# *Outline*

- Precipitation Hardening
- Dispersion Strengthening
- Martensite
- Mechanical Properties of Steel
- Effect of Pearlite



# Precipitation Hardening

- Particles impede dislocations.
- Things that slow down/hinder/impede dislocation movement will increase, $\sigma_y$ and $\sigma_{TS}$

- And also other phases - especially v. small, well dispersed particles.

*In some alloys, we can get small, uniform particles to precipitate out of (solid) solution. Hence named "precipitation hardening" also known as "AGE" - hardening. Examples include:*

Al-Cu
Cu-Be
Cu-S
Mg-Al
Some alloy and stainless steels

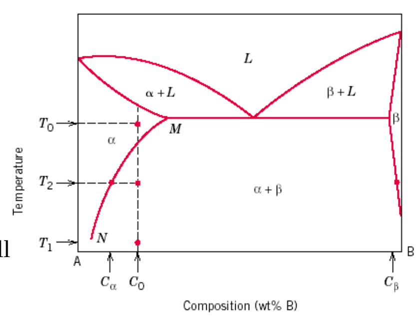
- Many Al-alloys are precipitation hardenable
- **Al - Cu** is best known alloy, e.g. Al - 4%Cu

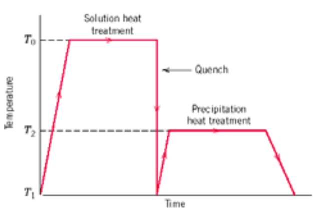


# Precipitation Hardening

**Procedure:**

- Heat to $T_o$ ; Hold until only α - phase present.
- Quench (*rapid cooling*) to $T_1$ ; because rapid, no diffusion occurs - SSSS - Super-saturated solid solution of α forms. B atoms "……….." in α. Not thermodynamically stable.
- Reheat to $T_2$ ; diffusion can occur, small precipitates of β-phase form.




**M** = Max. solubility of metal B in metal A.

Solid solubility decreases to **N** as T↓



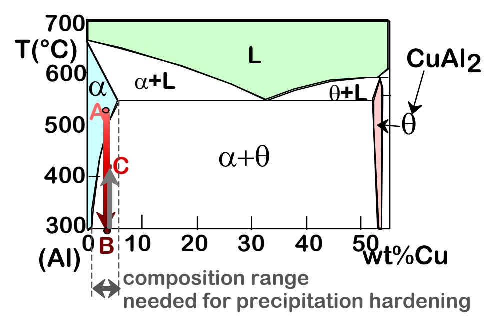
# Precipitation Hardening

- Ex: Al-Cu system
- Procedure:

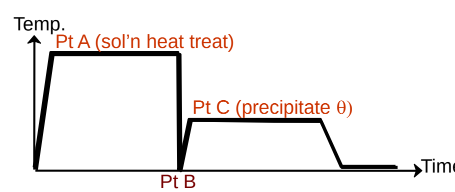
*- Pt A: solution heat treat (get a solid solution)*

*- Pt B: quench to room temp.*

*- Pt C: reheat to nucleate small θ crystals within α crystals.*

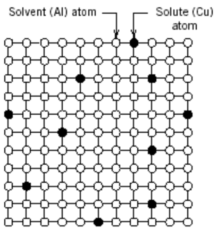



$\alpha + \theta \rightarrow$ Heat (~550°C) $\rightarrow$ Quench (0°C) $\rightarrow \alpha$ (ssss) $\rightarrow$ Heat/age (~150°C) $\alpha + \theta_{ppt}$



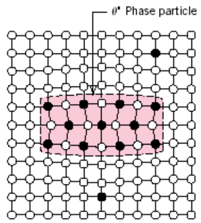
# Precipitation Hardening

Single phase - α (SSSS)



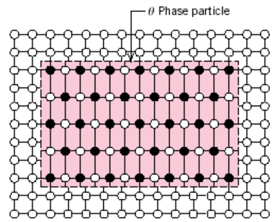

Initially have a supersaturated solid solution of Cu in Al

$\alpha + \theta''_{ppt}$




- form various zones or small Cu **clusters**
- upon further aging form **θ'' particles**

$\alpha + \theta_{ppt}$



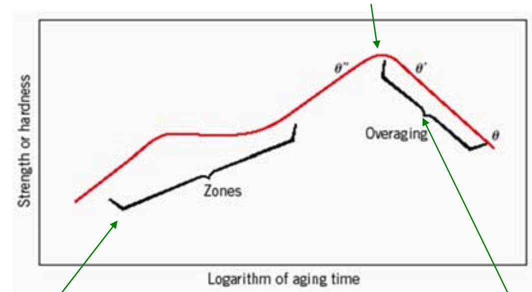

Can no longer match up with each other (………….)
- **less** resistance to dislocation movement

Lattices are trying to match up with each other (*stay* …………) - large lattice strain - high resistance to dislocation movement



# Precipitation Hardening

Max. strength/hardness




Formation & growth of precipitates. These are very small ($5 \times 10^{-9}$m) initially but grow with time.

