HEAT TREATMENT

Heat Treatment

- **process of *controlled heating and cooling of metals***
- ***Alter their physical and mechanical properties***
- ***without changing the product shape***
- **sometimes takes place inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming.**

Heat Treatment

DEFINATION:

A combination of heating & cooling operation timed & applied to a metal or alloy in the solid state in a way that will produce desired properties.- Metal Hand Book (ASM)

Heat Treatment

- **Often associated with *increasing the strength of material***

- **Can also be used to *obtain certain manufacturing* objectives like**
  - **To improve machining & formability,**
  - **To restore ductility**
  - **To recover grain size etc.**
  - **Known as Process Heat Treatment**

Heat Treatment

- **Heat treatment done for one of the following objective:**
  - **Hardening.**
  - **Softening.**
  - **Property modification.**

Heat Treatment

- **Hardening heat treatments particularly suitable for Steels**
  - **Many phase transformation involved even in plain carbon steel and low-alloy steel.**
- **Other type of heat treatments equally applicable to ferrous & non-ferrous**

Hardening Heat Treatment

- **Hardening of steels is done *to increase the strength and wear properties.***
- **Hardening (Quenching followed by Tempering) is intended for improving the mechanical properties of steel.**
- **Generally increases hardness at the cost of toughness**

Hardening Heat Treatment

- **Pre-requisites for hardening is *sufficient carbon and/or alloy content*.**
  - **Sufficient Carbon - Direct hardening/Case hardening.**
  - **Otherwise- Case hardening**

Hardening Heat Treatment

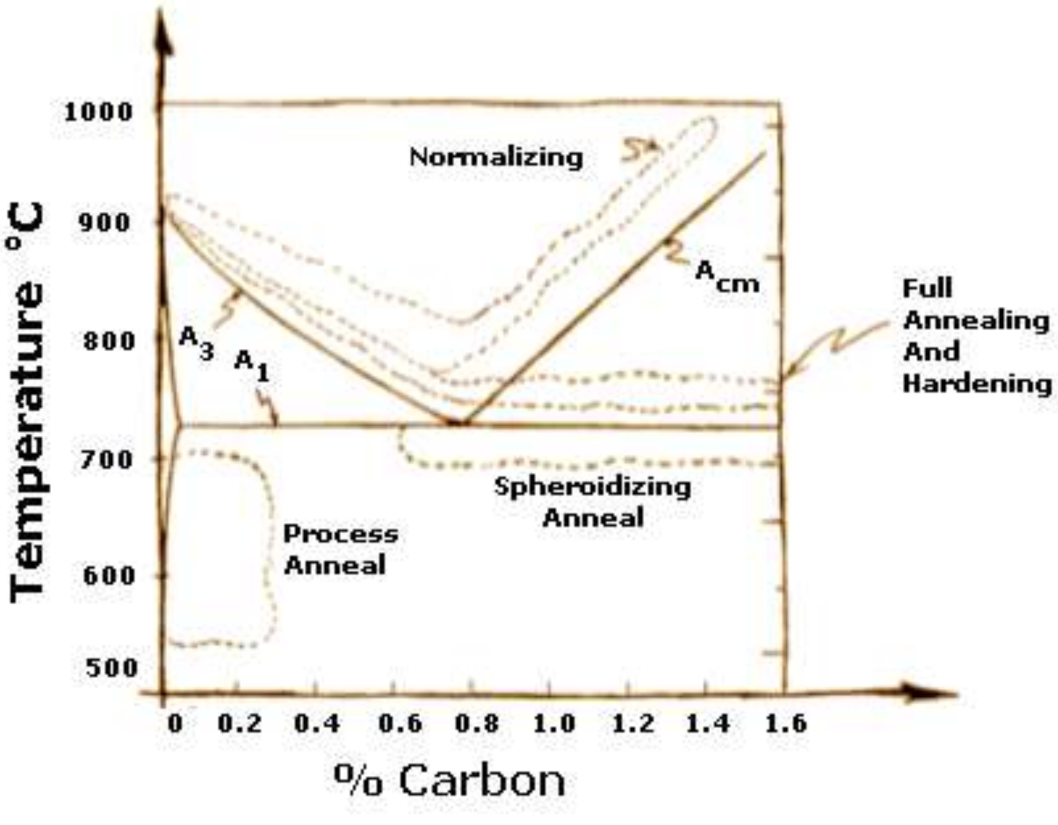
Common Hardening Heat Treatments:

- Direct Hardening
  - Heating → Quenching → Tempering
- Austempering
- Martempering
- Case Hardening
  - Case carburizing

Hardening Heat Treatment

- Case Hardening (Contd..)
  - Case Nitriding
  - Case Carbo-nitriding or Cyaniding
  - Flame hardening
  - Induction hardening etc
- Precipitation Hardening

Heat Treatment Temperatures



HEAT TREATMENT PROCESS

Hardening Heat Treatment

An act of

- Heating to austenizing range, 30 – 50^0C above Ac_3 (Hypoeutectoid) or Ac_1 (Hypereutectoid)
- Holding sufficiently long time for full transformation (1hr/per inch of maxm. Thickness)
- Dipping in Quench Medium

Hardening Heat Treatment

Result

- Avoidance of normal Ferritic-Pearlitic transformation
- Formation of a hard & brittle structure known as Martensite.

Mechanism of Quenching

- **Austenite to Ferrite transformation takes place by a time dependant process of Nucleation & Growth**
- **Under slow or moderate cooling rates, the carbon atoms diffuse out of the austenite structure (FCC) forming ferrite (BCC) & cementite (Orthorhombic)**
- **With increase in cooling rate, time allowed is insufficient**

