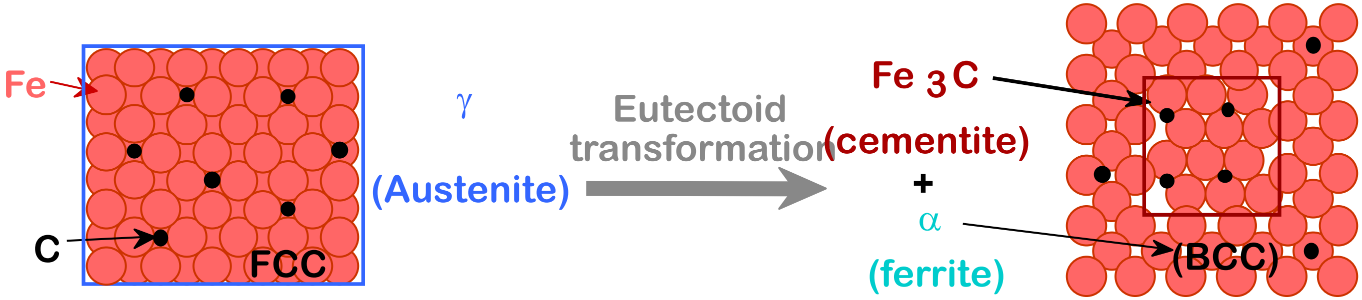
CHAPTER 10:
PHASE TRANSFORMATIONS

ISSUES TO ADDRESS...

- Transforming one phase into another takes time.



Fe

C

FCC

γ (Austenite)

Eutectoid transformation

Fe_3C (cementite)

+

α (ferrite)

(BCC)

- How does the rate of transformation depend on time and T?
- How can we slow down the transformation so that we can engineering non-equilibrium structures?
- Are the mechanical properties of non-equilibrium structures better?

Development of Microstructure and Alterations of Mechanical Properties

- Phase Transformations in metals
- Kinetics of Solid State Reactions
- Multiphase Transformations
- Changes in Iron-Carbon Alloys
- Isothermal Transformations
- Continuous Cooling Transformations
- Mechanical Behavior
- Tempered Martensite

PHASE TRANSFORMATIONS

- The patterns in which atoms are arranged in a solid depend on parameters such as the chemical composition, temperature and magnetic field. ***A phase transformation*** is a change in the arrangement of atoms. Prediction of phase transformations helps to conceive novel alloys or processes using calculations & critical experiments.

•***Three classes*** of phase transformations can be outlined:

- *Simple Diffusion-dependent*:
  no change in number or composition of phases
- *Diffusion-dependent*
  with changing of phase composition and often their number
- *Diffusionless*
  formation of the metastable phases

Phase Equilibrium

We are all familiar with ***phase transitions*** where a substance transforms from one stable phase to another at an equilibrium temperature. For example, ice will be in ***equilibrium*** with liquid water at 273.15 K and 1 atmosphere pressure, or liquid water will be in equilibrium with water vapor at 373.15 K and 1 atmosphere.

Let us briefly consider the thermodynamic principles involved in phase transitions. We assume that we know nothing about the conditions under which two phases can be in equilibrium. The only things we know are the ***criteria for equilibrium*** under certain conditions:

- for a closed isolated system - that is, the ***entropy***, S, seeks a maximum: $dS_{U,V} \geq 0$
- for a system at constant temperature and volume - the ***Helmholtz free energy***, A, seeks a minimum: $dA_{T,V} \leq 0$
- for a system at constant temperature and pressure - the ***Gibbs free energy***, G, seeks a minimum: $dG_{T,P} \leq 0$

The Enthalpy

Enthalpy is an energy-like property or state function, it has the dimensions of energy, and its value is determined entirely by the temperature, pressure, and composition of the system and not by its history.

In symbols, the **enthalpy**, H, equals the sum of the internal energy, U, and the product of the pressure, P, and volume, V, of the system:

$$\boxed{H = U + PV}$$

According to the law of energy conservation, if the only work done is a change of volume at *constant pressure*, the **enthalpy** change is exactly equal to the heat transferred to the system:

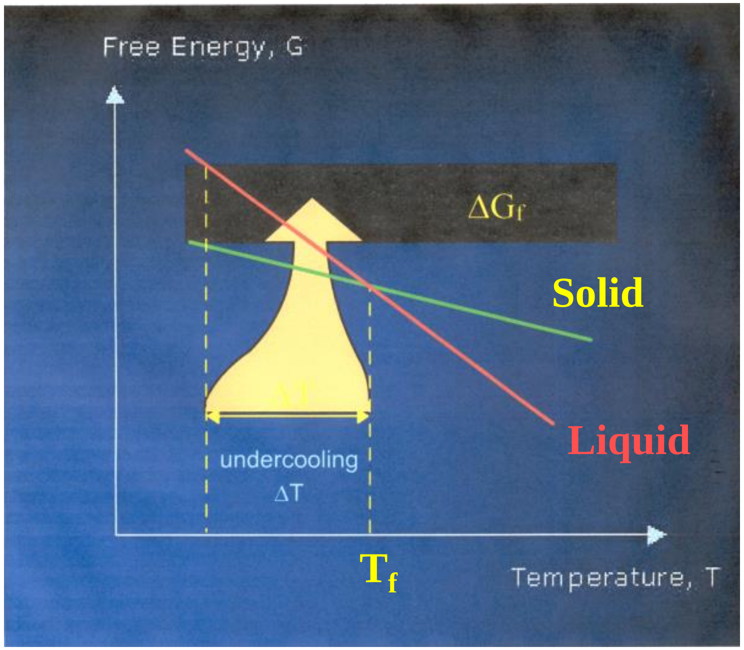
$$C_p = (\delta H/\delta T)_p$$

Simple Diffusion-dependent PT

- Example: solidification of a pure element

Solidification is undoubtedly the most important processing route for metals and alloys. Consider a pure metal. At the fusion temperature T_f , $\Delta G = 0$ so that:

$$\boldsymbol{\Delta G_f = \Delta H_f - T_f \Delta S_f = 0} \text{ or } \boldsymbol{\Delta H_f = T_f \Delta S_f}$$



where ΔH_f is the latent heat of fusion and $\Delta S_f > 0$ for melting.

For any temperature other than T_f ,

$$\Delta G = \Delta H - T\Delta S \cong \Delta H_f - T\Delta S_f = \Delta S_f (T_f - T) = \Delta S_f \Delta T$$

where ΔT is **undercooling**

The ***driving force*** is therefore proportional to the ***undercooling*** because the latent heat and the entropy of fusion do not vary much with temperature

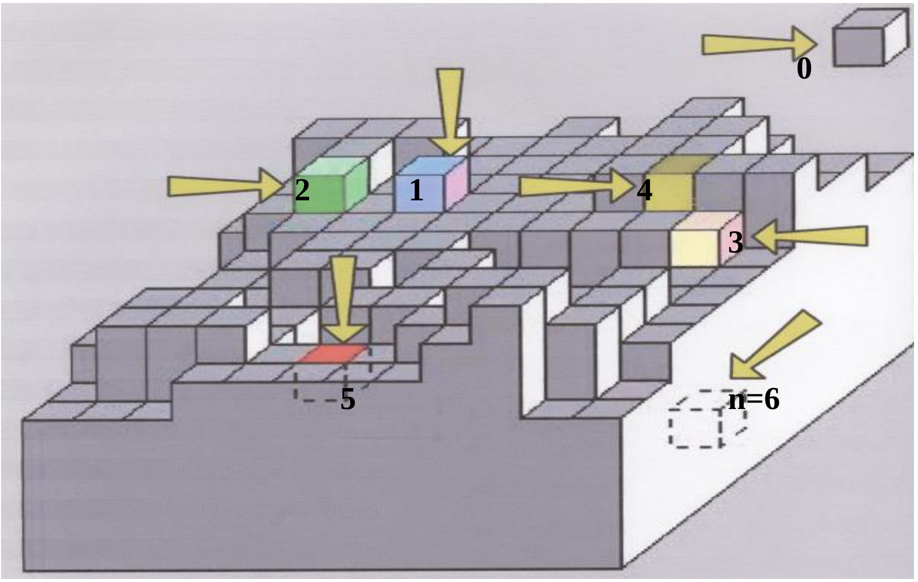
Solidification of a Pure Elements

- Any molecule near the solid/liquid Interface has a certain number of bonds (in the range 0 to 6) with the solid phase.

- The molecules attached to the interface may become "***melted off***" into the liquid as a result of ***thermal fluctuations*** (***diffusion***).

- The molecule resists this to a degree which depends on the energy with which it is bound to the solid.

- Since the ***maximum binding energy*** is given by the ***enthalpy of fusion***, ΔH_f, the value for a molecule exposed to the liquid will be $n\Delta H_f / 6$, where **n** is the number of bonds.



Solidification of a Pure Elements

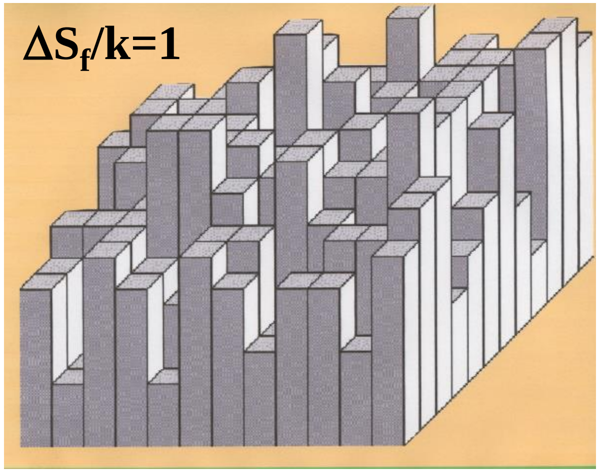
- The probability of an interfacial molecule being melted off, i.e. the fraction of this type of molecule which will be detached, is given by a ***Boltzmann expression***:

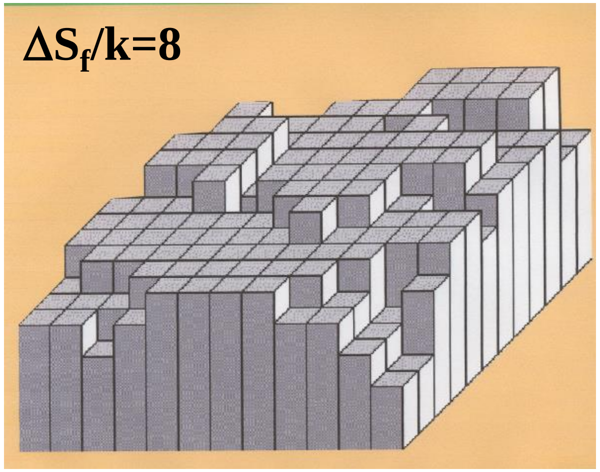
$$f(n) = \exp\left(-\frac{n\Delta H_f/6}{kT}\right)$$

- A smooth interface will be one for which there are few remaining molecules with n=1 and many with n=5. Using the expression $\Delta H_\mathrm{f} = \Delta S_\mathrm{f}\, T_\mathrm{f}$, and assuming that the temperature is close to T_f, the ratio can be written as:

$$\frac{f(1)}{f(5)} = \exp\left(\frac{2/3\Delta S_f}{k}\right)$$

- A high value (≥10), obtained when $\Delta S_\mathrm{f} / k$ is greater than about 5-6, will give a smooth interface





Solidification of a Pure Elements

- If all adsorption sites are equivalent, then a simple model can be used to relate solidification velocity to undercooling An adsorption event is assumed to be similar to a normal ***diffusive jump*** in the liquid

- The advance ***velocity*** from ***adsorption*** events can be written as the product of jump distance, λ*, vibration frequency, ω_0, and the probability of making a diffusive jump

$$V_{ads} = \lambda_* \omega_0 \exp\left(-\frac{\Delta G_{mL}}{kT}\right)$$

.

- Account must also be taken of ***desorption*** events. These are less frequent (if the interface is undercooled) because of the larger energy barrier

$$V_{des} = \lambda_* \omega_0 \exp\left(-\frac{\Delta G_{mL} + \Delta G_f}{kT}\right)$$

The net velocity is given by the difference between these two.

$$V = \lambda_* \omega_0 \exp\left(-\frac{\Delta G_{mL}}{kT}\right)\left[1 - \exp\left(\frac{\Delta G_f}{kT}\right)\right] = \lambda_* \omega_L \left[1 - \exp\left(-\frac{\Delta G_f}{kT}\right)\right]$$

Solidification of a Pure Elements

- Elementary diffusion theory relates the jump frequency to the diffusion coefficient and the jump distance

$$\omega_I = \frac{D_I}{\lambda_I^2}$$

- Assuming $\lambda^* \cong \lambda_L \cong d$ (molecular diameter), the velocity can be written as

$$V = \frac{D_I}{d}[(1 - \exp(\frac{\Delta G_f}{kT})]$$

which is often termed the ***Wilson-Frenkel equation***. Since ΔG_f is given by $\Delta H_f \, \Delta T / T_f$ and assuming ΔT is small, so that the approximation $1 - \exp(-x) \cong x$ for small x can be used, this equation reduces to:

$$\boxed{V \cong \frac{D_I}{d} \frac{\Delta H_f}{kT_f^2} \Delta T = B \Delta T}$$

Typical data:

D_I	$\approx$	$5\,10^{-9}$	m^2/s
ΔH_f	$\approx$	10^{-20}	$J/molecule$
d	$\approx$	$3\,10^{-10}$	m
T_f	$\approx$	10^3	K
k	$\approx$	$1.4\,10^{-23}$	$J/(K\,molecule)$

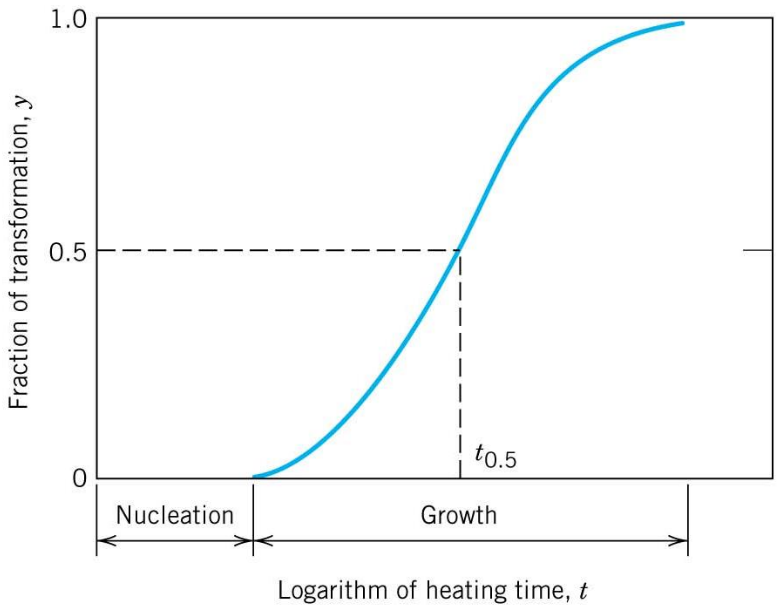
$$\} B \cong 10^{-2}\, m/sK$$

Even a relatively high velocity of ~ 1 mm/s thus requires a (kinetic) undercooling of ***only about 0.1K***. Conversely, if a melt is significantly undercooled before a crystal forms, the initial growth rate will be ***very fast***.

