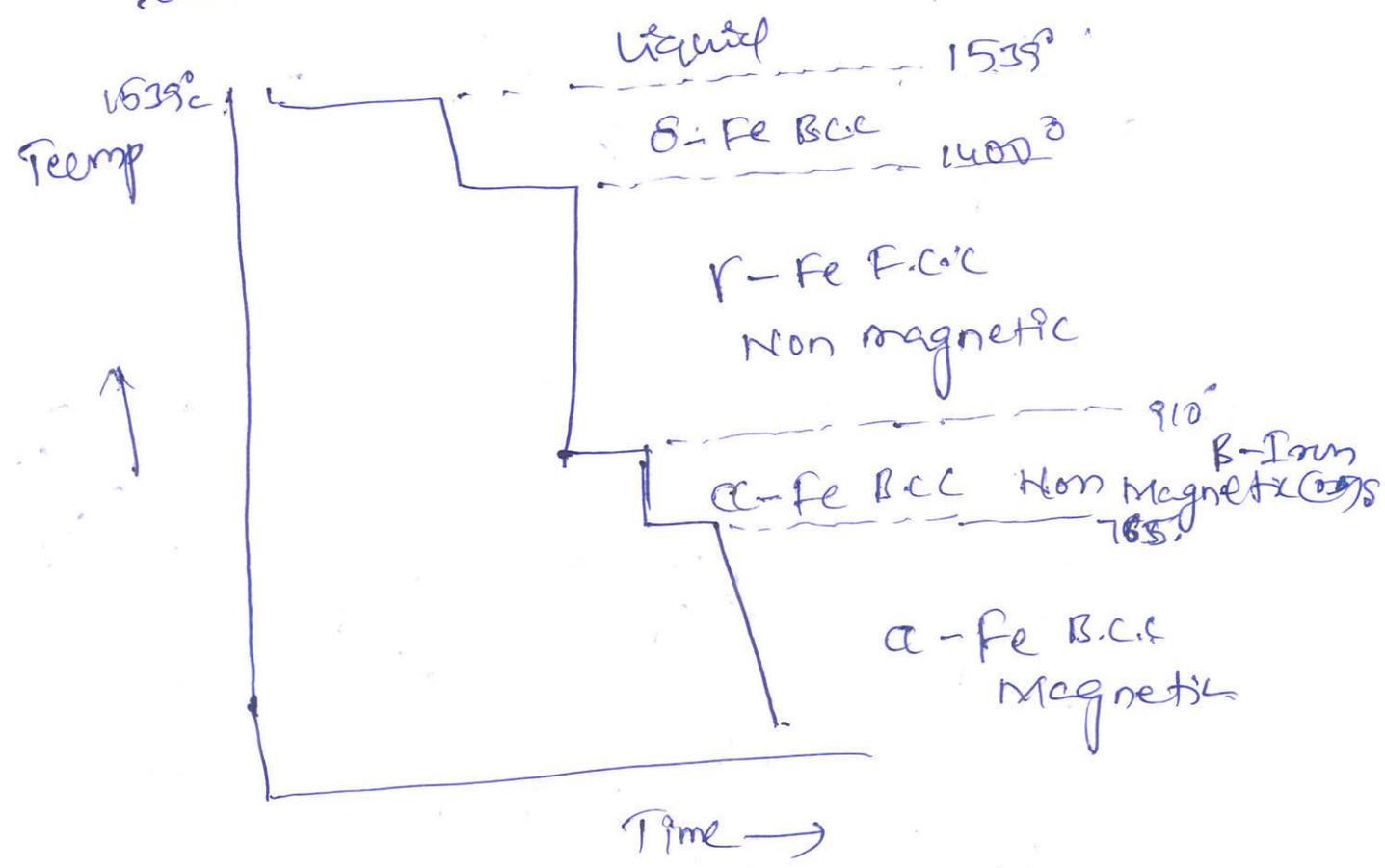
The hardening of steel depends entirely upon the formation of Martensite. Martensite is super saturated solid solution of carbon in $[Fe-Fe_3C]$