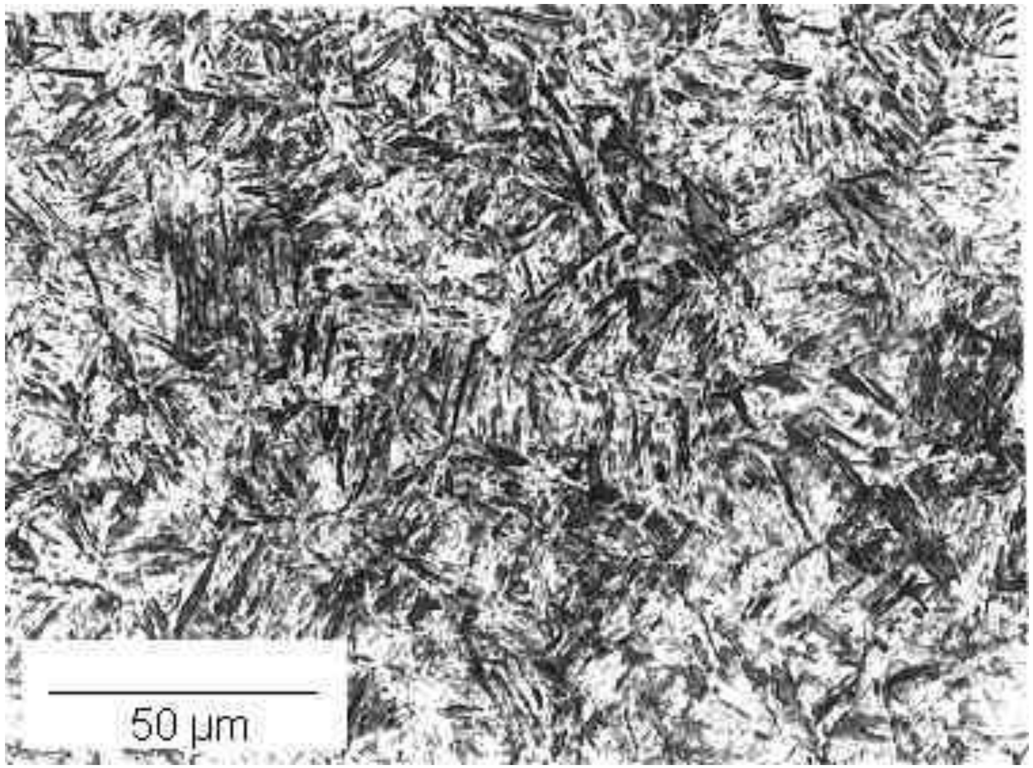
Mechanism of Quenching

Although some movement of carbon atoms take place

- **The structure can not be BCC**
- **The carbon is trapped in solution**
- **The resultant structure, Martensite is a supersaturated solution of carbon trapped in a body centered tetragonal structure (BCT).**

Quenching Contd..

- **Quenched steel (Martensite)**
- **Highly stressed condition**
- **Too brittle for any practical purpose.**
- **Quenching is always followed by tempering to**
  - **Reduce the brittleness.**
  - **Relieve the internal stresses caused by hardening.**



Martensite

Tempering

- Tempering means subsequent heating
  - to a specific intermediate temperature
  - and holding for specific time
- Tempering leads to the decomposition of martensite into ferrite-cementite mixture
  - Strongly affects all properties of steel.
- At low tempering temperature (up to 200^0C or 250^0C),
  - Hardness changes only to a small extent
  - True tensile strength increases
  - Bending strength increases

Tempering

- This may be explained by
- separation of carbon atom from the martensite lattice
- corresponding reduction in its stressed state and accicularity

Tempering

- Higher tempering temperature reduces
  - Hardness
  - True tensile strength
  - Yield point
  - While relative elongation and reduction area increases.
- This is due to formation of ferrite and cementite mixture.
- .

Tempering

- At still higher temperature or holding time
  - Spherodisation of cementite
  - Coarsening of ferrite grains
- Leads to fall in hardness as well as toughness

Hardening Heat Treatment

Some features of Hardening Heat Treatment

- **Retained ferrite detrimental to uniform properties – so heating beyond Ac_3 for Hypoeutectoid steel**
- **Retained Cementite is beneficial as it is more hard & wear resistant than martensite – so heating beyond Ac_1, not AC_M, for Hepereutechtoid steel**

Hardening Heat Treatment

Some features of Hardening Heat Treatment (Contd…)

- Addition of C shifts TTT curve to right and increases hardness of martensite
- Addition of Alloy elements shifts TTT curve to right and changes the shape
- Higher the Alloy% - Higher the stability of M
- Higher the degree of super cooling – Higher the amount of retained Austenite.

Temper Embrittleness

- A sharp fall in Impact strength when tempered at 250^0C to 400^0C for extended hours
- All steels, in varying degree, suffer from this
- Carbon steels display slight loss of toughness.
- For alloy steel reduction by 50% to 60%
- The reason associated with
  - Drecipitation of alloy carbides
  - Decomposition of retained austenite.
- Temperature range is avoided.

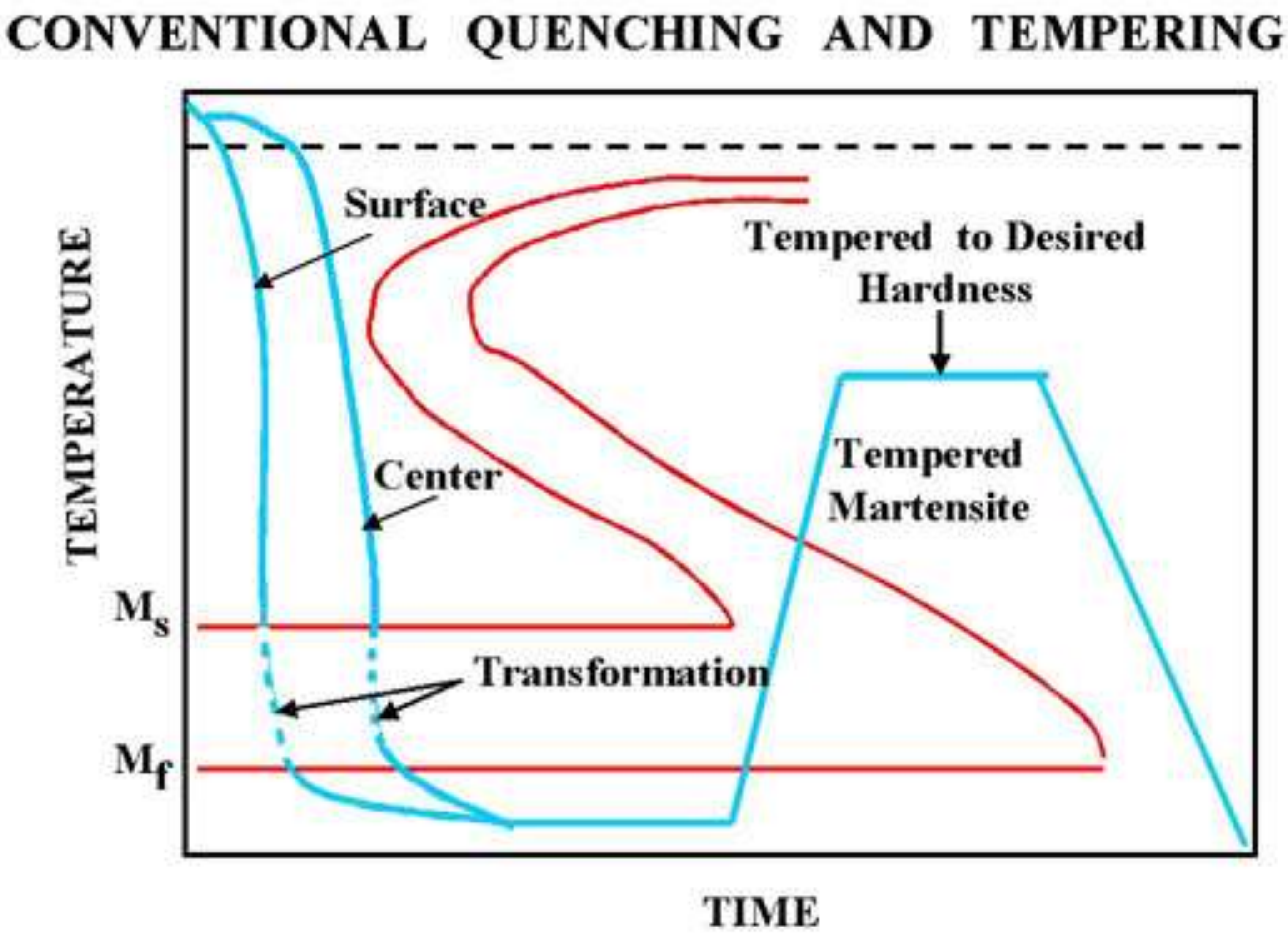
Quenching Media

- **Quenching media with increased degree of severity of quenching**
  - **Normal Cooling**
  - **Forced Air or draft cooling**
  - **Oil**
  - **Polymer**
  - **Water and**
  - **Brine**