KINETICS of SOLID STATE TRANSFORMATION

- ***Kinetics*** **- a time dependence of transformation rate.**

<u>Example:</u> typical kinetics for variety of solid-state transformation at constant temperature



- Can be described by so-called ***Avrami Equation***:

$$\boxed{y = 1 - e^{-kt^{n}}}$$

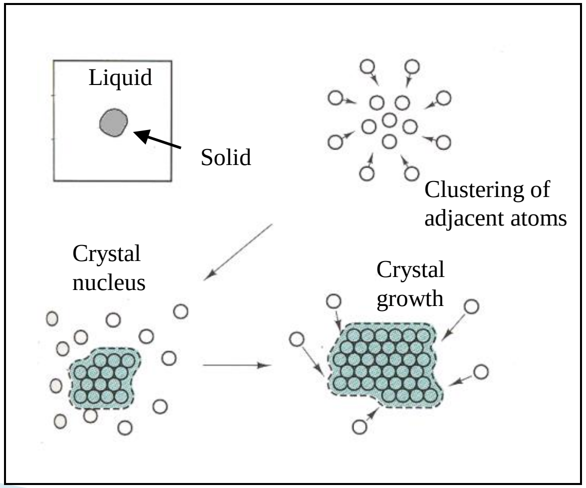
fraction transformed

time

- By convention, the rate of transformation **r** is taken as the reciprocal of time required to reach half completion:

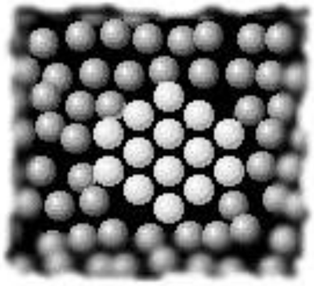
$$\boxed{r = 1/t_{0.5}}$$

Two stages of transformation process:
- ***Nucleation*** – formation of extremely fine particles, i.e. ***nuclei,*** of ***new phases***
- ***Growth –*** increase of nuclei size



Homogeneous Nucleation

***Homogeneous Nucleation* –** precipitation occurs within a **homogeneous medium**.

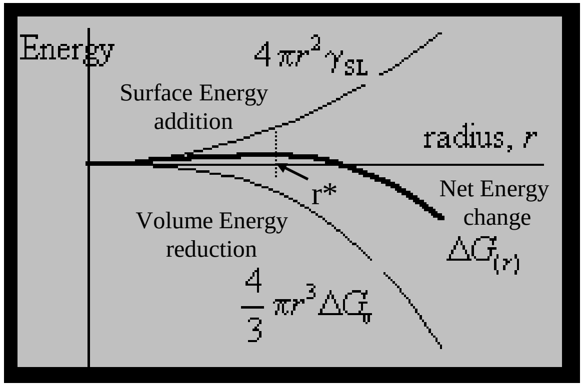


The small clusters of crystallized solid forming from a liquid metal. These arise due to the random motion of atoms within the liquid

•By assuming that solid phase nucleates are spherical 'clusters' of radius, *r*, one can define the excess of free energy change for a single nucleus, $\Delta G_{(r)}$:

$$\Delta G_{(r)} = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma_{SL}$$

where γ_{SL} is the solid/liquid interfacial energy.



The critical radius r^* (defined as the radius at which $\Delta G_{(r)}$ is maximum) is given by:

$$r^* = \frac{-2\gamma_{SL}}{\Delta G_v} = \frac{-2\gamma_{SL} T_m}{\Delta H_v \Delta T}$$

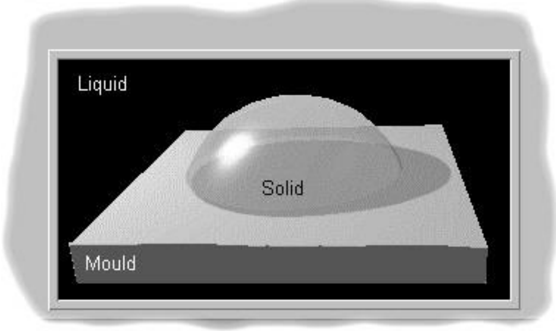
The associated energy barrier to homogeneous nucleation, ΔG^* is:

$$\Delta G^* = \frac{16\pi\gamma_{SL}^3}{3\Delta G_v^2} = \frac{16\pi\gamma_{SL}^3 T_m^2}{\Delta H_v^2 \Delta T^2}$$

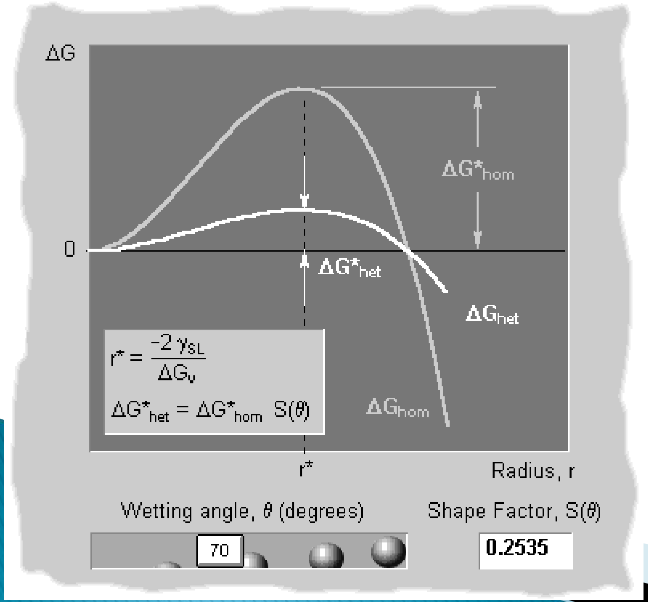
Important : the temperature-dependence of these terms are: $r^* \propto 1/\Delta T$ and $\Delta G^* \propto 1/\Delta T^2$

Heterogeneous Nucleation

- *Heterogeneous Nucleation*



The nuclei can form at preferential sites (e.g. mould wall, impurities or catalysts). By this, the ***energy barrier to nucleation***, ΔG^* can be ***substantially reduced***.



•Let us consider that a solid cluster forms on a mould wall. In this case, one can define the excess of free energy change for a nucleus, $\Delta G_{(r)}$ as follows:

$$\Delta G_{(r)} = V\Delta G_v + A_{SL}\gamma_{SL} + A_{SM}\gamma_{SM} - A_{SM}\gamma_{ML}$$

Note that as compared to homogeneous case two new interface should be taken into account i.e. **solid-mould** and **liquid mould**

- It can be shown that the critical radius r^*_{het} for heterogeneous nucleation ***is equal*** to r^*_{hom}:

$$r^*_{het} = \frac{-2\gamma_{SL}}{\Delta G_v} = r^*_{hom}$$

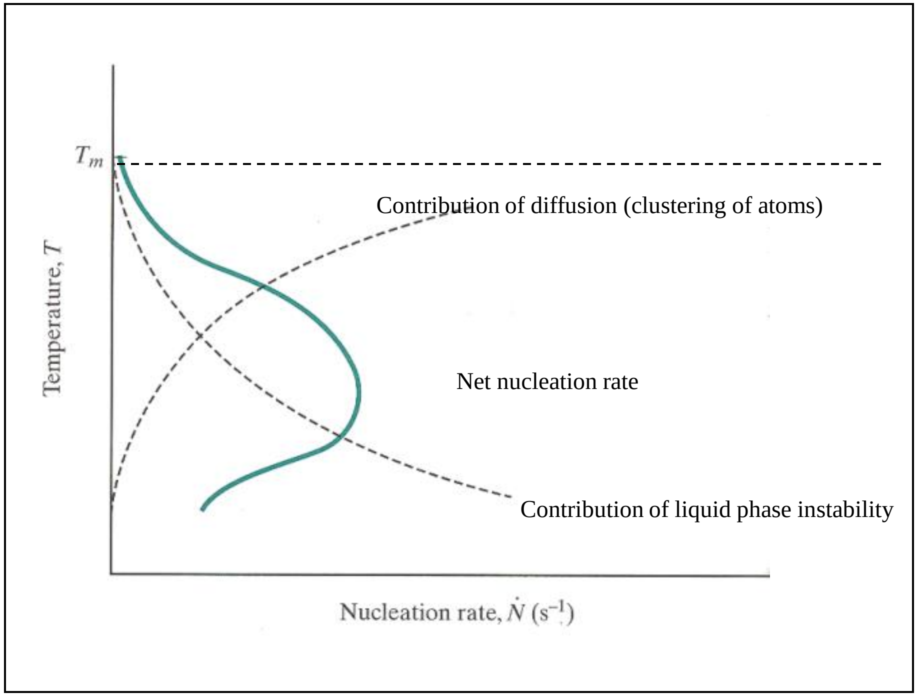
- And:

$$\Delta G^*_{het} = \frac{16\pi\gamma_{SL}^3}{3\Delta G_v^2} S(\theta) = \Delta G^*_{hom} S(\theta)$$

where S(θ) is a geometrical factor and θ is a **wetting angle**:

$$S(\theta) = \frac{(2+\cos\theta)(1-\cos\theta)^2}{4}$$

Nucleation Rate–Temperature Diagram



- The overall nucleation rate is a product of two opposite working factors:

- the driving force for solidification ***increases*** with T decrease;

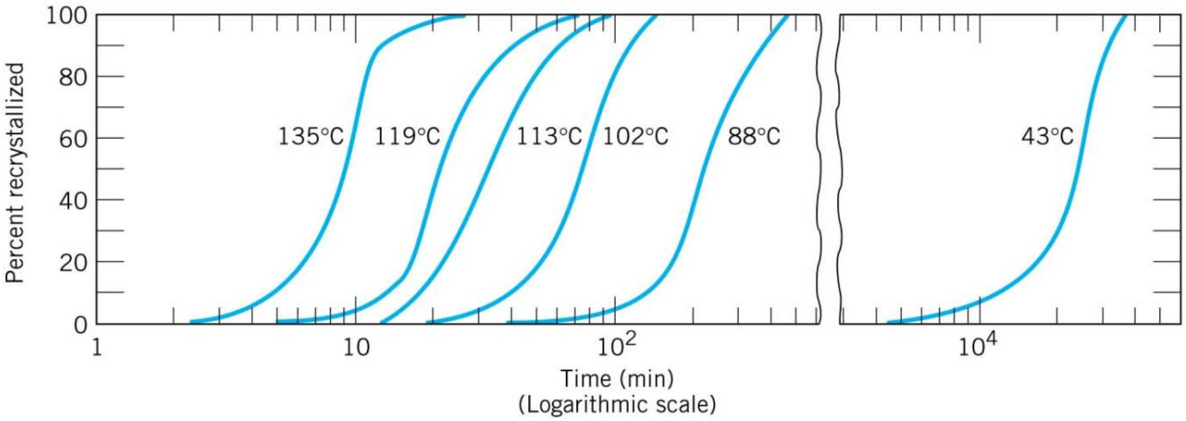
- while the diffusion that is responsible for the clustering process ***decrease*** with T decrease.

- These explain the “knee-shaped” nature of the transformation curve with maximum at some value below T_f

KINETICS of SOLID STATE TRANSFORMATION

- ***Kinetics* - a time dependence of transformation rate.**

<u>Example:</u> kinetics of solid-state transformation as a function of temperature



Recrystallization kinetics
for pure copper

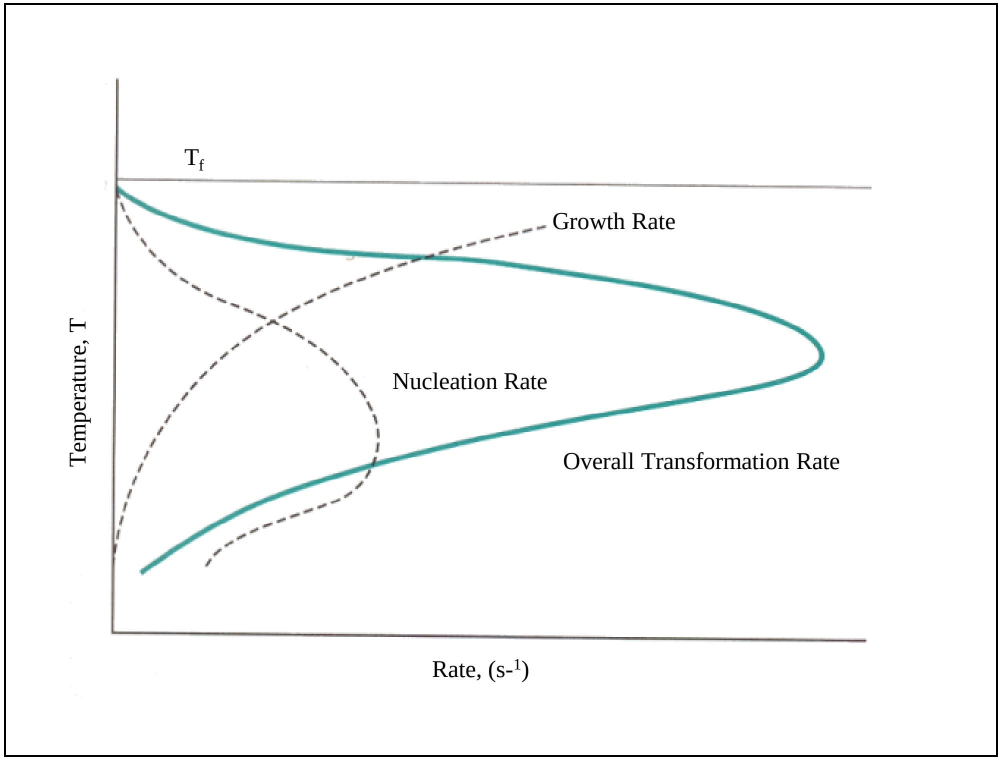
Nucleation time decreases and transformation rate increases with increase of temperature

activation energy

$$r = Ae^{-Q/RT}$$ - Arrhenius expression

Thermally activated process

Overall Transformation Rate–Temperature Diagram



- The overall transformation rate is a product of two factors:

  \- ***nucleation***;

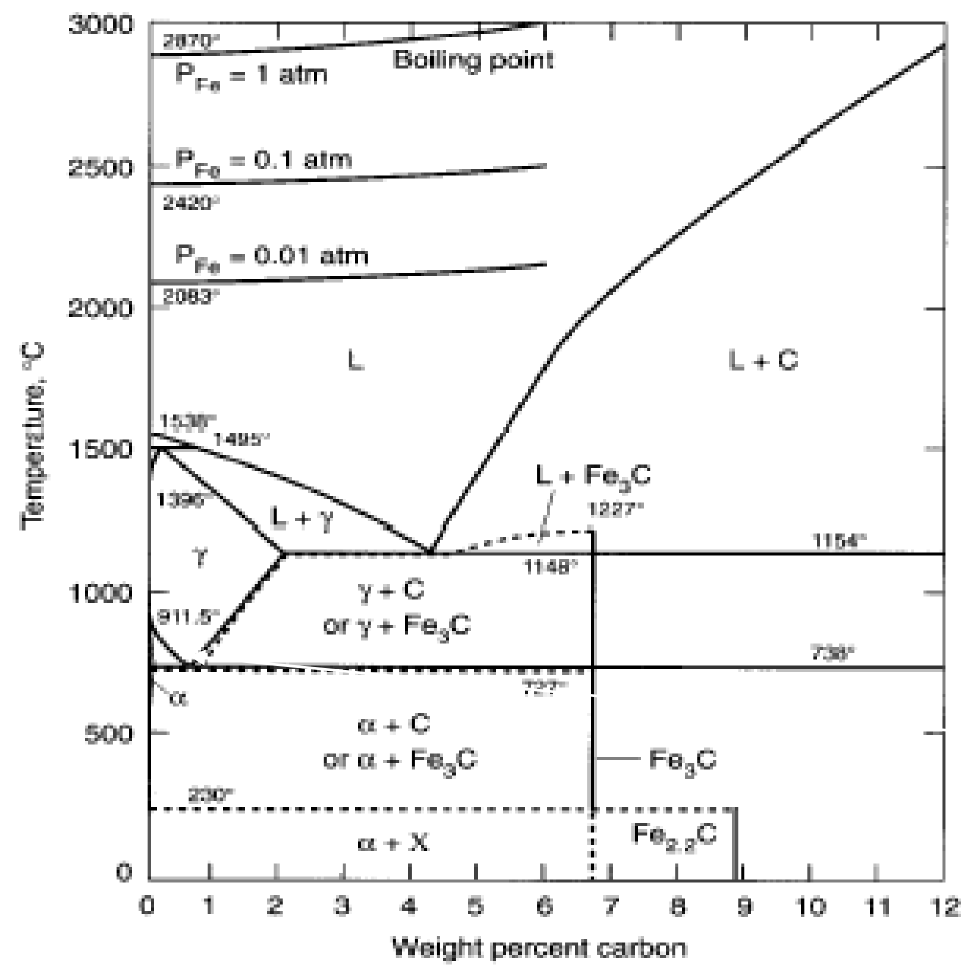
  \- ***growth***, which is thermally activated process, typically described by Arrhenius function
- Note that for many practical engineering materials we must account for additional factors, such as ***mechanical strain*** associated with solid-state transformation

Diffusion-dependent PT with changing of phase composition

Example:

Eutectoid Transformation in Steels

Iron Carbon (Fe–C) System: Eutectoid Reaction



- ***Iron*** are alloys with less than 0.008 wt% of carbon
- ***Steels*** are carbon-iron alloys with carbon in the range 0.008 wt.% to2.14%.
- ***Cast irons*** contain 2.14 – 6.7wt% of carbon
- Iron and carbons combined to form ***Fe-Fe$_3$C*** at the 6.67 % C end of the diagram.