Cooling medium (Quenching media)	Cooling Rate	Micro structure
water	very fast	Martensite
oil	fast	very fine pearlite
Air	medium	Fine pearlite
Furnace oil	very slow	Coarse pearlite

→
Time Temperature Transformation Diagram

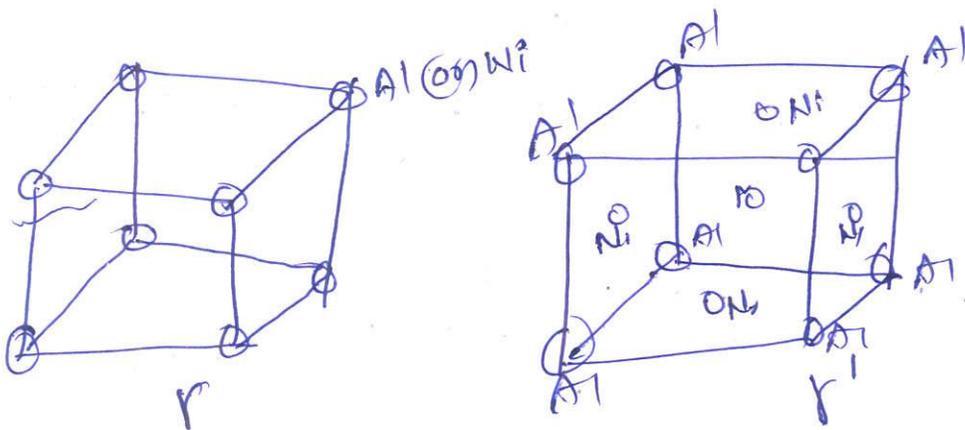
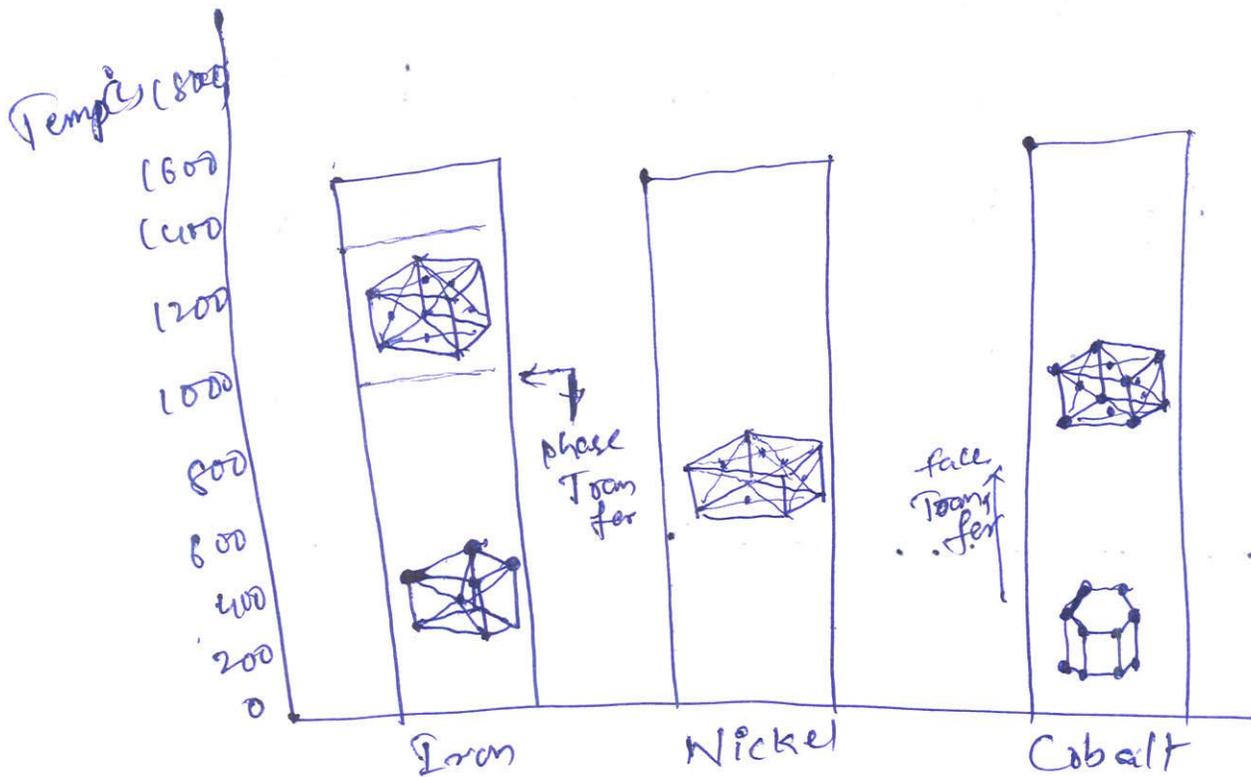