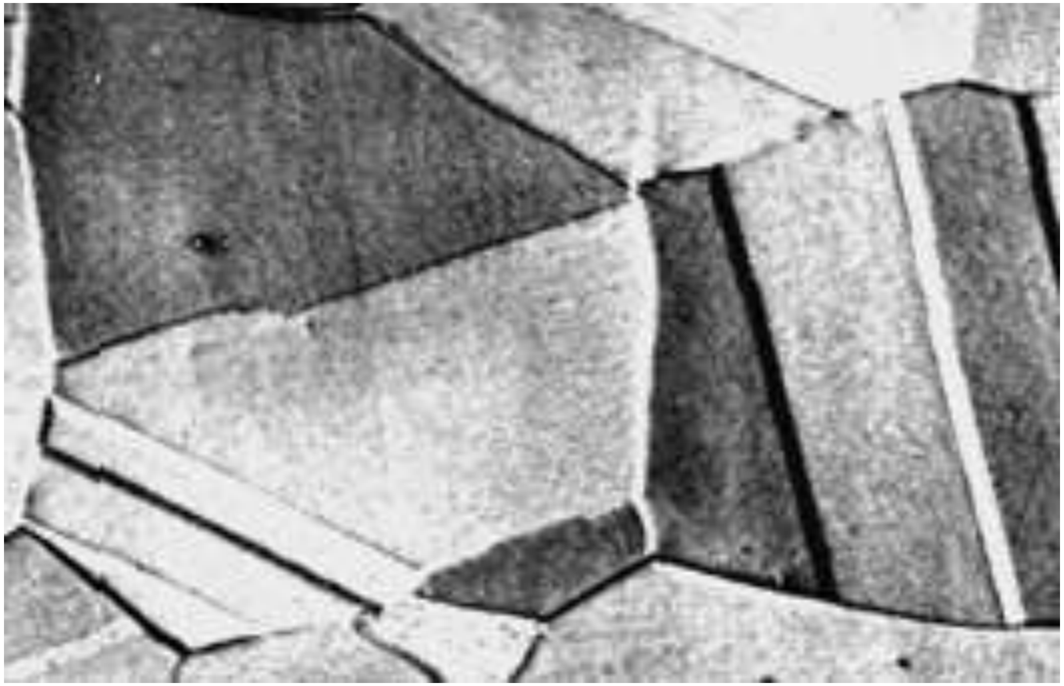
Quenching Media

- **quenching medium depends on**
  - **Material composition**
  - **Weight of job**
- **Aim is to have a cooling rate just bye-passing the nose of TTT curve for**
  - **minimum stress**
  - **minimum warping/crack during quenching.**
- **Cooling rate varies from surface to core: slower cooling towards centre.**

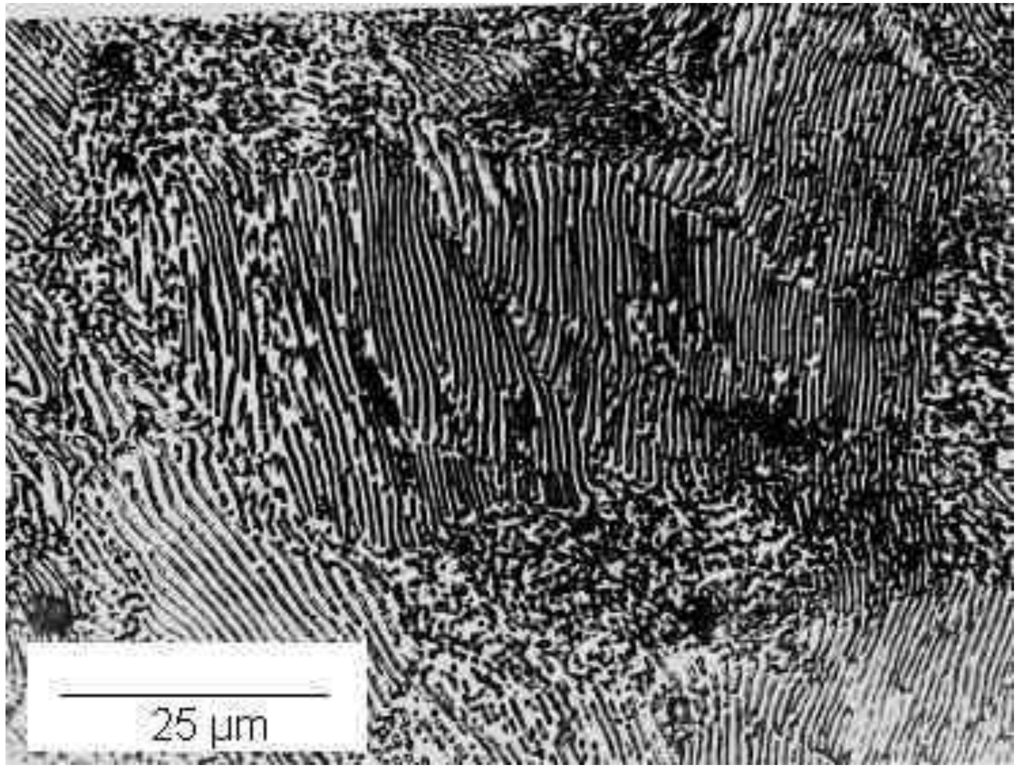
Tempering contd..