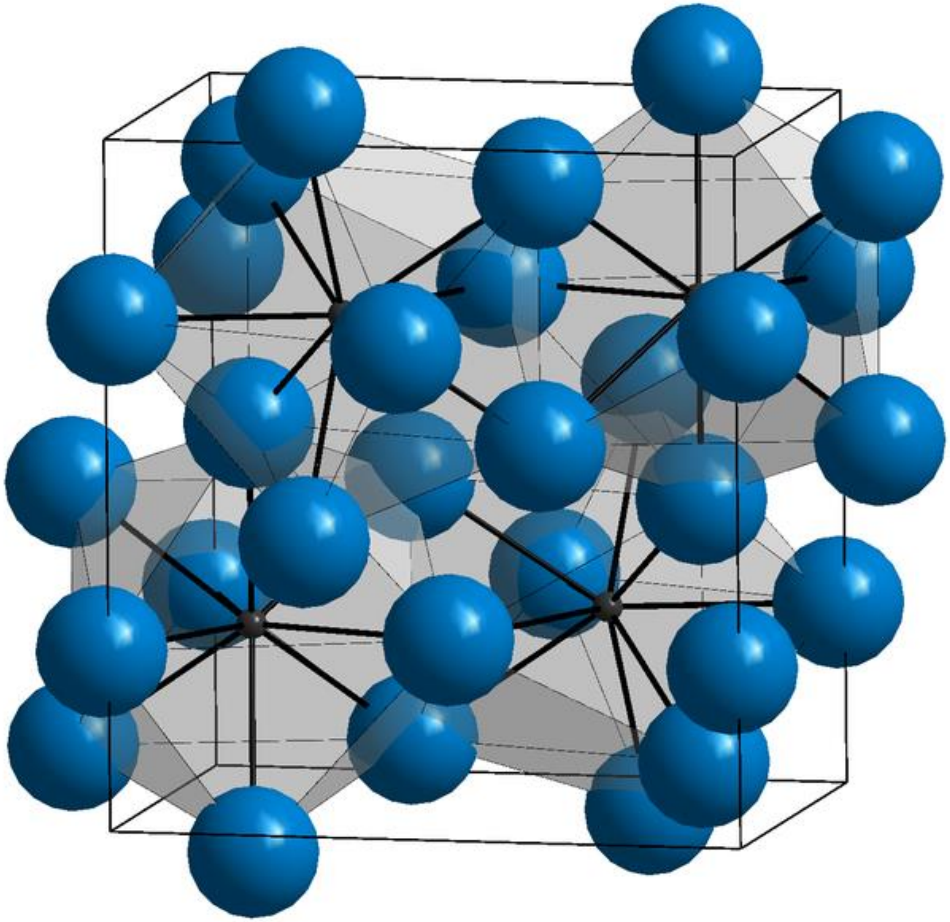
- **Eutectoid**: 0.76 wt%C, 727°C

  $\gamma \Leftrightarrow \alpha(0.022\text{wt\%C}) + Fe_3C$

- **Eutectic**: 4.30 wt%C, 1147°C

  $L \Leftrightarrow \gamma\ (2.14\ \text{wt\%C}) + Fe_3C$

Cementite Crystal Structure



Iron carbide is a chemical compound with the formula Fe_3C (or Fe_2C:Fe),

orthorhombic crystal structure

Iron atoms are blue, carbon - black

Eutectoid Reaction: Pearlite

- **Eutectoid** transformation:

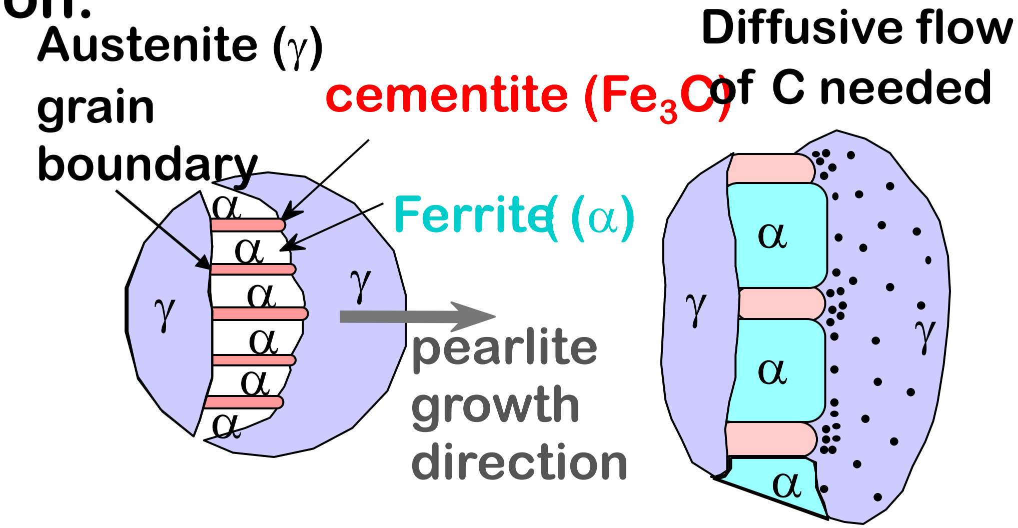
T_E=727 °C

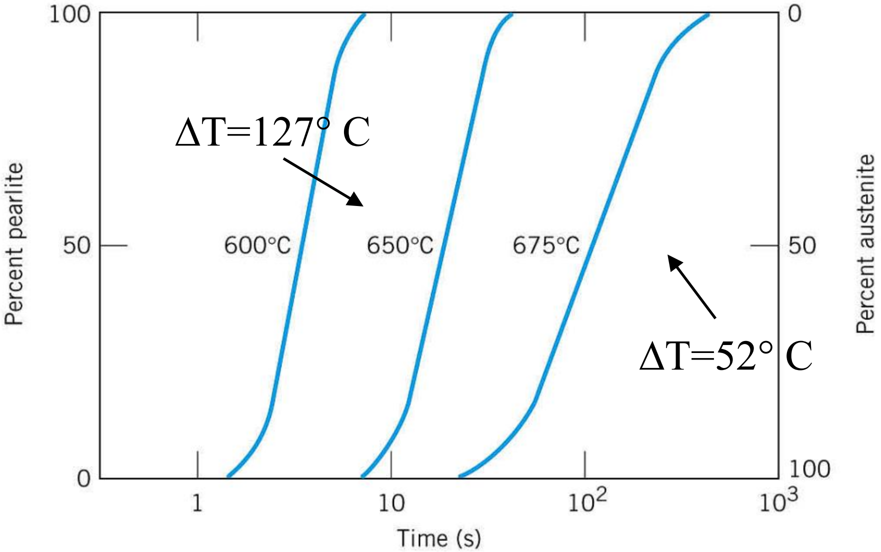
$$\gamma \Rightarrow \alpha + Fe_3C$$

0.76wt%C

0.022wt%C

6.7wt%C

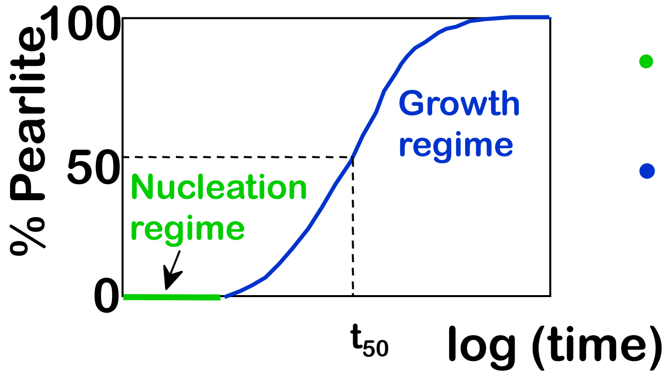




- Larger under cooling, ΔT=T_E-T, leads to faster transformation

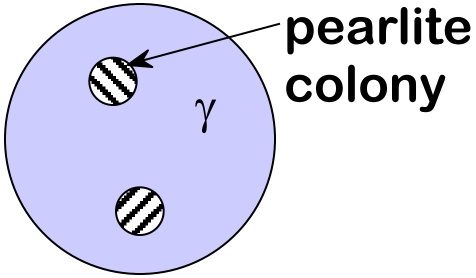
NUCLEATION AND GROWTH

- Again: transformation rate is a result of nucleation <u>and</u> growth of crystals.



- In general nucleation rate increases ~ ΔT
- Growth rate increases ~T

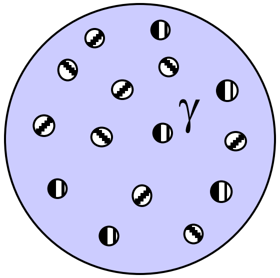
- **<u>Examples:</u>**



T just below T_E

Nucleation rate low

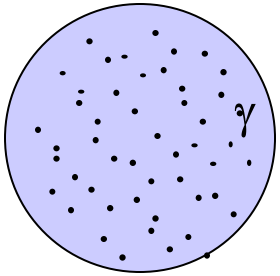
Growth rate high



T moderately below T_E

Nucleation rate med.

Growth rate med.



T way below T_E

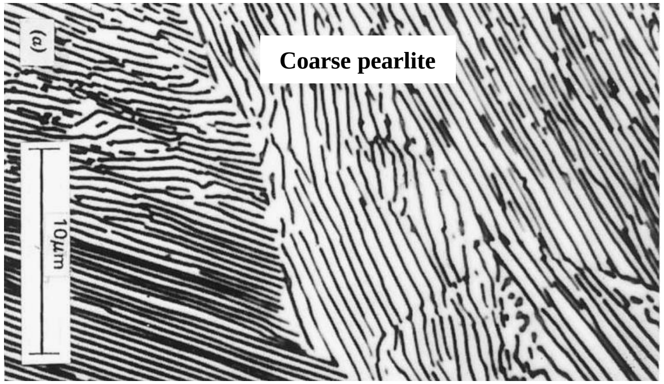
Nucleation rate high

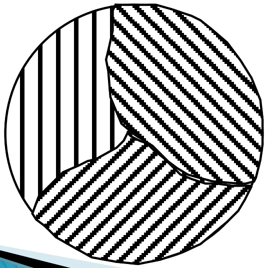
Growth rate low

PEARLITE MORPHOLOGY

Two cases:

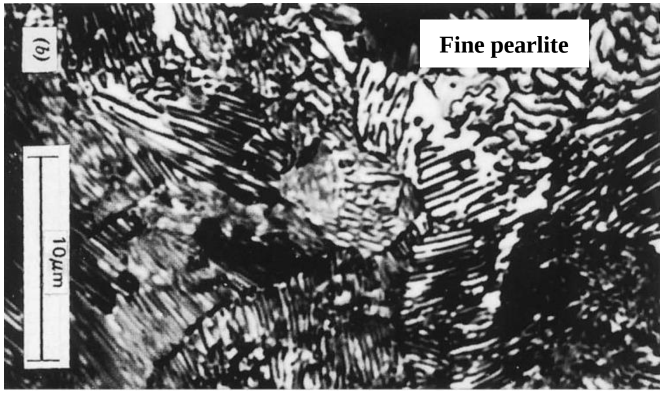
- e.g. $600^\circ < T_{transf} < 727^\circ C$
  --Larger T: diffusion is faster
  --Pearlite is coarser.

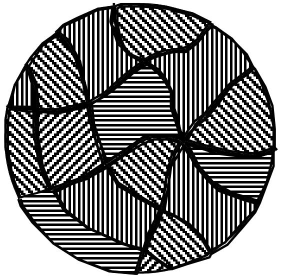




- Smaller ΔT: colonies are larger

- $540\,^\circ C < T_{transf} < 600^\circ C$
  --Smaller T: diffusion is slower
  --Pearlite is finer.





- Larger ΔT: colonies are smaller

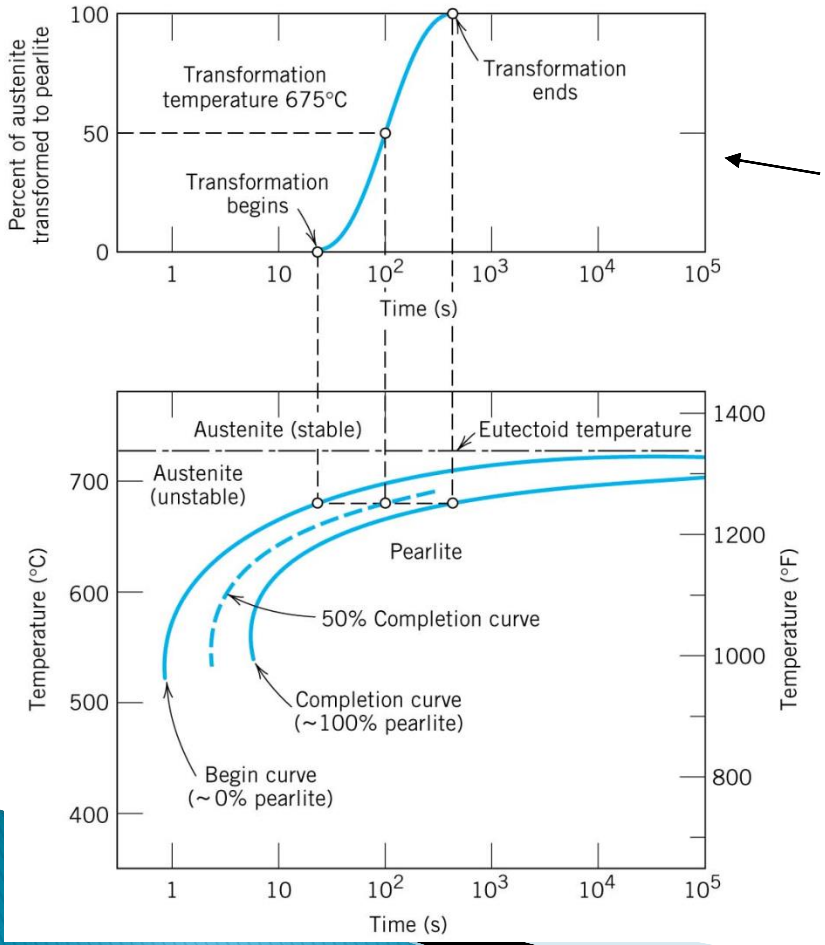
Temperature-Time-Transformation (TTT) Diagram