Allotropic Forms & Cooling Curve of pure Iron

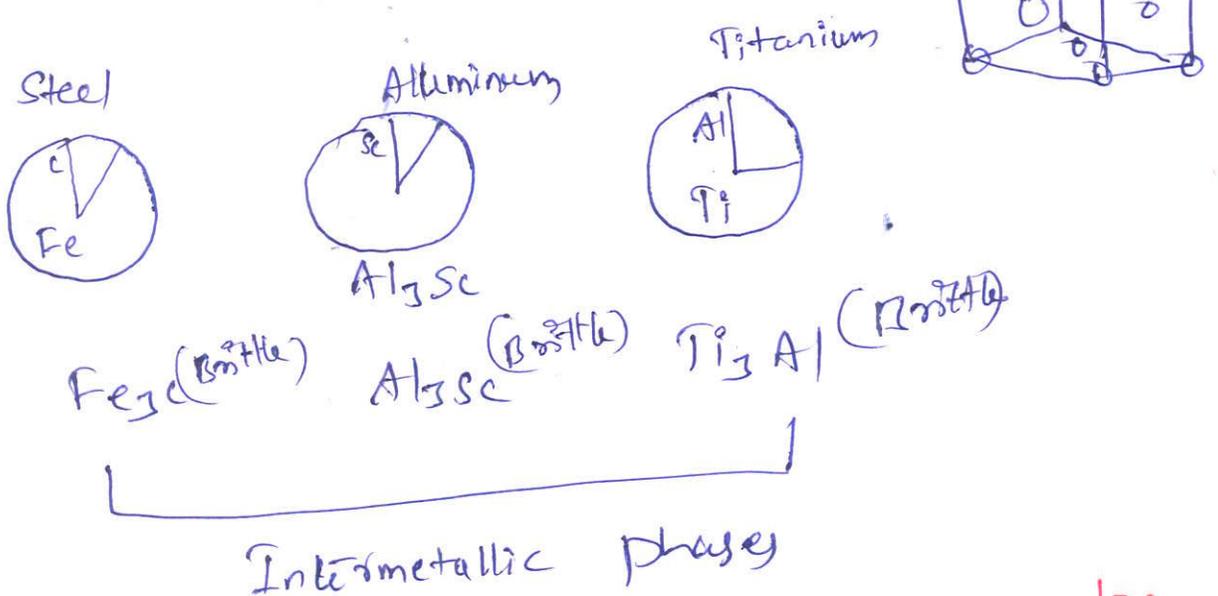


Alloy Design

Fe Ni Cobalt



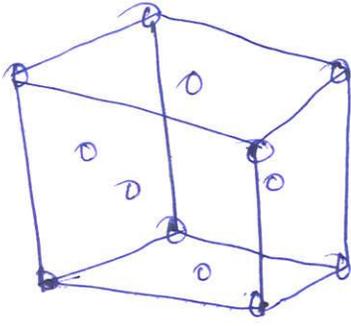
The Intermetallic Material



Gamma

Gamma prime

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Al (or) Ni