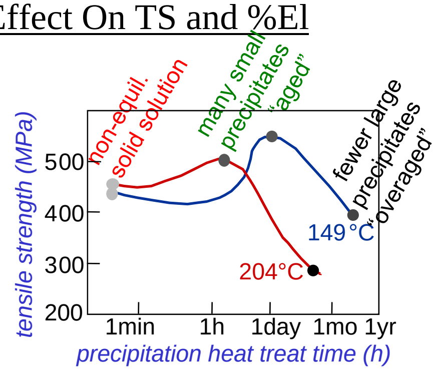
Too long at temperature and precipitates get too large and ………… occurs.

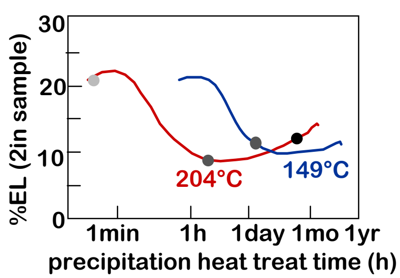
- *θ' is the optimum for strengthening*
- *θ is overaged because the precipitates are becoming* ***incoherent*** *with the Al matrix*



# Precipitate Effect On TS and %El

- TS peaks with precipitation time.
- Increasing T …………… process.
- %EL reaches minimum with precipitation time.




- **Higher** strength achieved at <u>lower</u> ageing temperatures but for **longer** times
- Consequently, if cold-working is to be done, it should be carried out **after** ……………. and **before** ……….



## Simulation of Effect of Precipitate Size on Dislocation Movement

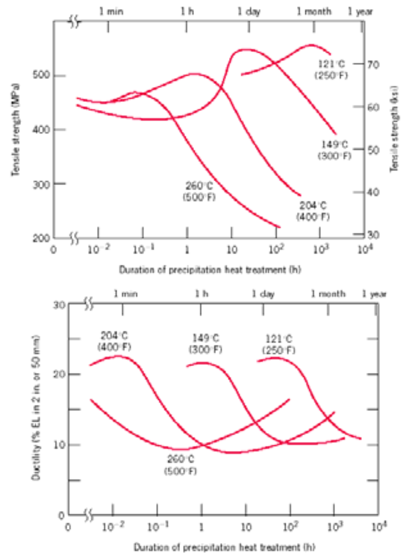
# Precipitation Hardening

2014 Al Alloy:

- **Natural aging** occurs at room temperature
  - *so will start aging at RT unless stored at low temperature - freezer! E.g. some Al-alloys for rivets*
- **Artificial aging** occurs at elevated temperature and is accelerated

• Aluminum alloys which show *age hardening* are:

- Al-Cu
- Al-Mg
- Al-Mg-Zn
- combinations of above






# Dispersion Strengthening

• Adding very small foreign particles (hard + inert/non-reactive) into matrix metal.

• Particles may be metals/non-metals but <u>oxides are often</u> used - Thorium oxide (Thoria/$ThO_2$)

• *Like precipitation hardening*, particles interfere with dislocation movement

• But not as large strengthening effect, however, not greatly affected by temperature - so good for ……..……, …………… applications.

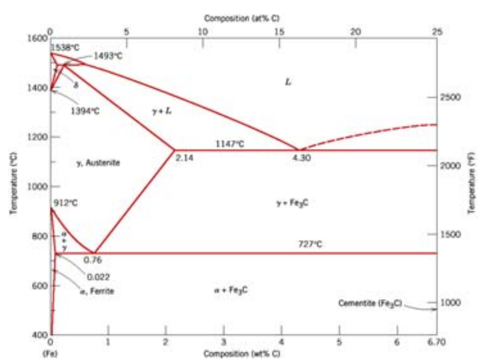
Examples:

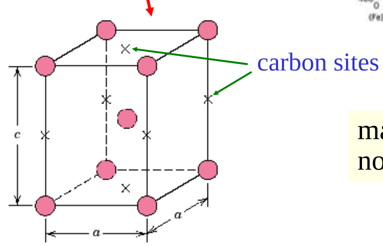
- Nickel + 3 vol% Thoria (*TD Nickel*)
- SAP (*sintered Al. powder*)