Example:

TTT diagrams (or isothermal transformation diagrams) for eutectoid reaction in Fe-C System

Eutectoid Reaction: Temperature–Time–Transformation (TTT) Diagram

- **<u>Example:</u> TTT diagrams or isothermal transformation diagrams for eutectoid reaction in Fe-C System**

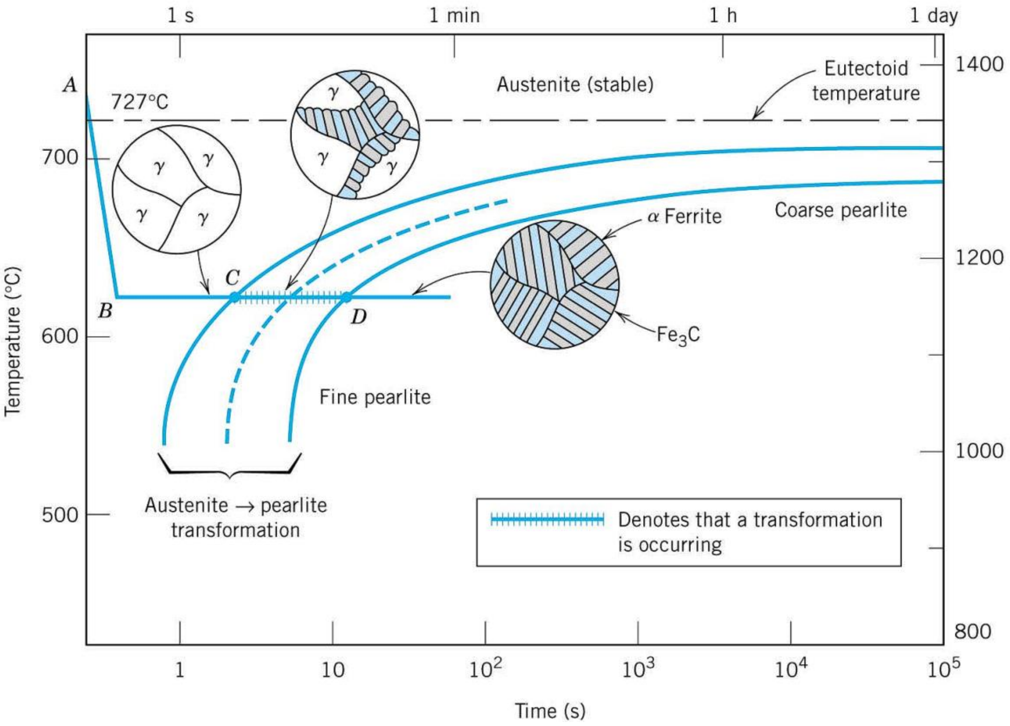


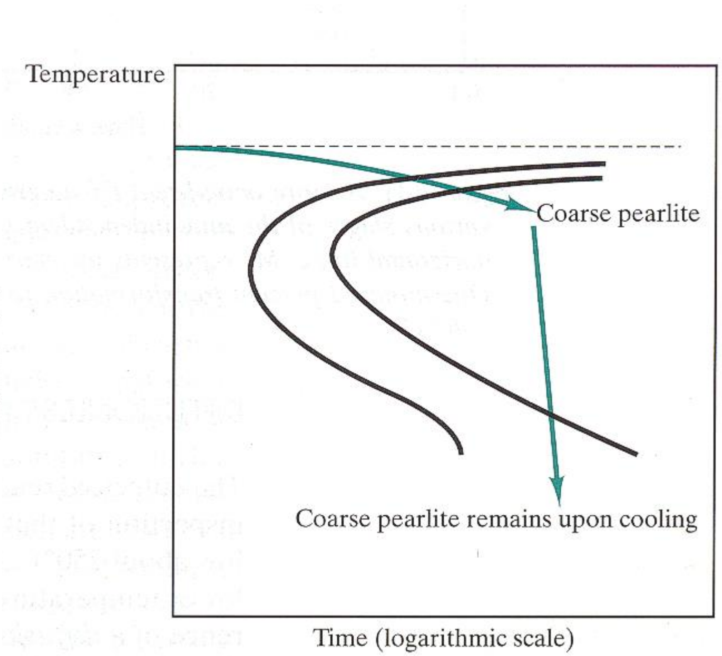
- TTT diagram is generated from numbers of percentage transformation-versus-time (PTT) diagrams. One of the PTT is shown on the figure.

- Note that at T=675°C it takes 105 s for full transformation, while at T=540 °C only 3 seconds!!

- And now you know why?!!

TTT Diagram and Steel Structure





At relatively high T < T_E ***diffusion is fast*** enough to produce relatively long and thick lamellae.

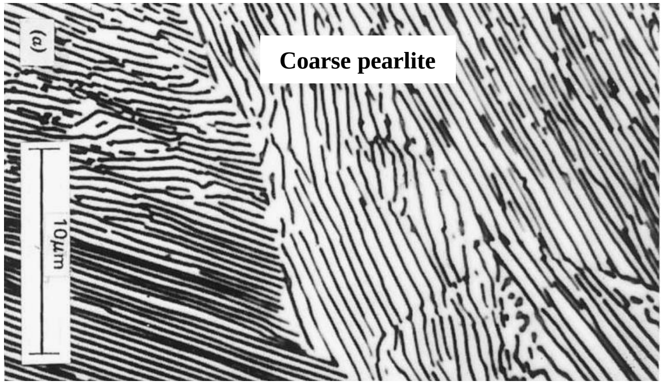
- A slow cooling path leads to coarse pearlite formation, which once formed, remains stable upon further cooling

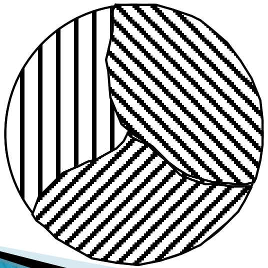
Q: What will be at **higher under cooling** ? Answer: **Fine pearlite** !!

PEARLITE MORPHOLOGY

Two cases:

- e.g. 600 ° <T_{transf}<727 ° C
  --Larger T: diffusion is faster
  --Pearlite is coarser.





- Smaller ΔT: colonies are larger

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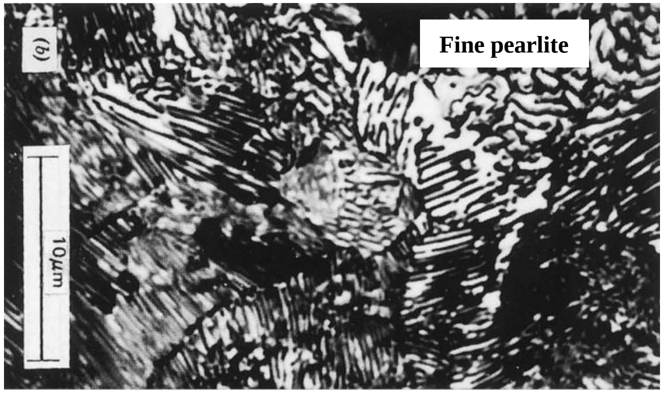
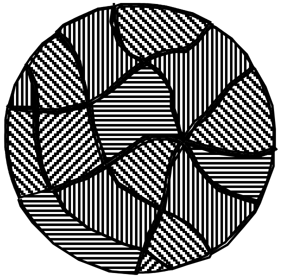




- Larger ΔT: colonies are smaller

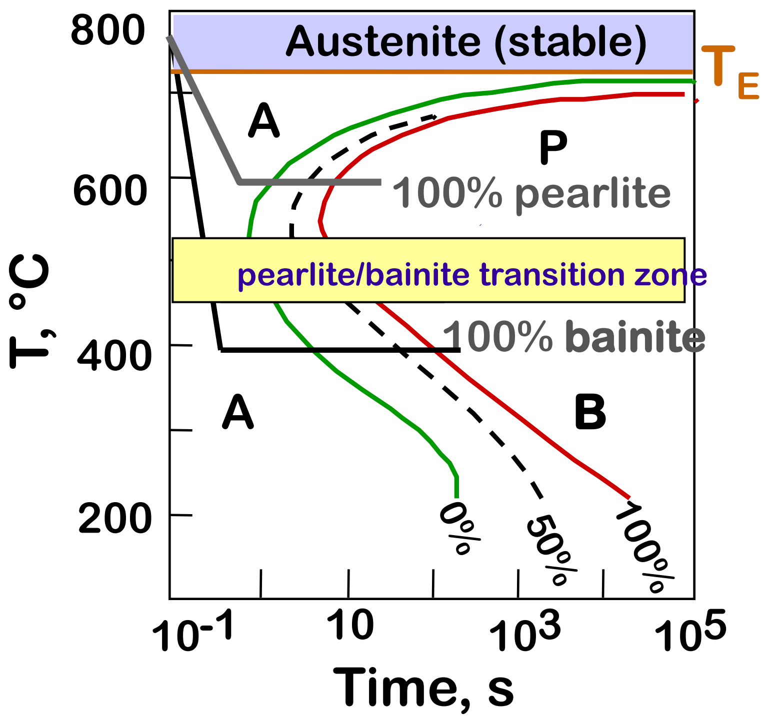
And if one increases ΔT even more!?

More fine Microstructures will form:

Bainite !!

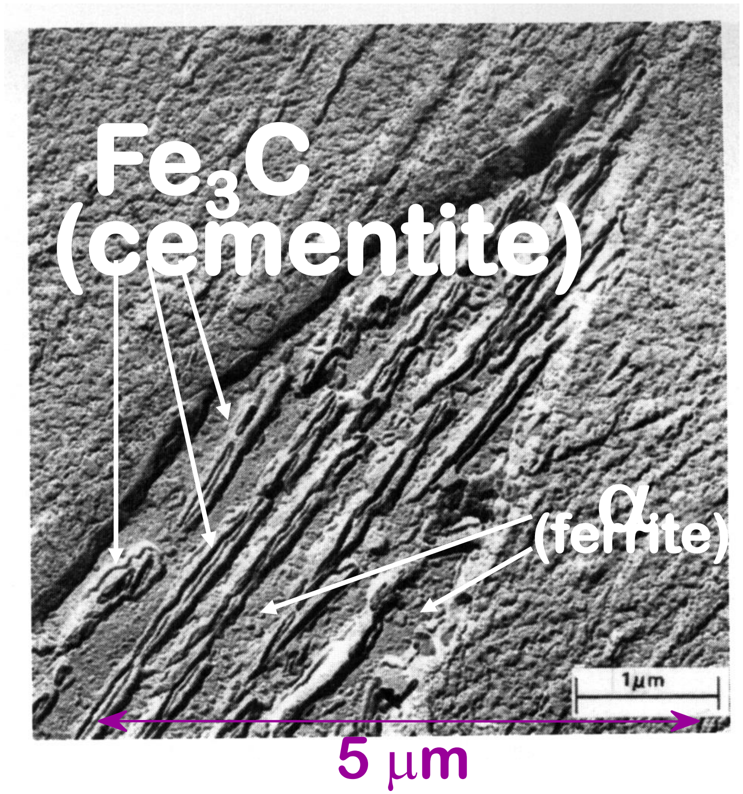
OTHER PRODUCTS: Fe–C SYSTEM (1)

- **TTT Diagram**



Bainite – a fine structure formed at temperatures below 400° C

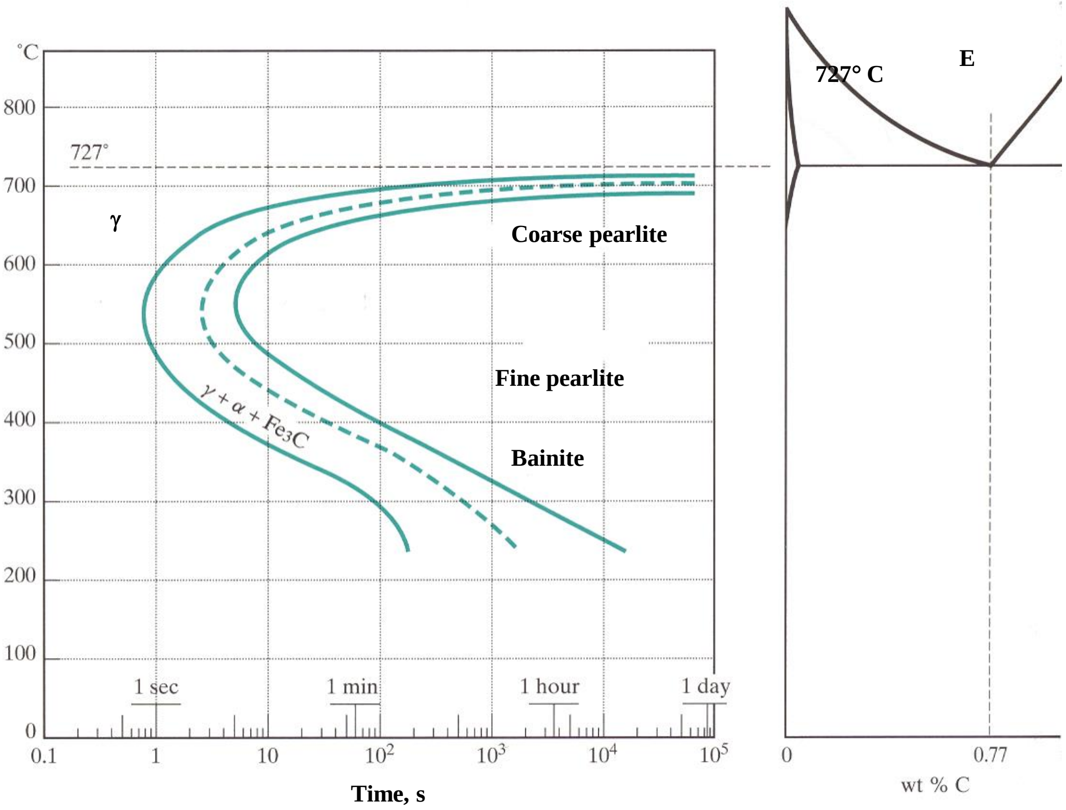
-bainite formation is also *diffusion dependent* process

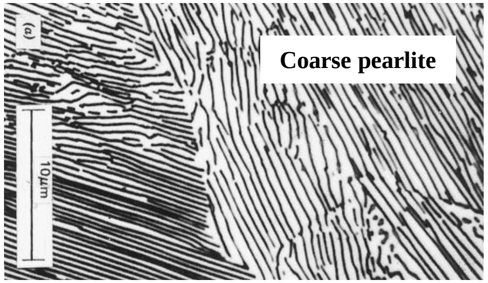


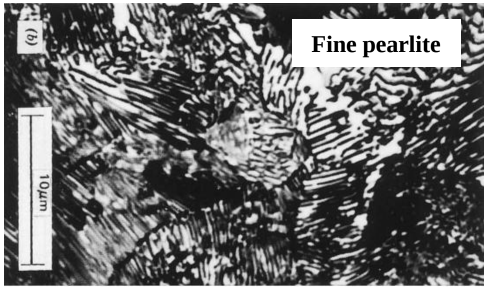
Example of bainite microstructure: α–ferrite strips with long cementite (Fe_3C) rods

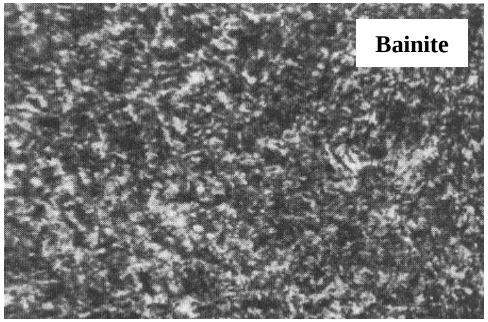
Summary: TTT Diagram and Steel Structure