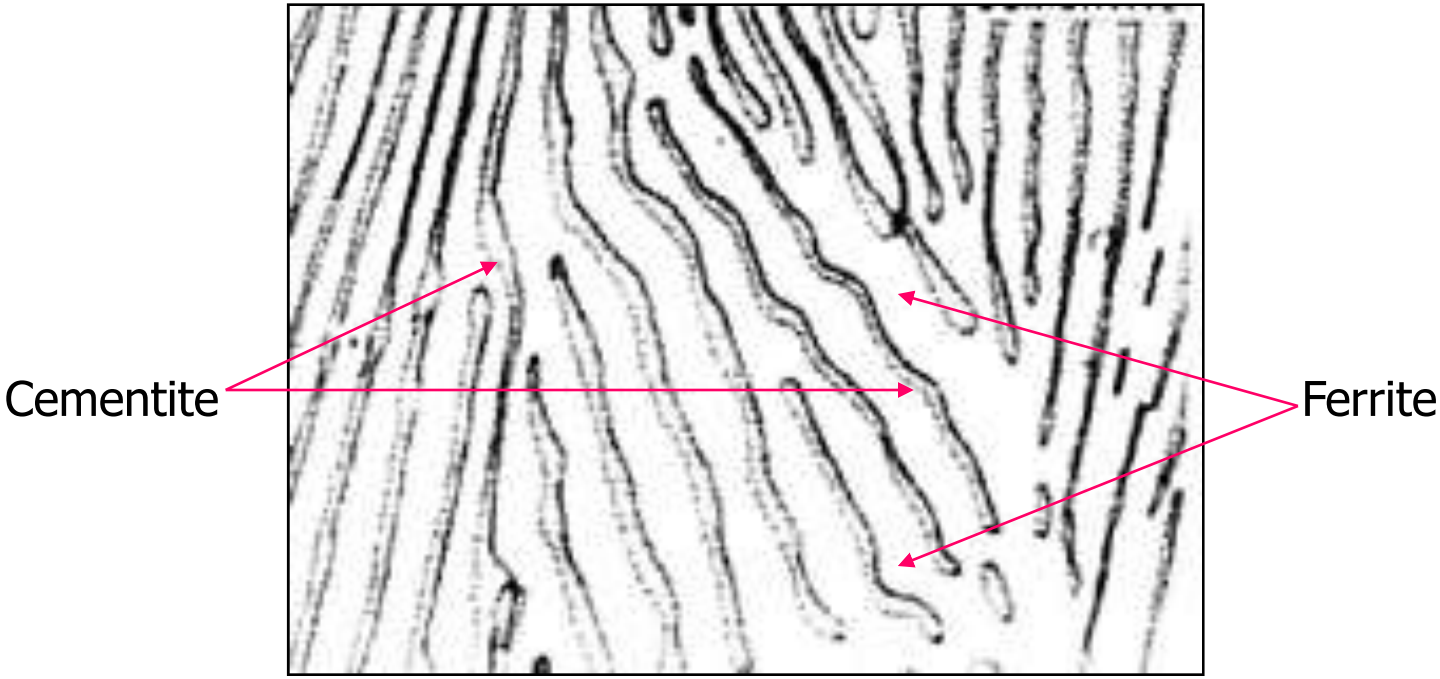
<u>Figure 1</u>. Conventional quenching and tempering process



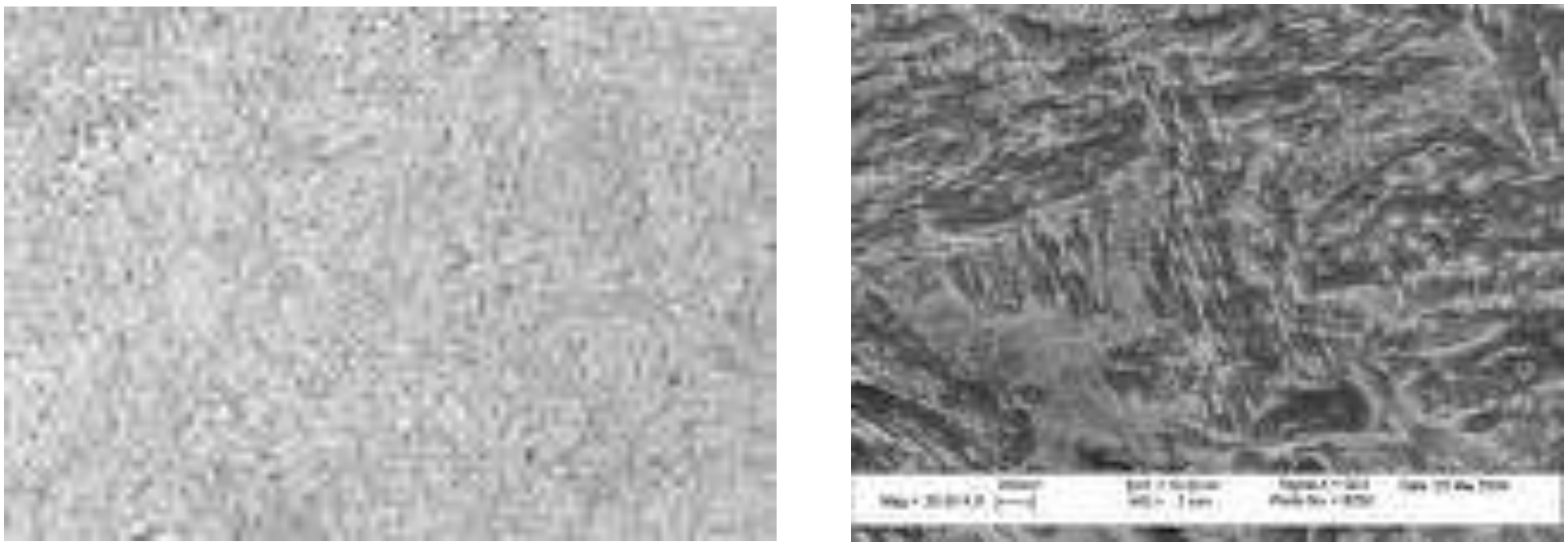
Equiaxed Austenite Grain



Pearlite



Pearlite at high Magnification
(Lamellar arrangement of Cementite & Ferrite)