# Martensite

- Austenite dissolves ~2%C whereas ferrite only dissolves 0.022% max.
- If a medium to high carbon steel is *quenched* then **<u>C remains</u>** in solid solution forming a body-centred tetragonal phase (BCT) called ***martensite***



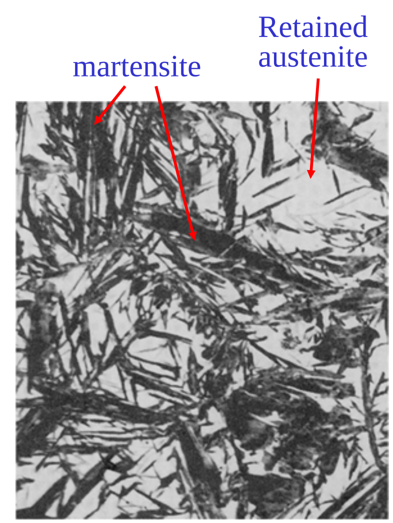




martensite is …………… and does not appear on the phase diagram

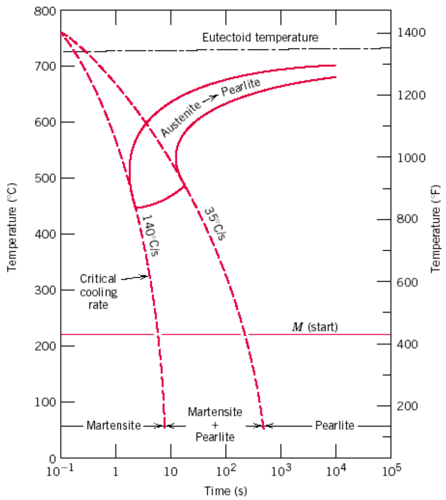


# Martensite Microstructure

- Diffusionless transformation: $\gamma \rightarrow \alpha$-martensite (*very fast*)
- platelike or needle-like appearance
- microstructure always contains *retained austenite*
- microstructural development of *martensite* and *bainite* defined by transformation curves,
  - e.g.: time, temperature, transformation (TTT)
- alloying element affect the *ease* of martensite formation



## Martensite




*Eutectoid steal*

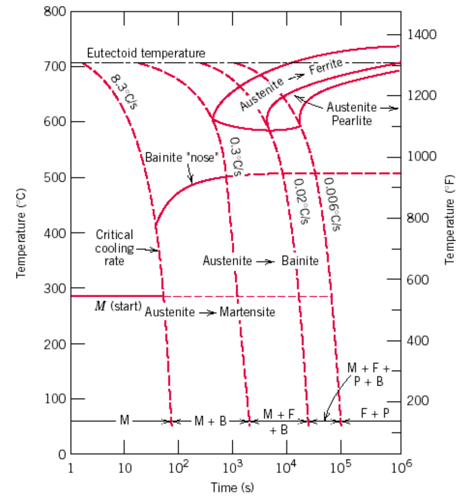
Note: need to cool faster than 140°C/s to get 100% martensite!



## Martensite

Alloy steel; + Ni, Cr, Mo.

Get martensite at slower cooling rates.






## Bainite

How does the bainite look like?

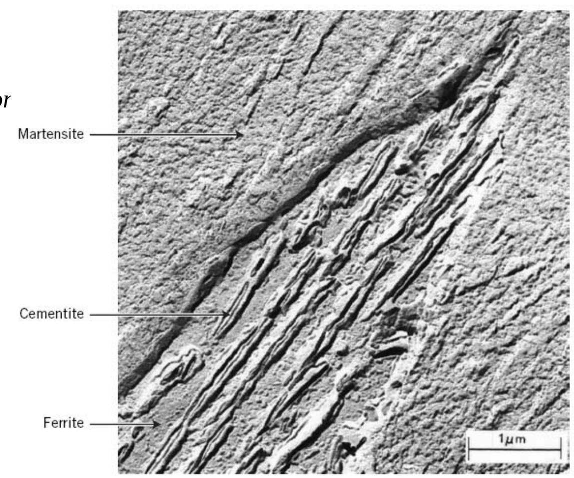
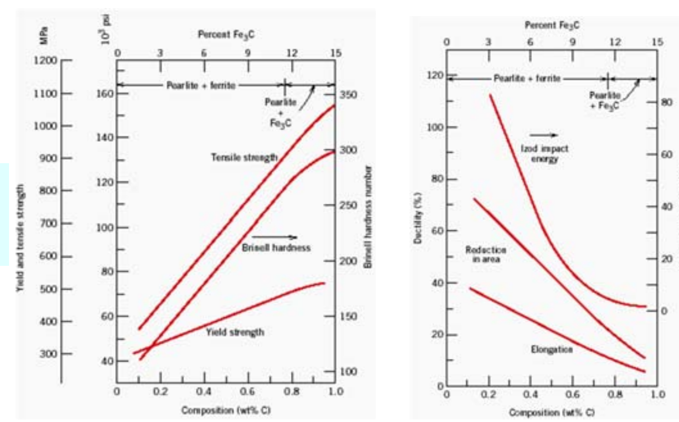