- **Structure of products depends on the its specific *thermal history***





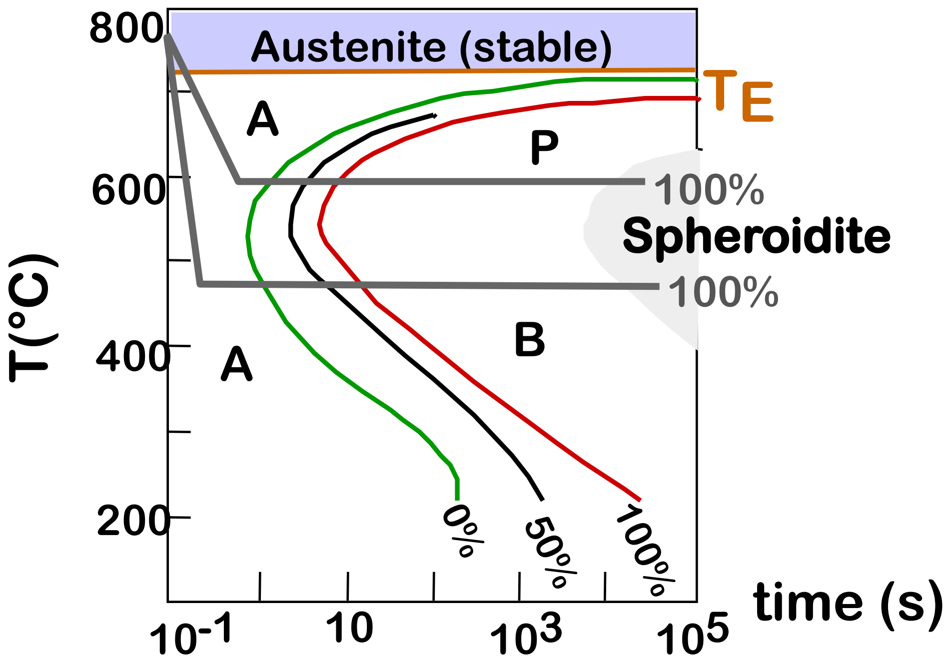




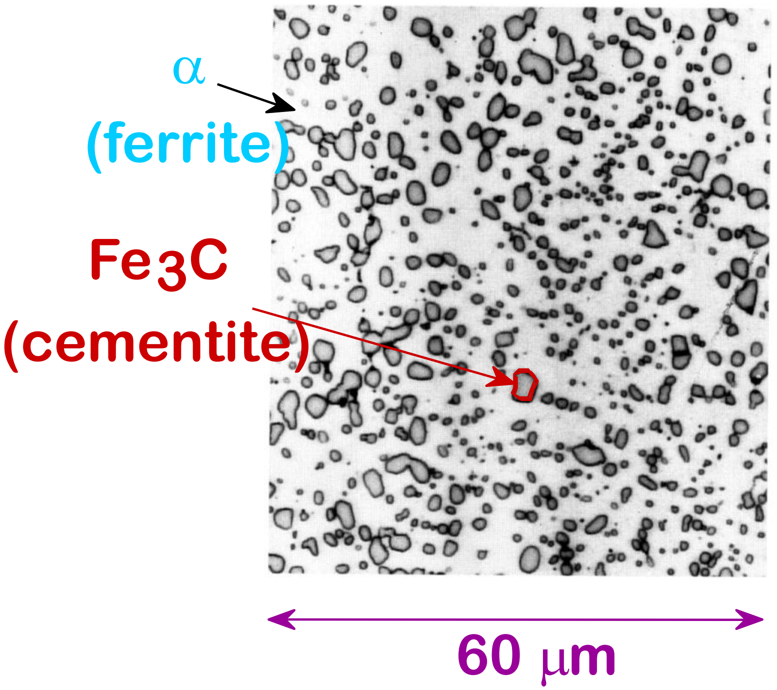
- Important! Although they possess ***different*** microstructure they do have the ***same*** phase composition and relative amount of phases

ONE MORE PRODUCT: Fe–C SYSTEM

- **TTT Diagram**



- ***Spheroidite*** is a structure formed as a result of long term (> 24 h) heat treatment of bainite or pearlite structures



<u>Spheroidite microstructure</u>: spherical cementite (Fe_3C) particles in a – iron matrix;

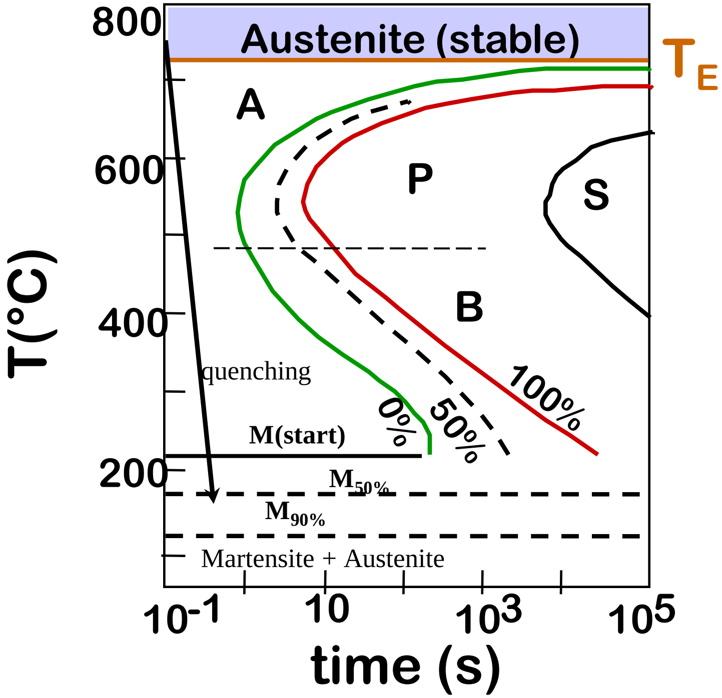
• **Driving force** of PT is the ***reduce of interfacial area***, which proceeds by additional carbon ***diffusion*** with ***no change*** in the composition and relative amount of phases – thus it is ***Simple*** Diffusion Dependent transformation!

Diffusionless (Displacive) PT

Example: ***Martensitic transformation*** in eutectoid steels

Diffusionless Transformations

- ***Martensitic transformation*** is a ***diffusionless spontaneous*** process occurring when ***quenching*** rate is rapid enough to prevent diffusion controlled mechanisms.
- Example: Specific transformation in eutectoid steel during quenching of austenite to temperature lower than ~215° C



- **TTT Diagram**

- Martensitic microstructure: the martensitic phase needles in γ-Fe matrix

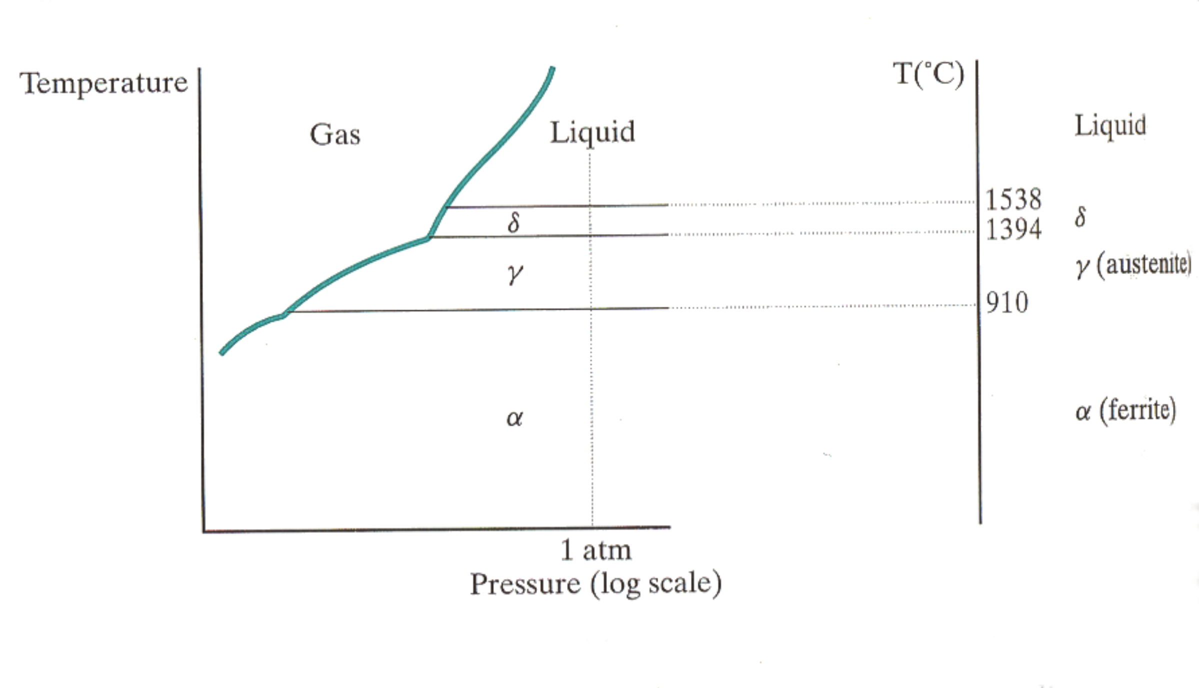
What is the nature of this unique PT?
What is the PT rate?

Pure Iron Phase Diagrams (P=1atm)

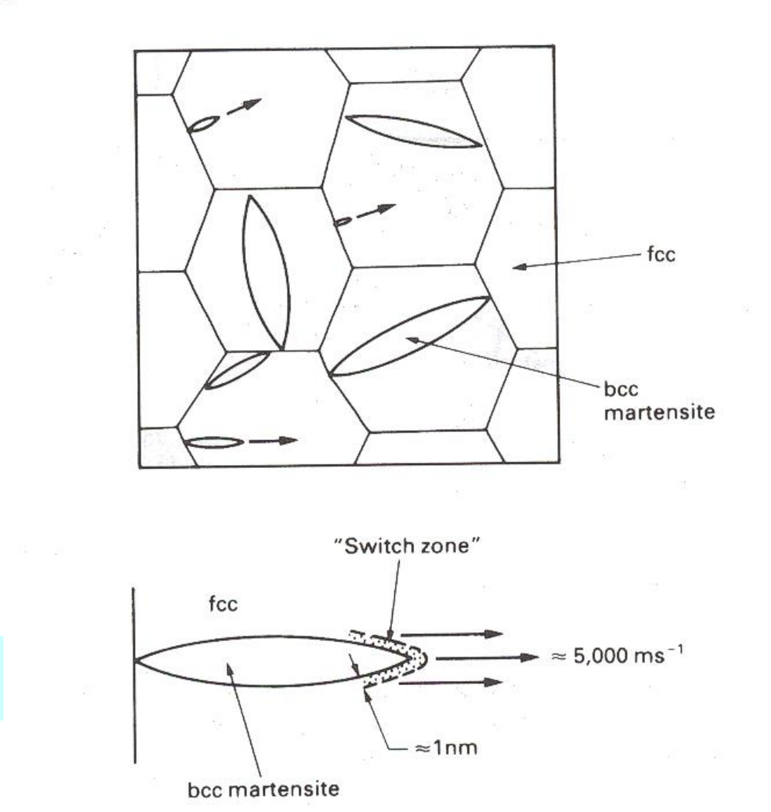
For simplicity let us consider first pure iron system.
At temperature (~910 C) we do have transformation:

γ (f.c.c) $\rightarrow$ α (b.c.c.)

which is also ***diffusionless***!!!



The Displacive F.C.C. → B.C.C.

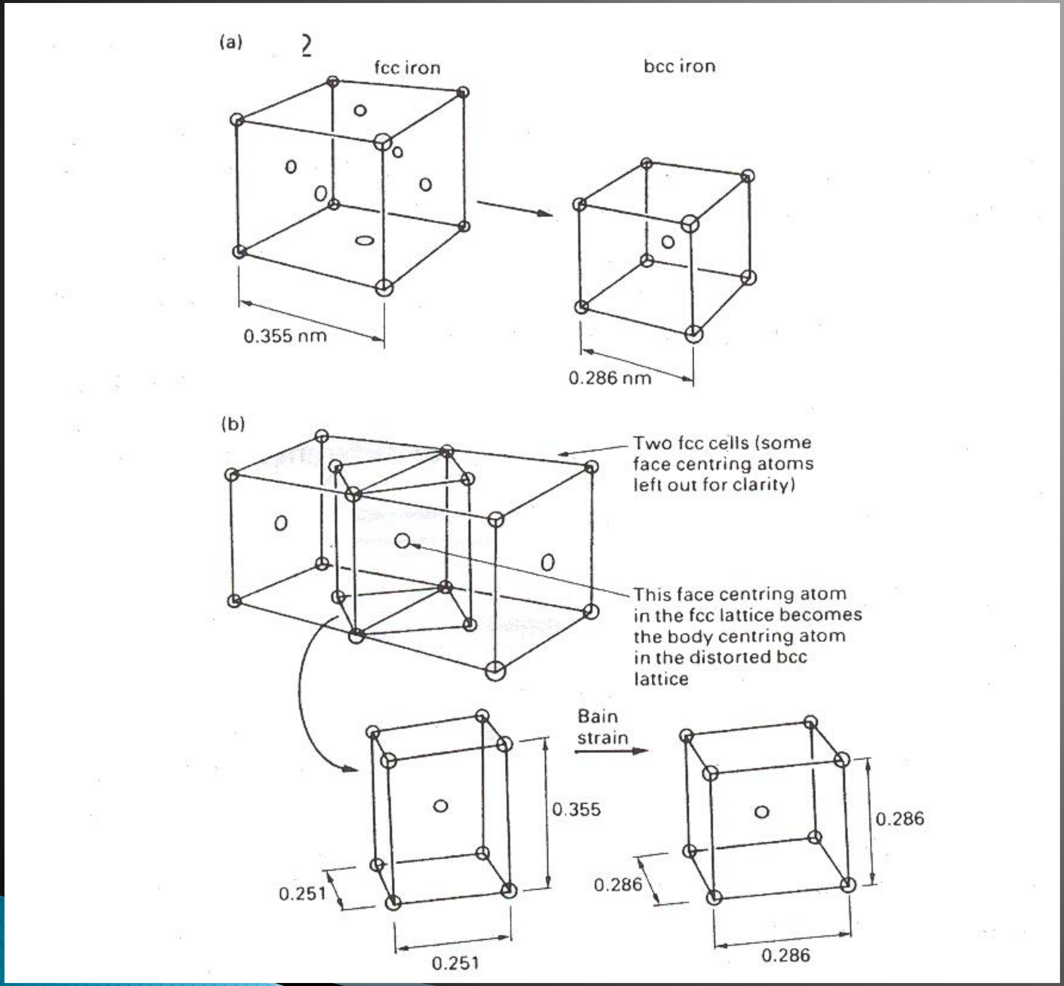


Heterogeneous nucleation is faster !!

Speed of sound !!

B.C.C. lenses nucleate at F.C.C. ***grain boundaries*** and grow almost ***instantaneously*** until they hit the next grain boundary

And what is going on the level of the *Crystalline Lattice*?