Tempered Martensite

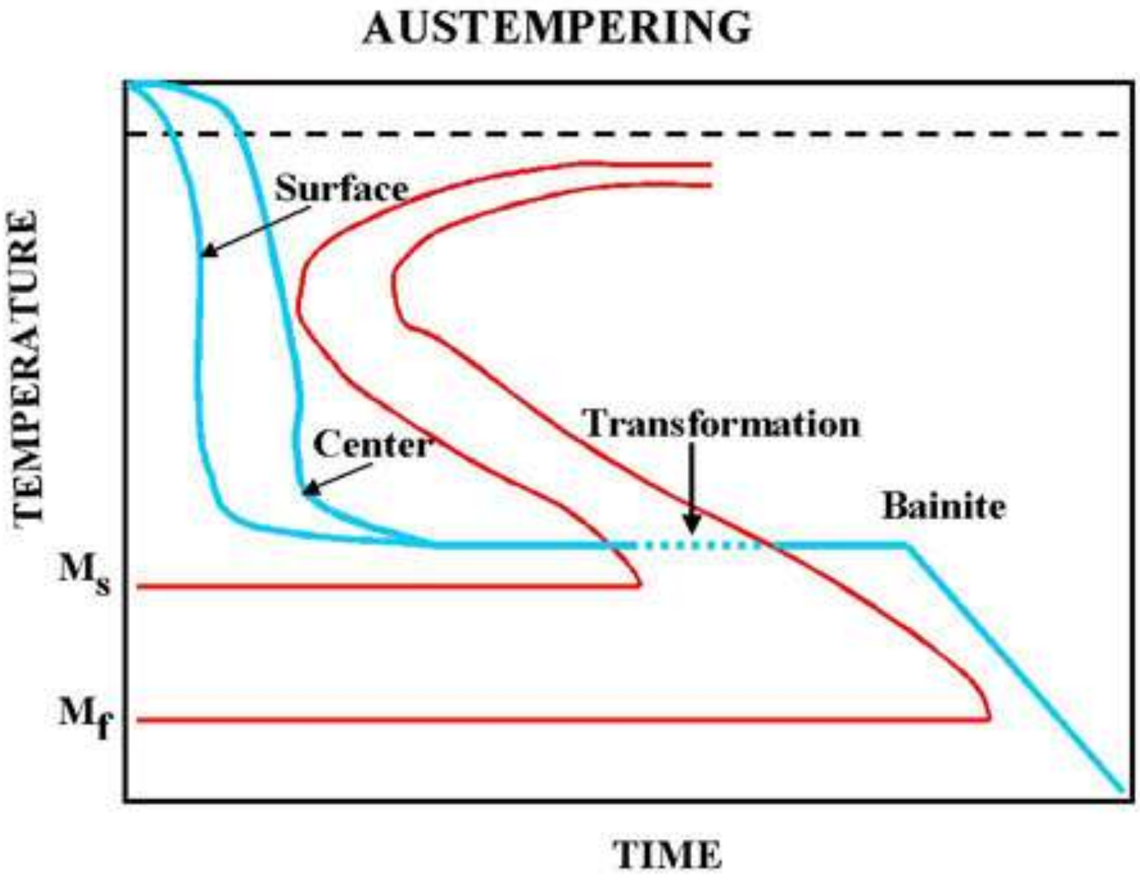
Austempering

- **A specially designed quenching technique.**
- **Quenched around 315 ºC (above M_s).**
- **Held at this temperature for sufficient time to**
  - **Homogenize surface & core temperature.**
  - **Undergo isothermal transformation from Austenite to Bainite.**

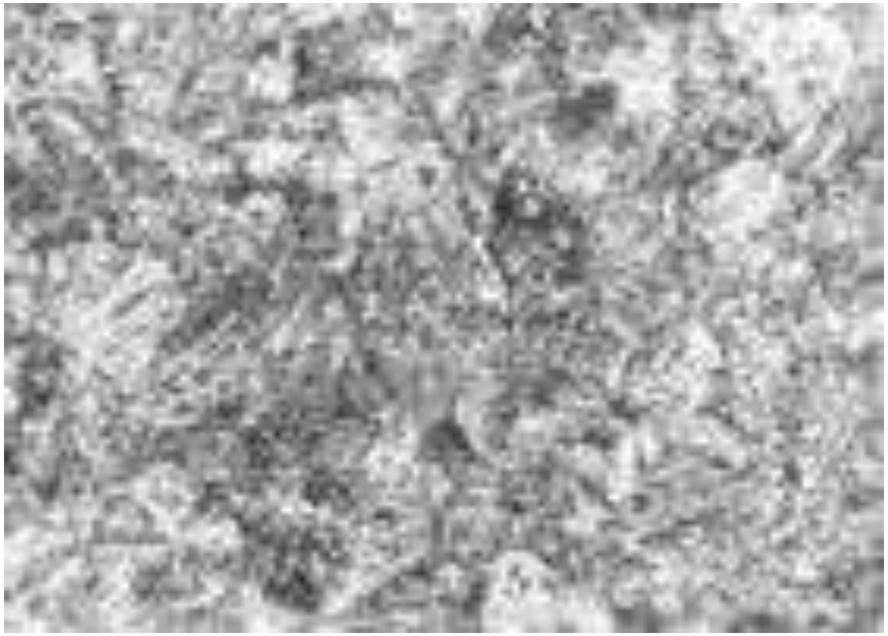
Austempering

- **Bainite has same composition as Pearlite with**
- **much finely spaced structure (inter lamellar spacing)**
- **is tough as well as hard**
- **Suitable for direct use in many application**

Austempering Contd..



Austempering process.



Bainite in prior Austenite matrix

Bainite at high magnification

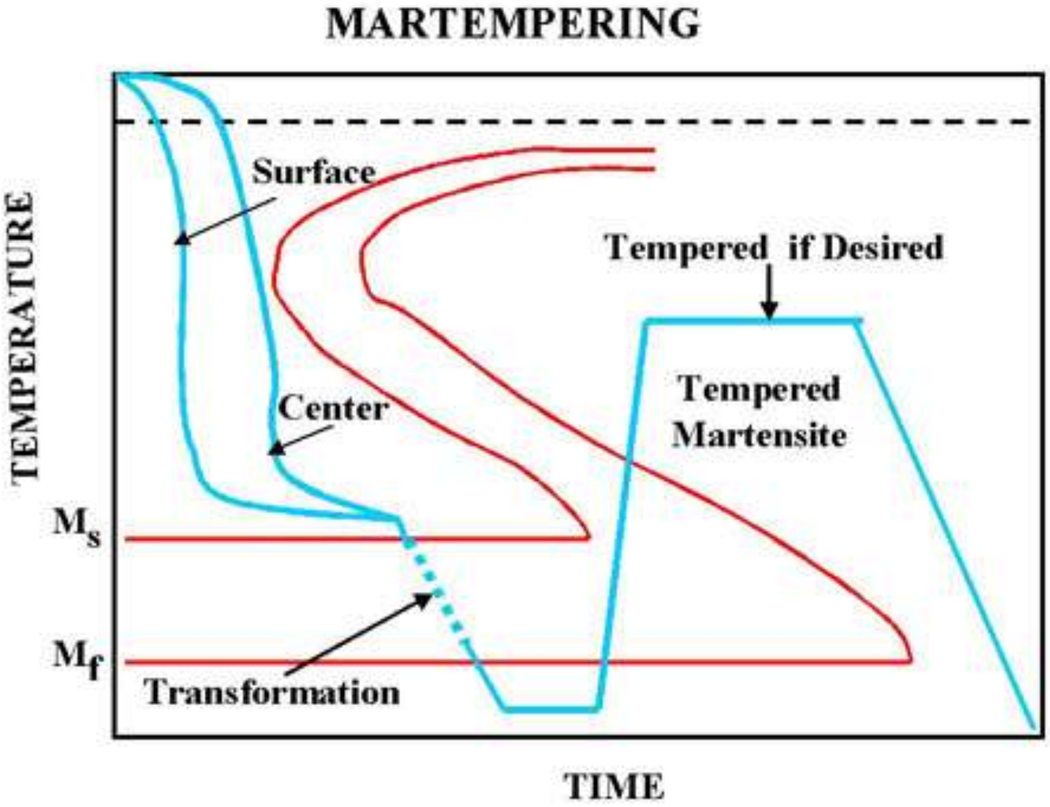
Martempering

- **Also a specially designed quenching technique.**
- **Quenched around 315 ºC (above M_s).**
- **Held at this temperature for sufficient time to**
  - **Homogenize surface & core temperature.**
- **Further quenched to M_S through M_F**
- **The structure is martensite**

Martempering

- Tempered to get desired combination of Hardness & Toughness
- Advantage over rapid quenching
  - More dimensional stability
  - Less Warping
  - Less chance of quench crack
  - Less residual stress

Martempering Contd..



Martempering process.

Case Hardening

- Objective is to harden the surface & subsurface selectively to obtain:
  - Hard and wear-resistant surface
  - Tough impact resistant core
  - The best of both worlds
- Case hardening can be done to all types of plain carbon steels and alloy steels

Case Hardening Contd..