***FIGURE 10.17*** *Transmission electron micrograph (TEM) showing the structure of bainite. A grain of bainite passes from lower left to upper right-hand corners, which consists of elongated and needle-shaped particles of $Fe_3C$ within a ferrite matrix. The phase surrounding the bainite is martensite.*



## Mechanical Properties of Steel

*Effect of $Fe_3C$ and pearlite*

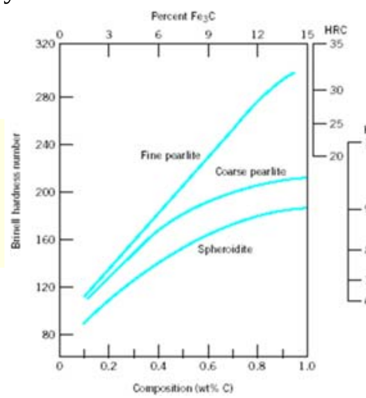


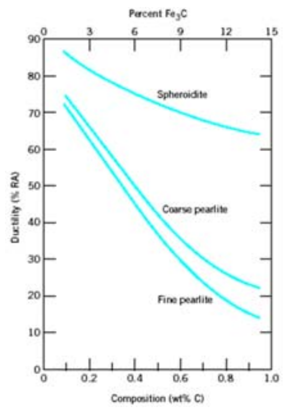

- Depending on microstructure, obtain different mech. properties
- amount of $Fe_3C$ (*hard phase*) in microstructure ……………the *hardness* and *strength*
- whereas, the *ductility* and *impact resistance* ……………

# Effect of Pearlite

- Fine pearlite is stronger and harder than coarse pearlite
- cementite adheres strongly to ferrite and restricts its deformation (*reinforces*)
- plastic deformation (dislocations) cannot cross $\alpha$-$Fe_3C$ phase boundary

Boundary area/unit volume is much **greater** in the case of ***fine pearlite***

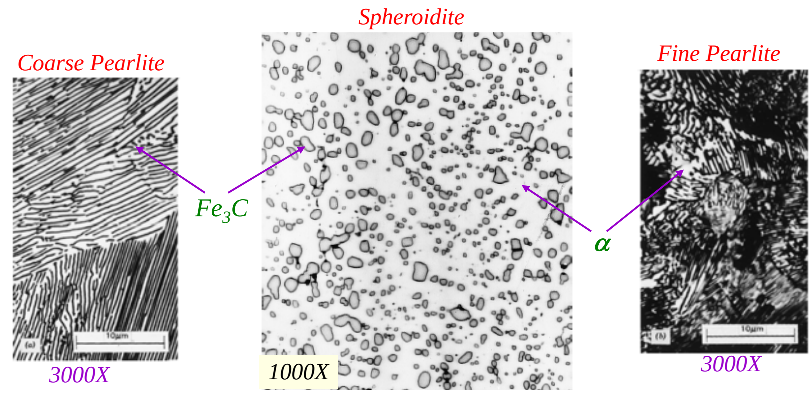





# Spheroidite

- **least** boundary area/unit volume
- soft, low strength and ductile structure (easy to machine)
- spheroidized carbide is a *low stress raiser*

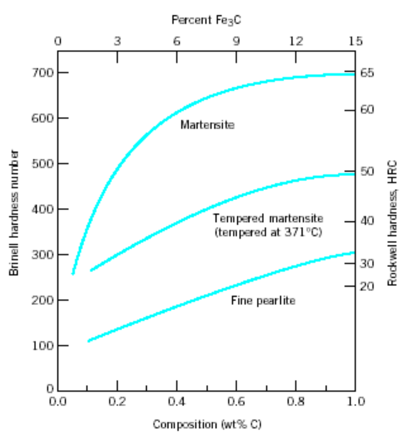



*Spheroidite vs. fine and coarse pearlite*



# Martensite

- Hardness of martensite is dependant on the carbon content up to ~0.6%C
- plastic deformation (dislocation motion) is restricted by *interstitial* carbon
- high carbon martensite is the *hardest* most *brittle* microstructure in steel
- there is an increase in volume upon quenching which can cause *cracking*