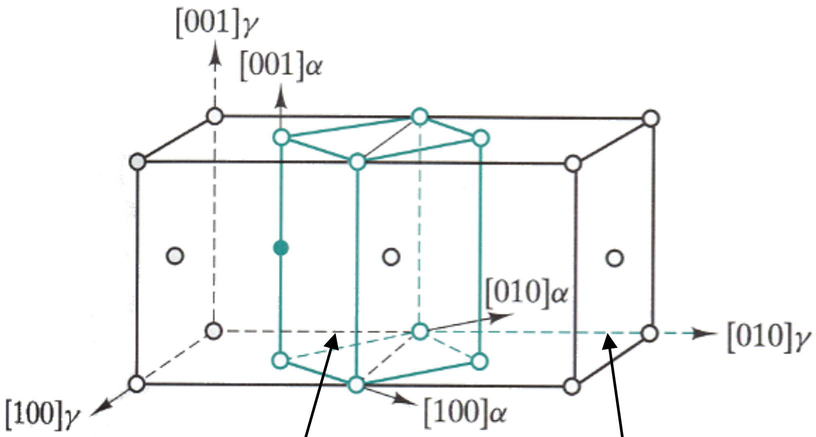
The unit cells of
the F.C.C and B.C.C. iron

Two adjacent F.C.C. cells
make a distorted B.C.C. cell

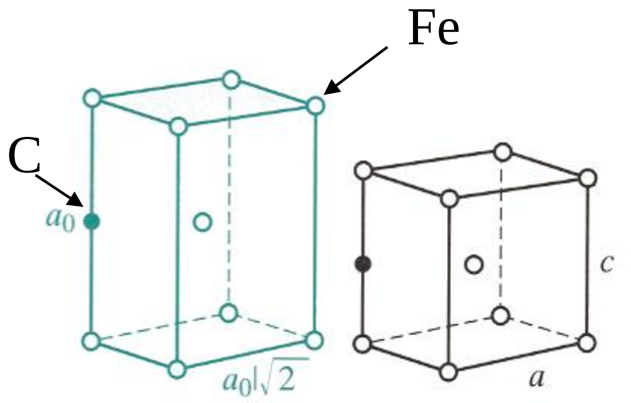
If this is subjected to the
“Brain strain” it becomes
an undistorted B.C.C. cell

Diffusionless Transformations

- **For steels, the martensitic transformation involves the *sudden reorientation*** of C and Fe atoms from fcc structure of γ-Fe to a body-centered tetragonal (bct) unit cell of matrensite



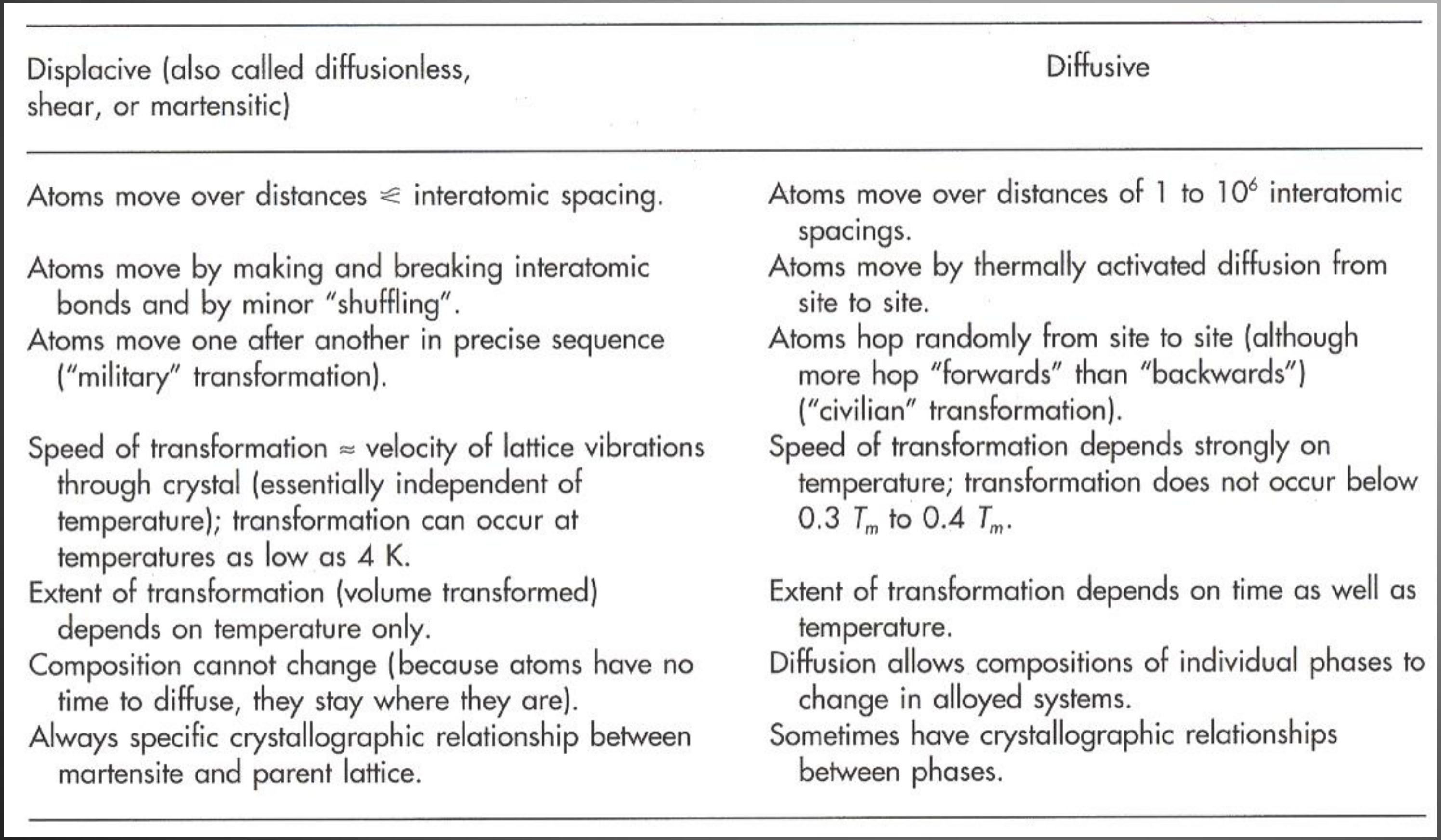
The bct unit cell relative to the fcc lattice



The bct unit cell before and after the transformation

Note: the open circles are Fe atoms, while the solid circles represent an *interstitially dissolved* carbon atoms

Characteristics of Transformations

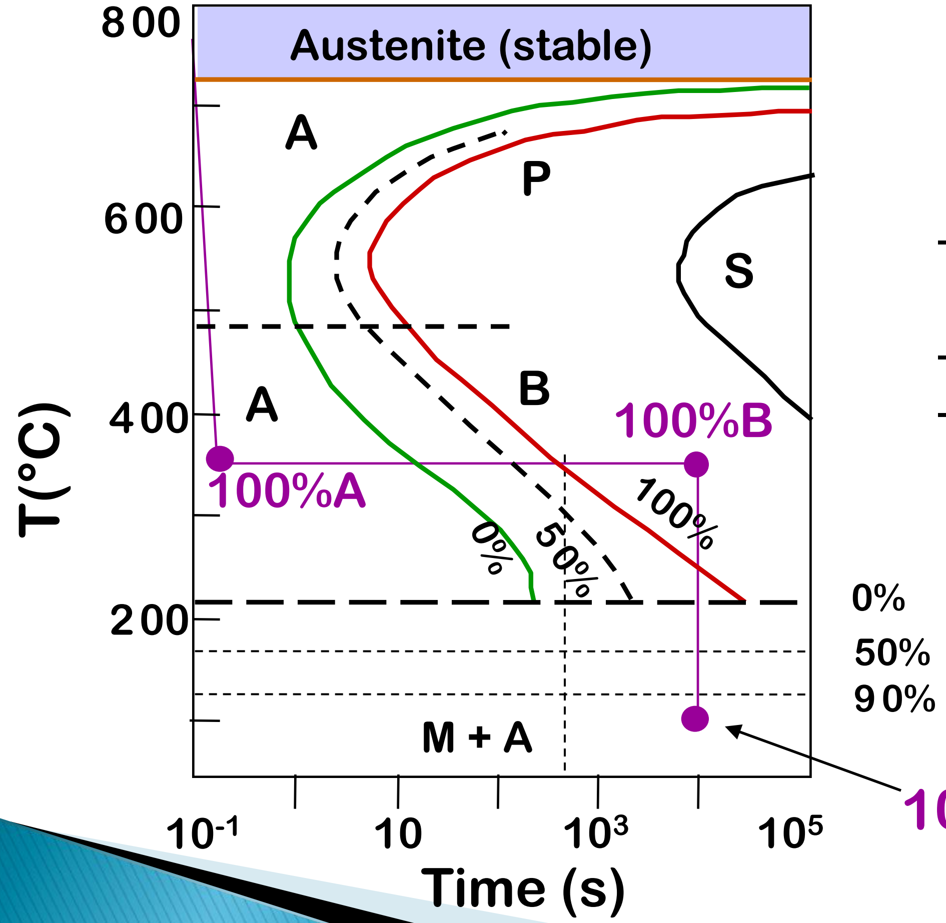


Displacive (also called diffusionless, shear, or martensitic)	Diffusive
Atoms move over distances $\leqslant$ interatomic spacing.	Atoms move over distances of 1 to 10^6 interatomic spacings.
Atoms move by making and breaking interatomic bonds and by minor "shuffling".	Atoms move by thermally activated diffusion from site to site.
Atoms move one after another in precise sequence ("military" transformation).	Atoms hop randomly from site to site (although more hop "forwards" than "backwards") ("civilian" transformation).
Speed of transformation ≈ velocity of lattice vibrations through crystal (essentially independent of temperature); transformation can occur at temperatures as low as 4 K.	Speed of transformation depends strongly on temperature; transformation does not occur below 0.3 T_m to 0.4 T_m.
Extent of transformation (volume transformed) depends on temperature only.	Extent of transformation depends on time as well as temperature.
Composition cannot change (because atoms have no time to diffuse, they stay where they are).	Diffusion allows compositions of individual phases to change in alloyed systems.
Always specific crystallographic relationship between martensite and parent lattice.	Sometimes have crystallographic relationships between phases.

COOLING EX: Fe-C SYSTEM (1)

- $C_o = C_{eutectoid}$

Case I



100% Bainite

Temperature-time path # 1:

Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}

-At 350 C γ-Fe isothermally transforms to bainite in ~600 s

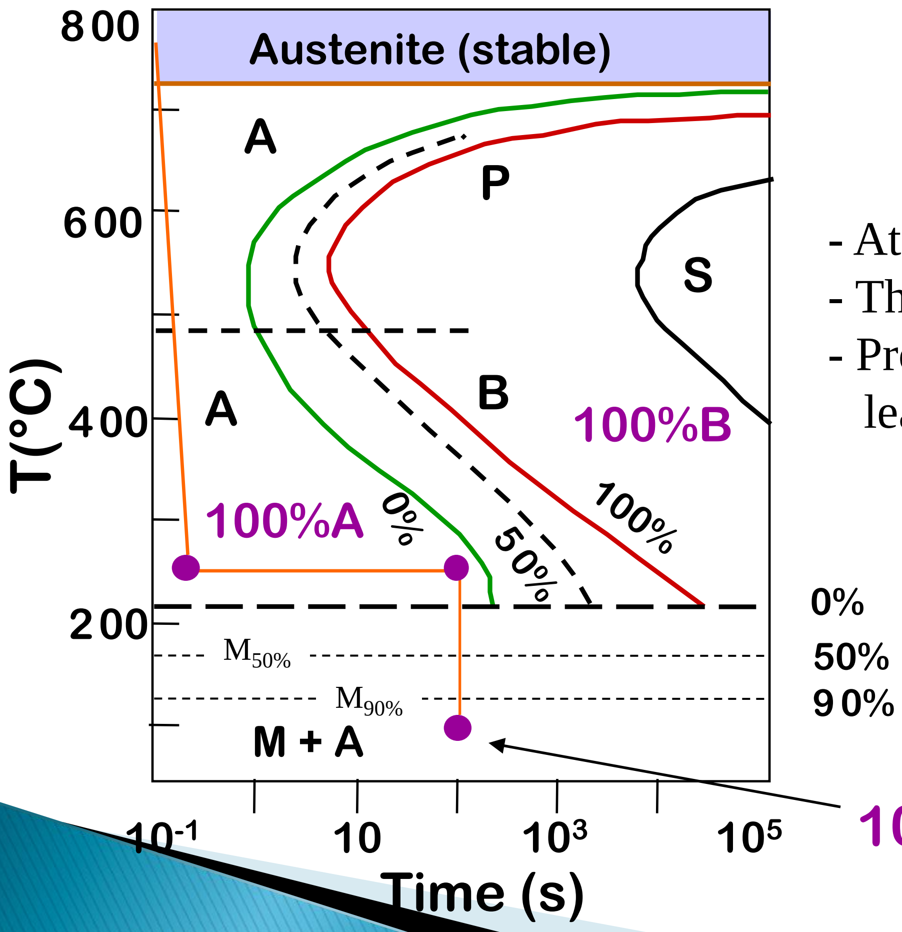
-Thus in 10^4 s 100% of specimen is bainite

-No other transformations are possible during quenching up to room temperature

COOLING EX: Fe–C SYSTEM (2)

- $C_o = C_{eutectoid}$

Case II



100% Martensite

Temperature-time path # 2:

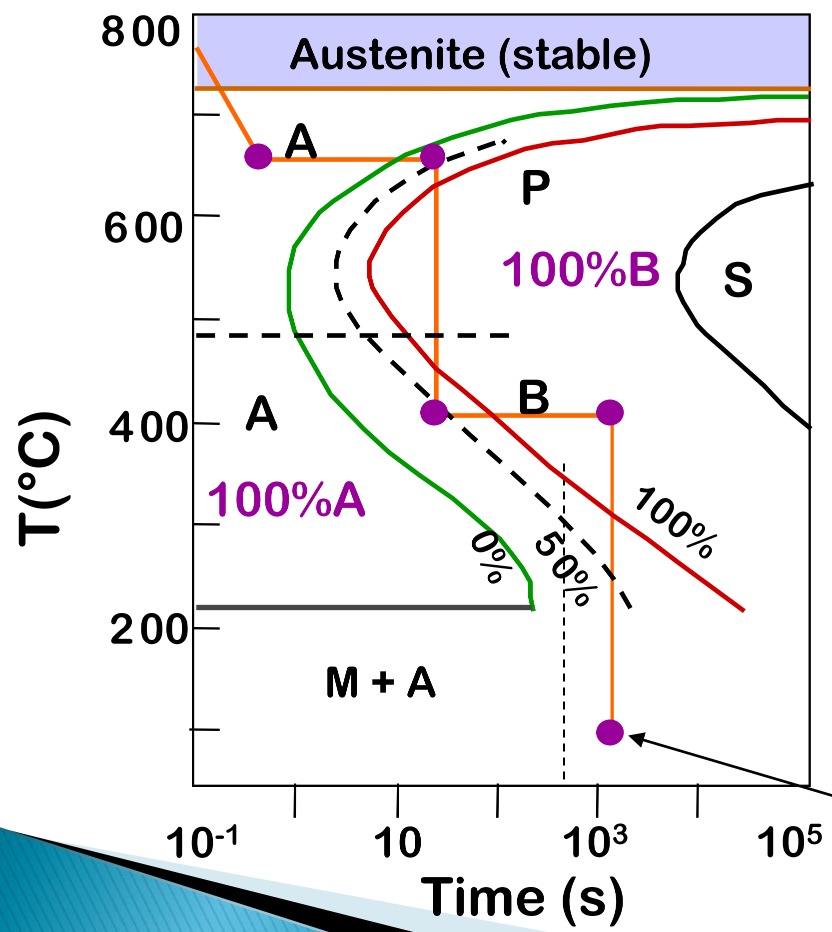
Rapid cool to:	Hold for:	Rapid cool to:
250°C	10^2s	T_{room}

- At 250 C it takes ~150 s to transform to bainite
- Thus in 10^2 s 100% of specimen is still austenite
- Progressive rapid cooling to room temperature leads to the formation of 100 % of martensite