- Selectivity is achieved

  a) For low carbon steels

    - By infusing carbon, boron or nitrogen in the steel by heating in appropriate medium
    - Being Diffusion controlled process, Infusion is selective to surface and subsurface

  b) For medium & High carbon or Alloy steel

    - By heating the surface selectively followed by Quenching

Case Carburizing

- **Heating of low carbon steel in carburizing medium like charcoal**
- **Carbon atoms diffuse in job surface**
- **Typical depth of carburisation; 0.5 to 5mm**
- **Typical Temperature is about 950^{0}C**
- **Quenching to achieve martensite on surface and sub-surface**
- **If needed, tempering to refine grain size and reduce stresses**

Case Nitriding

- Heating of steel containing Al in nitrogen medium like Nitride salt, Ammonia etc.
- Typical temperature is about 530^0C
- Nitrogen atoms diffuse in job surface
- Forms AlN, a very hard & wear resistant compound on surface & sub-surface
- Typical use is to harden tubes with small wall thickness like rifle barrel etc.

Case Carbo-nitriding

- **Heating of low carbon steel containing Al in cynide medium like cynide salt followed by Quenching**
- **Typical temperature is about 850^{0}C**
- **Nitrogen & Carbon atoms diffuse in job**
- **Typical case depth 0.07mm to 0.5mm**
- **Forms very hard & wear resistant complex compounds, on surface & sub-surface**
- **If needed, tempering to refine grain size and reduce stresses**

Induction and Flame Hardening

- Employed for medium & high carbon steel or alloy steels
- Local heating of the surface only either by flame or induction current
- Heating to austenizing range, 30 – 50^{0}C above Ac_3 (Hypoeutectoid) or Ac_1 (Hypereutectoid)
- Quenching in suitable quenching media
- If needed, tempering to refine grain size and reduce stresses

Precipitation Hardening

- Also known as Dispersion or Age hardening
- Applicable to common non-ferrous metals and alloys and some spl. Steels
- Technique used for strengthening
  - Al (Mg, Cu), Mg, Ti (Al, V) alloys
  - Some variety of SS, Maraging Steel etc.

Precipitation Hardening

- Hardening in steel is mainly due to martensite formation during quenching
- common non-ferrous metals normally don’t respond to quenching
- A method where finely dispersed second phase precipitates in the primary matrix
- These precipitations lock the movement of dislocation causing increase in hardness

Precipitation Hardening

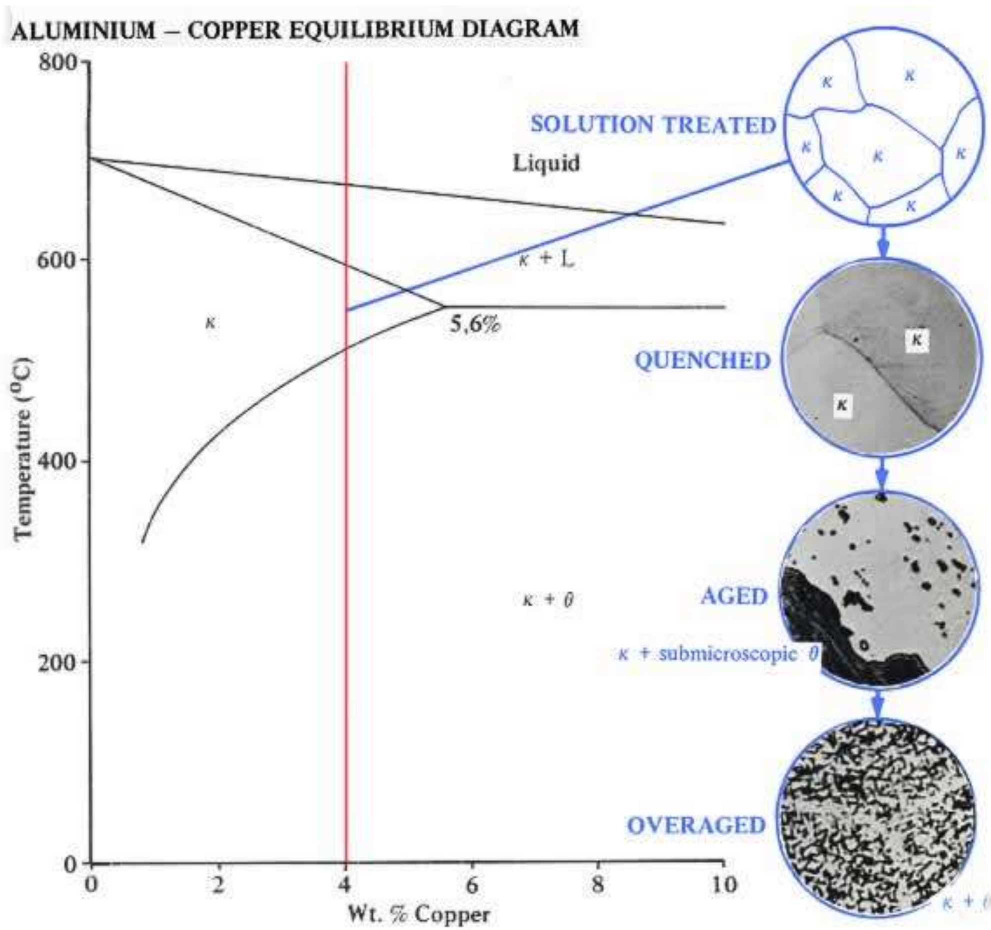
- Exploits phenomenon of super- saturation.
- Nucleation at a relatively high temperature (often just below the solubility limit)
  - Maximise number of precipitate particles.
- Lower the temperature an hold
  - These particles grow in size
  - The process called *aging*.
- Typical dislocation size is 5-30 nm

Precipitation Hardening

- Diffusion's exponential dependence upon temperature makes precipitation strengthening a fairly delicate process.
- Too little diffusion (*under aging*)
  - The particles will be too small to impede dislocations effectively
- Too much diffusion(*over aging*)
  - Particle will be too large and dispersed to interact with the majority of dislocations

Softening Heat Treatment

- **Softening Heat Treatment done to:**
  - ***Reduce strength or hardness***
  - ***Remove residual stresses***
  - ***Restore ductility***
  - ***Improve toughness***
  - ***Refine grain size***
- **necessary when a large amount of cold working, such as cold-rolling or wire drawing been performed**



Precipitation Hardening

Softening Heat Treatment

- Incomplete Annealing
  - Stress Relieving
  - Process Annealing
  - Spherodising
- Full Annealing
- Normalizing

Stress Relieving

- **To *reduce residual stresses* in large castings, welded and cold-formed parts.**
- **Such parts tend to have stresses due to thermal cycling or work hardening.**
- **Parts are**
  - heated to 600 - 650ºC (1112 - 1202ºF)
  - held for about 1 hour or more
  - then slowly cooled in still air.

Process Annealing

- used to treat work-hardened parts made out of low-Carbon steels (< 0.25% Carbon).
- In process heat treatment
- allows the parts to be soft enough to undergo further cold working without fracturing.