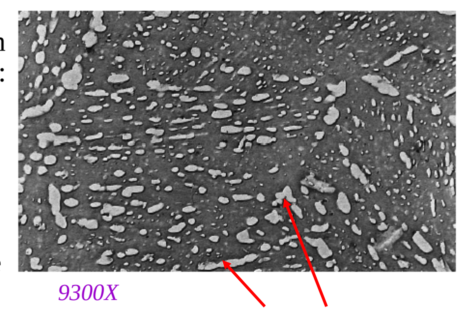



# Tempered Martensite

- *Tempering* (heating) at 250-650$^o$C allows diffusion of carbon out of *supersaturated* martensite:

$\alpha$-martensite $\rightarrow$ $\alpha$-ferrite + $Fe_3C$
(bct) (bcc)

- Microstructure is *tempered martensite*
- Cementite precipitates (hard) are **very fine** and *dispersed*
- Continuous $\alpha$ (ductile) phase
- Very large boundary area/unit volume
- This microstructure makes TM ……….. and …………………..

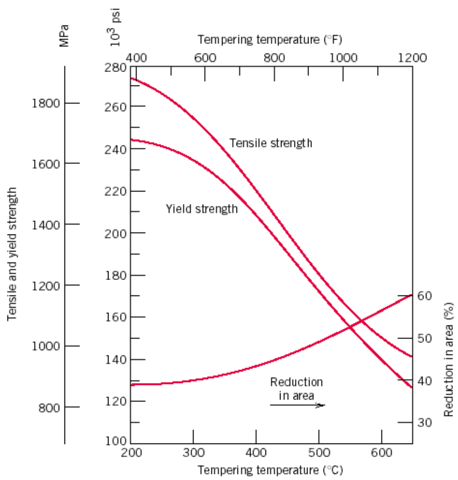


9300X

Cementite precipitates

*When both TM structure and pearlite structure have the same strength, the fracture toughness of TM structure will be much ……….. than that for pearlite structure.*

# Effect of Tempering on Mechanical Properties of Steel




*1 hour tempered 4340 steel*

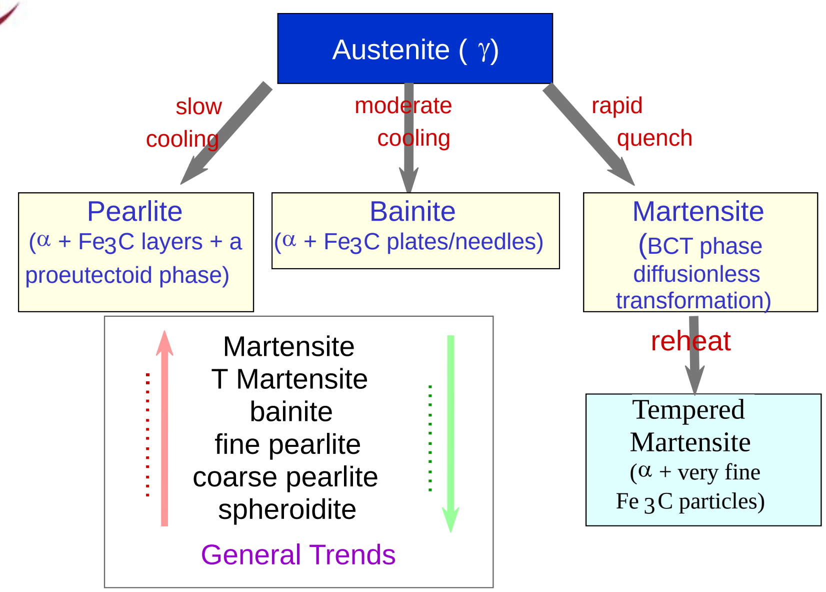
- The mechanical properties are affected by the precipitate size
- Precipitate size ………….. with tempering *time* and *temperature* up to the eutectoid composition (carbon diffusion)

***The microstructure will become Spheriodite***

Note high yield strength:
Maximum with fine pearlite was 500MPa.



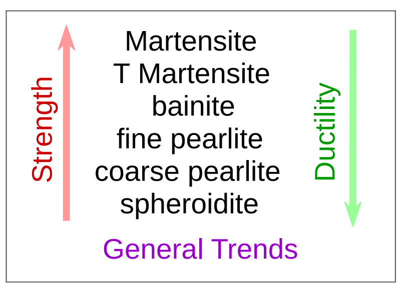
# Summary: Processing Options






# Summary

- The versatility of steel arises because of the wide range of microstructures that can be achieved, and the corresponding wide range of mechanical properties.
- In general, steel microstructures in which carbides are more finely dispersed have ……….. strength and ……….. fracture toughness.






Next topic:
Composites