COOLING EX: Fe–C SYSTEM (1)

- $C_o = C_{eutectoid}$

Case III



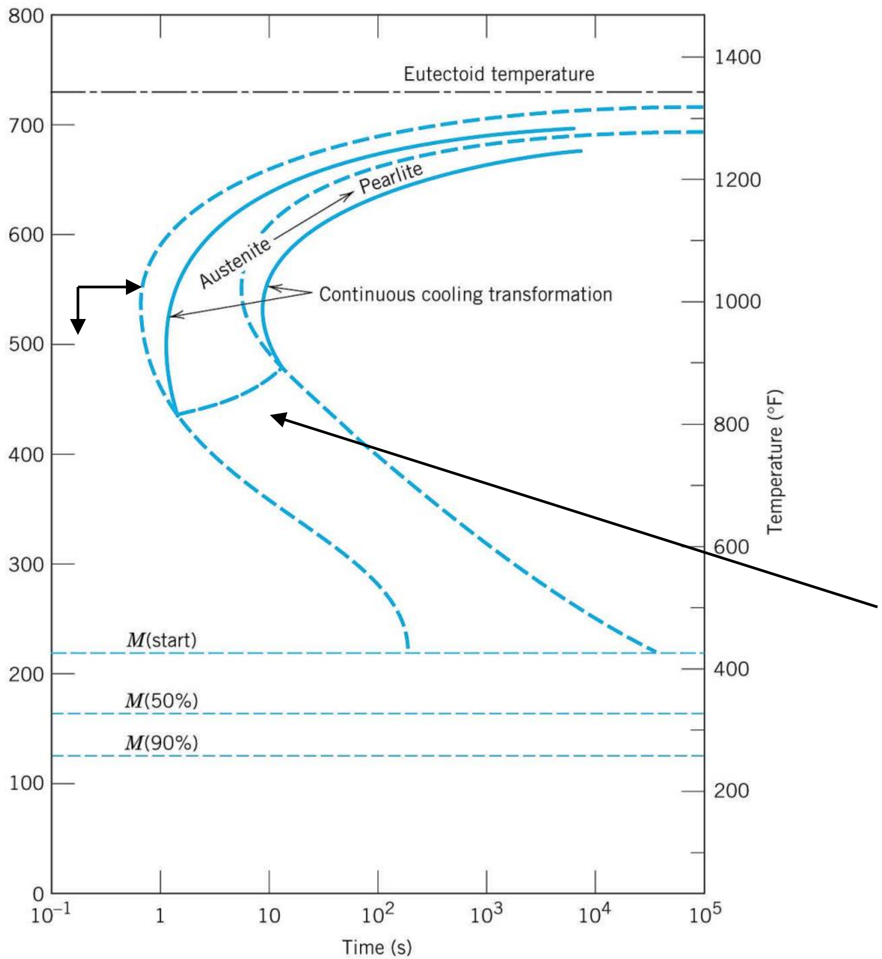
Temperature-time path # 1:

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
650°C	20s	400°C	10^3s	T_{room}

-At 650°C in 7s γ-Fe begins isothermal transformation to pearlite and after 20s ~50% of specimen has pearlite structure;
- Rapid cooling to 400°C does not significantly contribute to the changing of phase composition
- While 10^3 s treatment at this temperature completely converts remaining austenite to bainite.
-Finally, cooling down to room temperature results in no further transformations occur.

50% Pearlite+ 50% Bainite

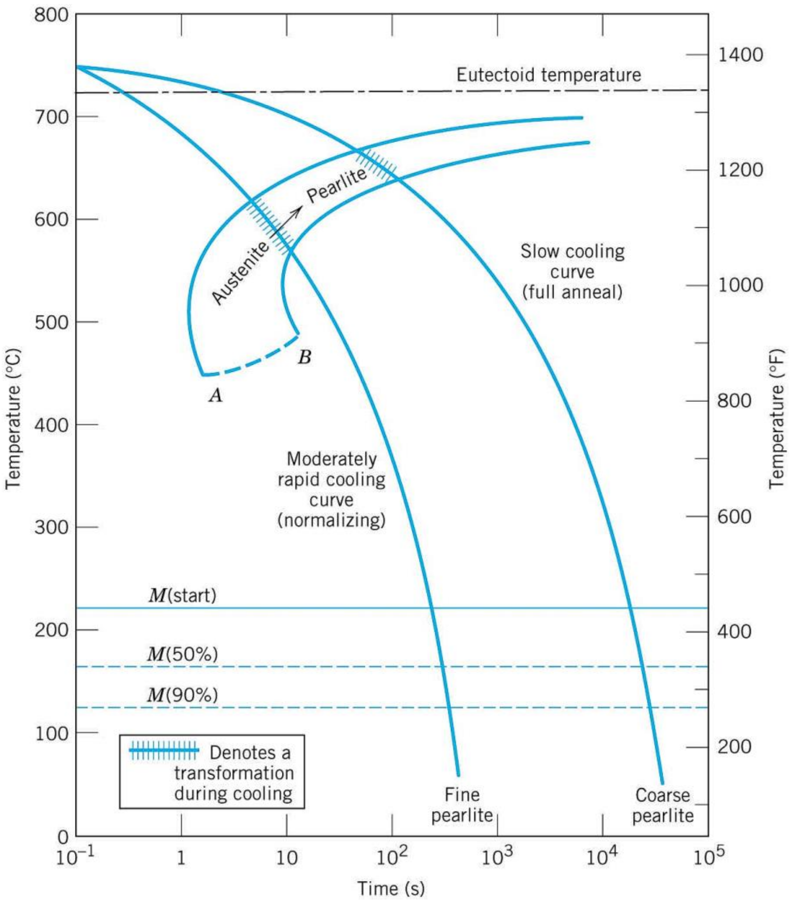
Continuous Cooling Transformation (CCT) Diagram

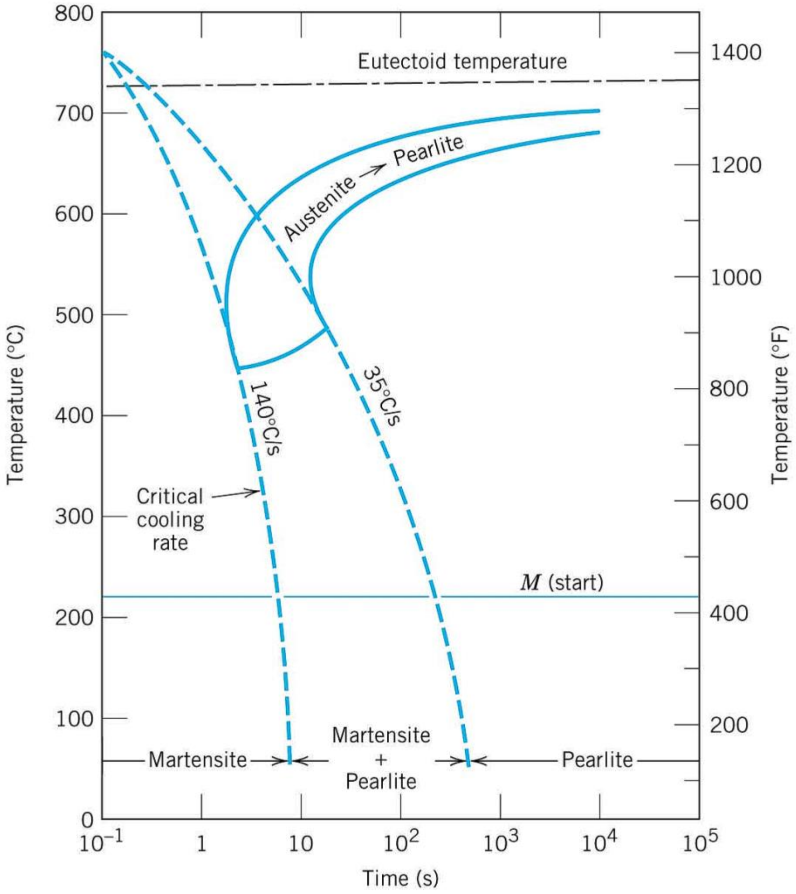


- The positions of transformation curves on CCT diagrams are shifted slightly ***downwards*** and towards the ***right*** as compared to TTT diagrams: the transformations start and end are delayed.

- Also, specifically for considered eutectoid composition in plane steel the ***bainite*** does not form during continuous cooling to room temperature.

CCT Diagram and Cooling Curves

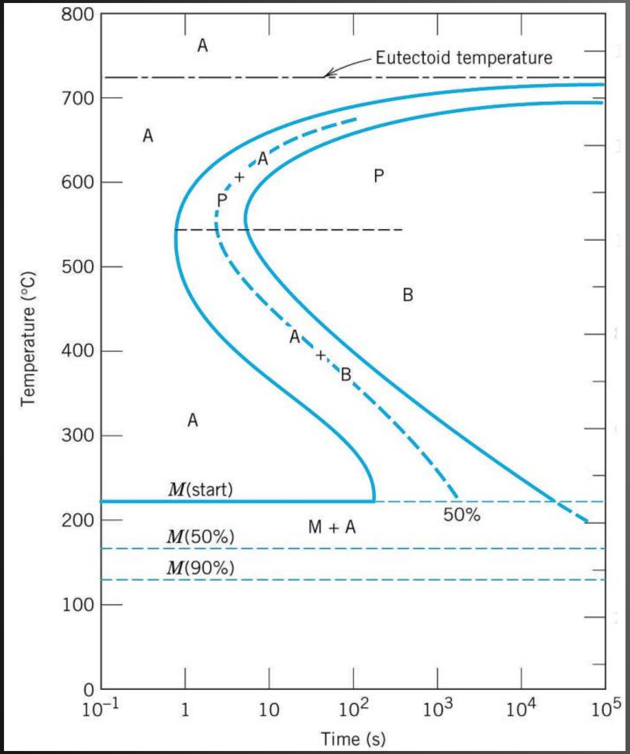




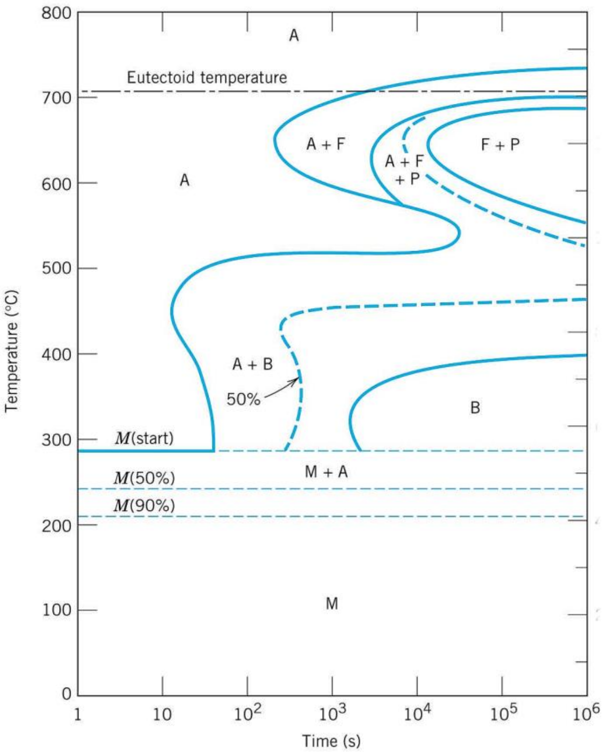
Microstructure depends on cooling rate:
slow cooling – ***coarse*** pearlite
moderately rapid cooling – ***fine*** pearlite

Critical cooling rates, ω, exist that define the characteristic regions of product microstructure: ω <35 C/s – pearlite;
ω >140C/s - martensite

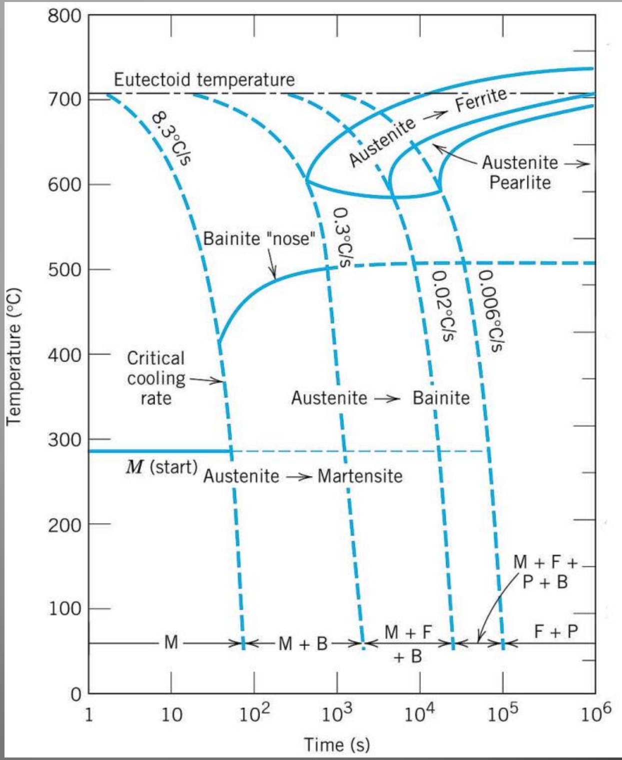
Transformation Diagrams and Alloying Elements



Plain carbon steel **:**
carbon is prime
alloying element



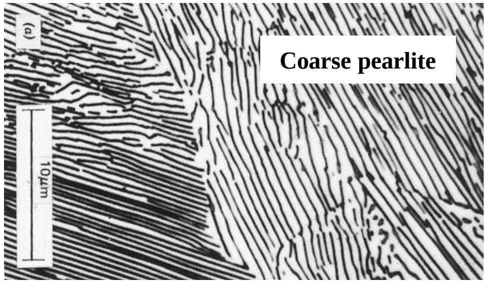
Alloy steel :
e.g. type 4340 with alloying
elements: ***Ni, Cr, Mo***



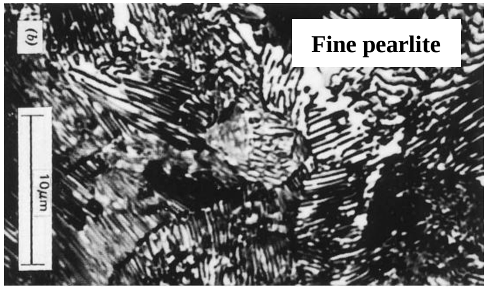
Critical cooling rates
for alloy steel: compare
with plane carbon steel

Mechanical Behavior of Iron Carbon Alloys and their Microstructures

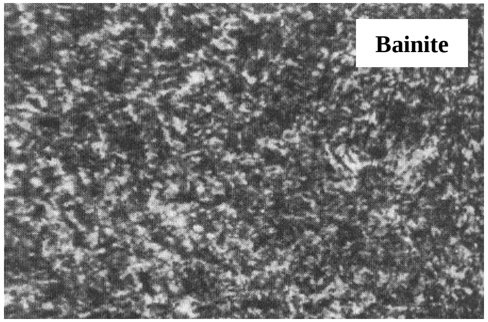
- Type of microstructures:
  - Pearlite
    - coarse
    - fine
  - Bainite
  - Spheroidite
  - Martensite

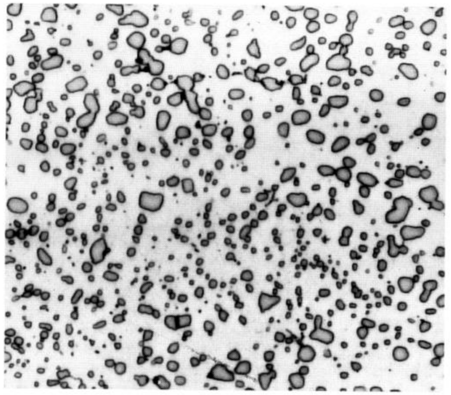


Coarse pearlite



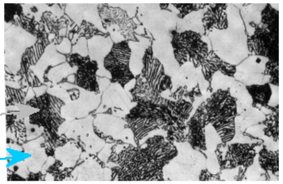
Fine pearlite


Bainite



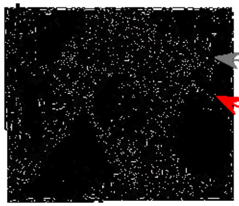
MECHANICAL PROP: Fe-C SYSTEM (1)