Process Annealing

- Temperature raised near the lower critical temperature line A_1 i. e. 650ºC to 700ºC
- Holding for sufficient time, followed by still air cooling
- **Initially, the strained lattices reorient to reduce internal stresses (recovery)**
- **When held long enough, new crystals grow (recrystallisation)**

Process Annealing

- Material stays in the same phase through out the process
  - Only change in size, shape and distribution of the grain structure
- This process is cheaper than either full annealing or normalizing
  - As material is not heated to a very high temperature or cooled in a furnace.

Spheroidization

- used for high carbon steels (Carbon > 0.6%) that will be machined or cold formed subsequently.

- Be done by one of the following ways:
  - Heat just below the line A_1 (727 ºC)
  - Hold for a prolonged time
  - Followed by fairly slow cooling.

Or

Spheroidization Contd..

- Cycle multiple times between
  - temperatures slightly above and below the A_1 say 700 and 750ºC
  - Slow cool.

Or

- For tool and alloy steels
  - heat to 750 to 800ºC
  - hold for several hours
  - followed by slow cooling.

Spheroidization Contd..

- Results formation of small globular cementite (spheroids)
- Dispersed throughout the ferrite matrix.
- Improved machinability
- Improved resistance to abrasion.

Full Annealing

- An act of
  - Heating to austenizing range, 30 – 50^{0}C above Ac_3 (Hypoeutectoid) or Ac_1 (Hypereutectoid)
  - Holding sufficiently long time for full transformation (1hr/per inch of maxm. Thickness)
  - Cooling slowly upto 500^{0}C
  - Normal cooling to room temperature

Full Annealing

- Cooling rate varies from 30ºC/hr to 200ºC/hr depending on composition
- Enable the austenite to decompose fully
- Higher the austenite stability, slower the cooling to ensure full decomposition.
- Thus, alloy steels, in which austenite is very stable should be cooled much slower than carbon steel.
- The microstructure is coarse Pearlite with ferrite or Cementite (depending on whether hypo or hyper eutectoid).

Full Annealing

- full annealing hyper eutectoid steel is required only for restoring grain size
- when hot working (rolling or forging) finished at high temperature resulted in coarse grained structure.
- For hot working finished at a normal temperature, incomplete annealing OK
- Hypoeutectoid hot worked steel (rolled stock, sheet, forgings, etc), castings of carbon & alloy steels, may undergo full annealing.

Normalizing

- Raising the temperature to 60ºC (140 ºF) above line A_3 (hypo) or line A_{CM} hyper)
- fully into the Austenite range.
- Held at this temperature to fully convert the structure into Austenite
- Removed from the furnace
- Cooled at room temperature under natural convection.
- Results a grain structure of fine Pearlite with pro-eutectoid Ferrite or Cementite.

Normalizing Vs Annealing

- Normalising considerably cheaper than full annealing
- no added cost of controlled cooling.
- Fully annealed parts are uniform in softness (and machinablilty)
- Normalized parts, depending on the part geometry, exhibit non-uniform material properties
- Annealing always produces a softer material than normalizing.

Hardenability

- **Ability of a metal to respond to hardening treatment**
- **For steel, the treatment is Quenching to form Martensite**
- **Two factors which decides hardenability**
  - **TTT Diagram specific to the composition**
  - **Heat extraction or cooling rate**

Hardenability Contd..

TTT Diagram

- For low carbon steel, the nose is quite close to temperature axis
- Hence very fast cooling rate is required to form Martensite
  - Causes much warp, distortion and stress
  - Often impossible for thick sections
- Carbon and Alloy addition shifts the nose to right and often changes the shape

Hardenability Contd..

Factors affecting cooling rate

- Heating Temperature
- Quenching bath temperature
- Specific heat of quenching medium
- Job thickness
- Stirring of bath to effect heat convection
- Continuous or batch process

Hardenability   Contd..

- Hardenability is quantified as the depth upto which full hardness can be achieved
- Amount of carbon affects both hardness of martensite and hardenability
- Type and amount of alloying elements affect mostly hardenability
- The significance of alloying element is in lowering cooling rate for lesser distortion and thick section

Property Modification Treatment

- **These heat treatments are aimed either to**
- **achieve a specific property**
- **to get rid of a undesired property**