- **Effect of wt%C**



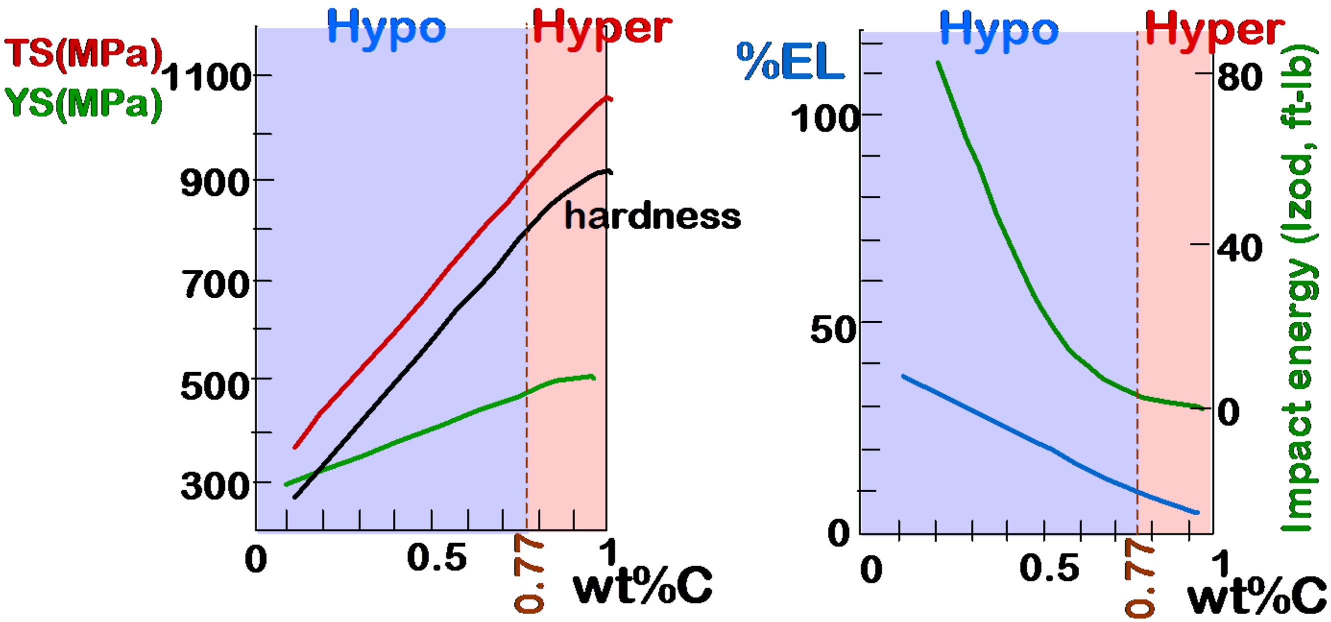
$C_o < 0.77$ wt%C

Hypoeutectoid



$C_o > 0.77$ wt%C

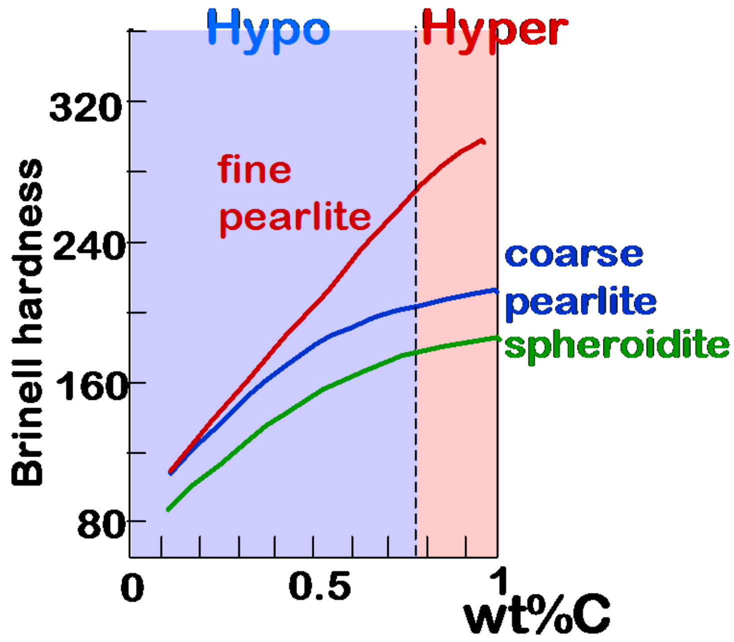
Hypereutectoid

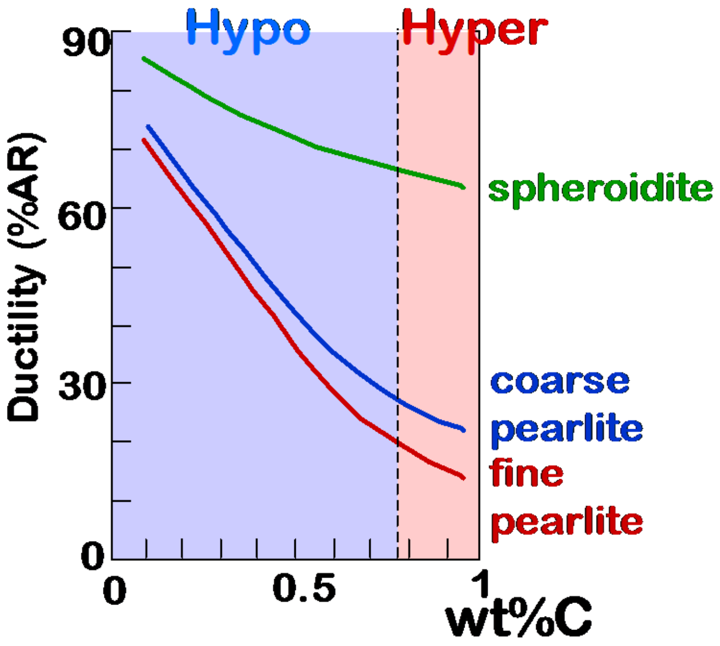


- **More wt%C: TS and YS increase, %EL decreases.**

MECHANICAL PROP: Fe-C SYSTEM (2)

- **Fine vs coarse pearlite vs spheroidite**

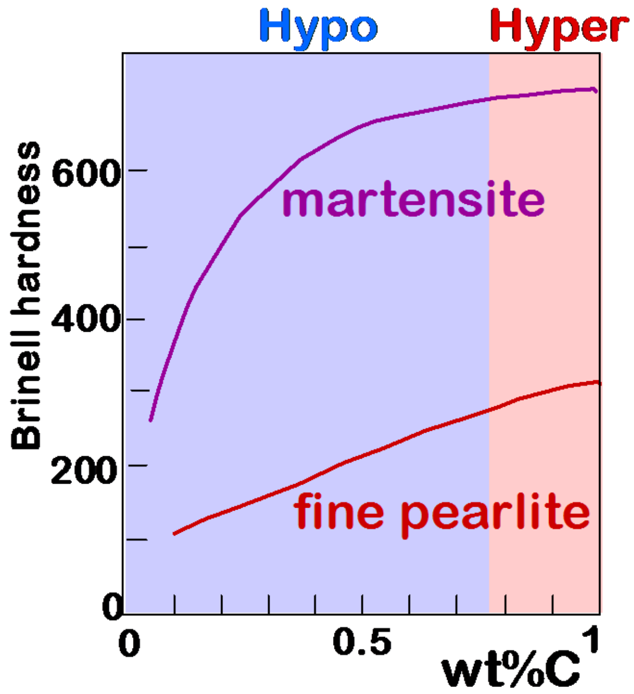




- **Hardness: fine > coarse > spheroidite**
- **%AR: fine < coarse < spheroidite**

MECHANICAL PROP: Fe–C SYSTEM (3)

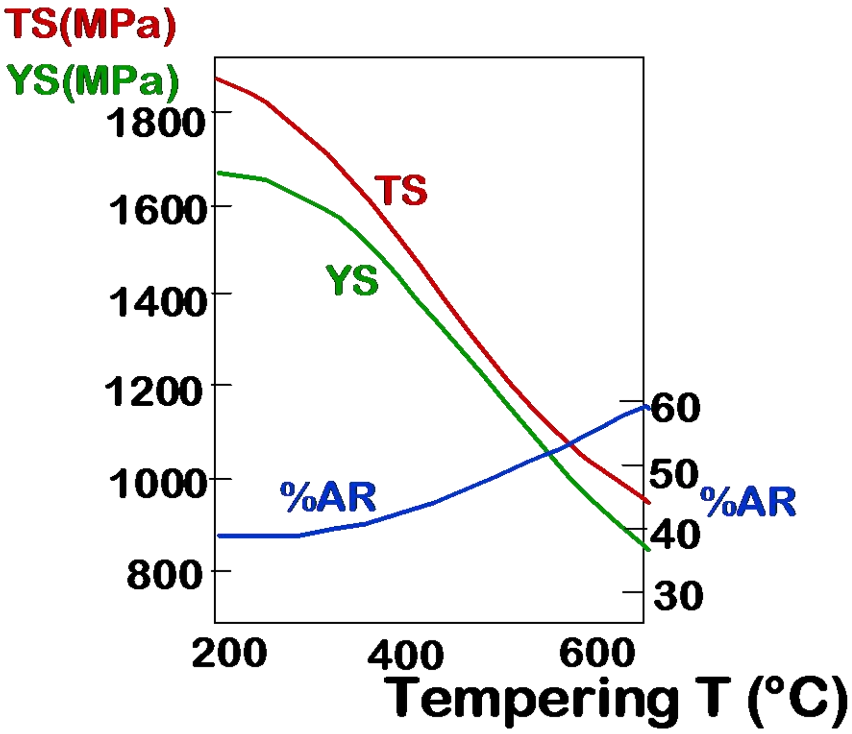
- **Fine Pearlite vs Martensite:**

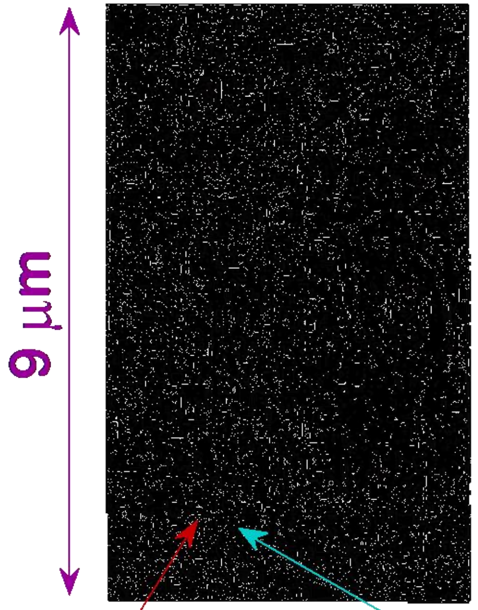


- **Hardness: fine pearlite << martensite.**

TEMPERING MARTENSITE

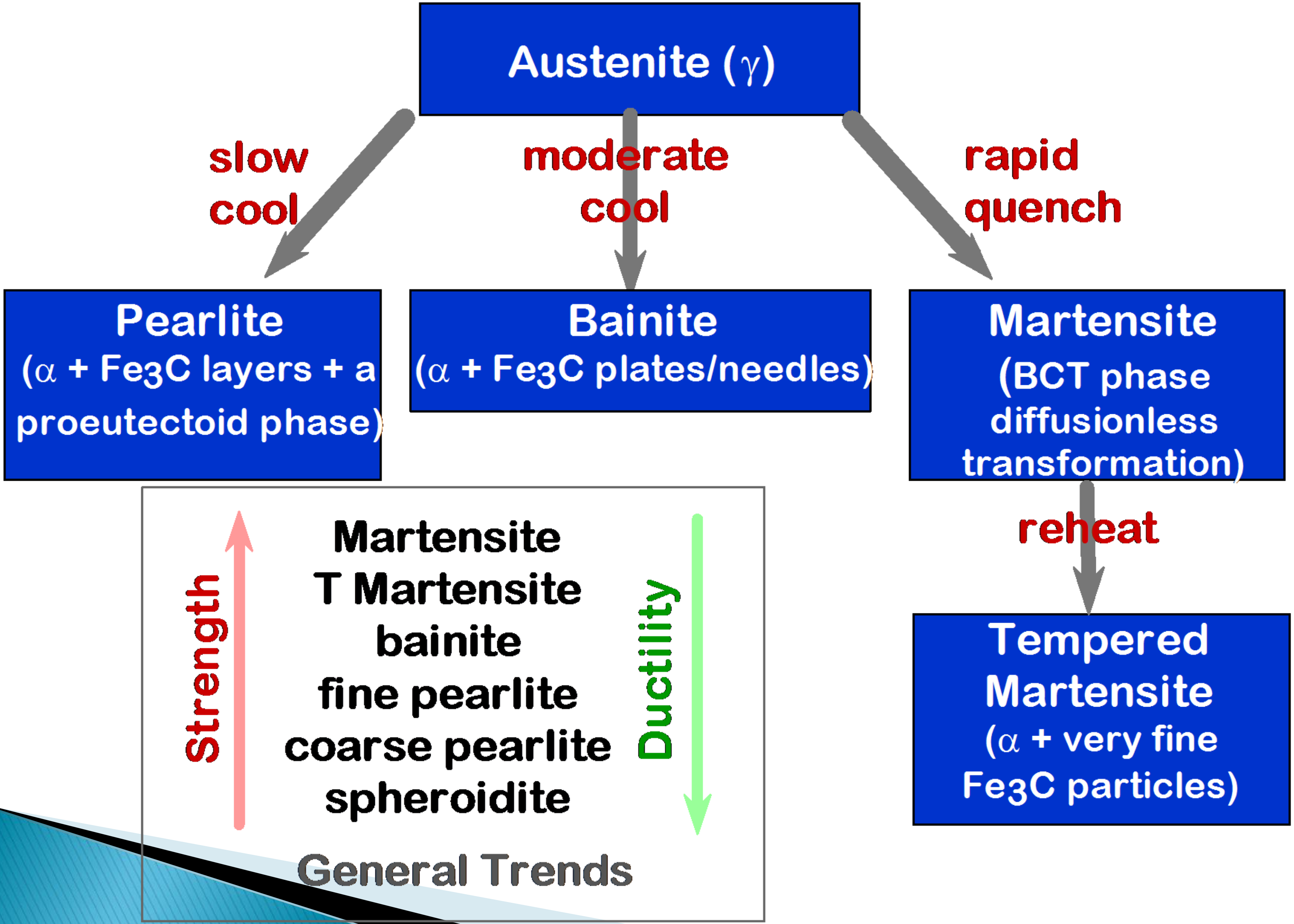
reduces brittleness of martensite,
reduces internal stress caused by quenching





- **produces extremely small Fe_3C particles surrounded by α.**
- **decreases TS, YS but increases %AR**

SUMMARY: PROCESSING OPTIONS



Austenite (γ)

slow cool

moderate cool

rapid quench

Pearlite
(α + Fe_3C layers + a proeutectoid phase)

Bainite
(α + Fe_3C plates/needles)

Martensite
(BCT phase diffusionless transformation)

reheat

Tempered Martensite
(α + very fine Fe_3C particles)

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

General Trends