Example

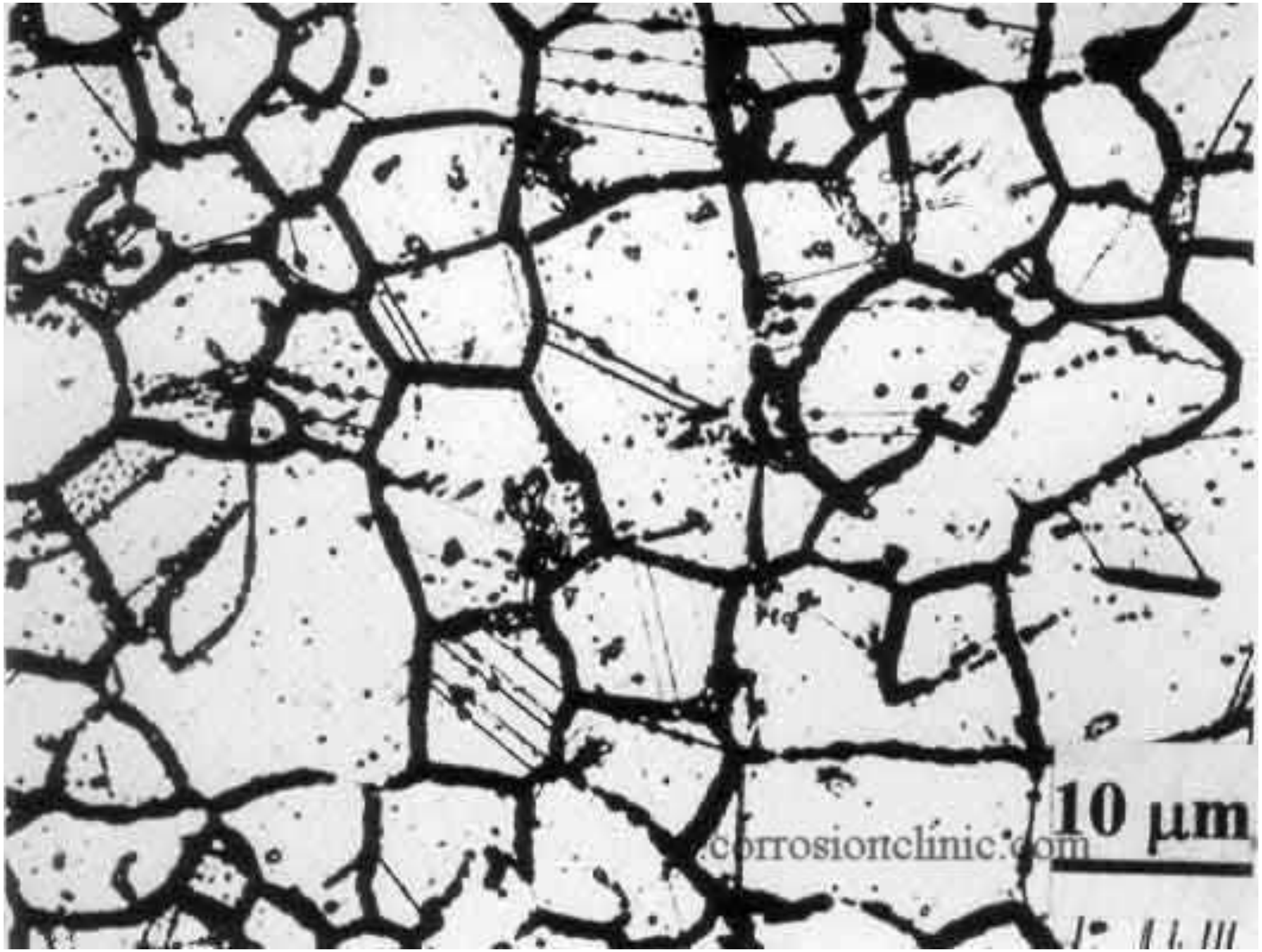
- **Solution heat treatment**

Solution Heat Treatment

- Refers to taking all the secondary phases into solution by heating and holding at a specific temperature
- Except martensite, all other phases in steel are diffusion product
- They appear or disappear in the primary matrix by diffusion controlled process
- Diffusion is Time & Temperature dependant

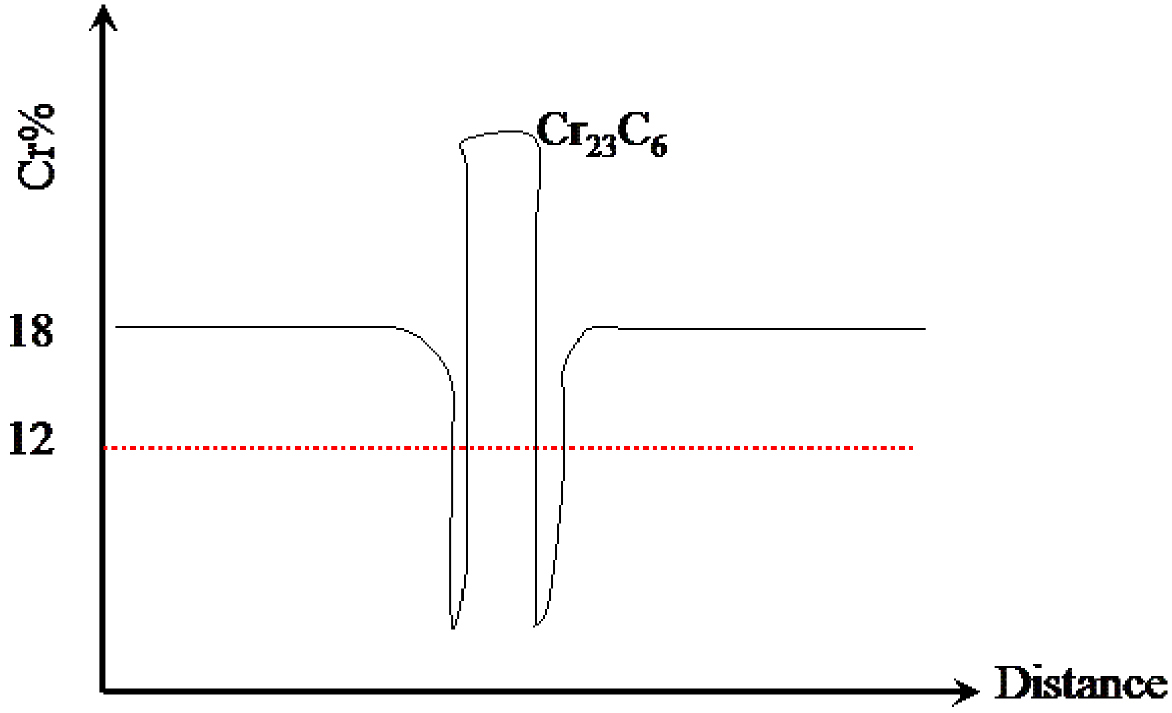
Solution Heat Treatment

- In SS, when held at temperature range of $500^0C – 800^0C$, Cr combines with Carbon at GB to form complex inter-metallic compounds
- This depletes the GB of Cr resulting in loss of corrosion resistance at GB
- Become susceptible to Inter Granular corrosion.



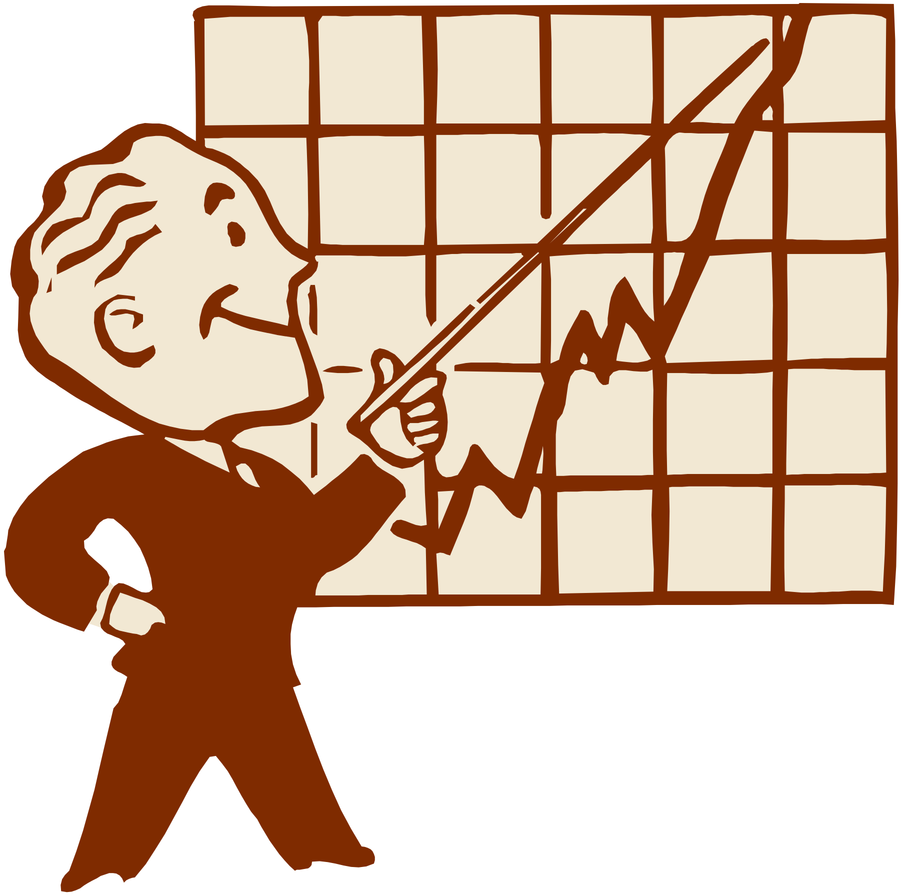
Sensitized Stainless Steel

Chromium Profile Across Grain



Solution Heat Treatment

- This situation may occur due to high service temperature or welding
- Remedy is
- Heat the job at 1050^0C
- Hold till all the carbide re-dissolves in matrix
- Fast cool to RT avoiding re-precipitation



THANK YOU