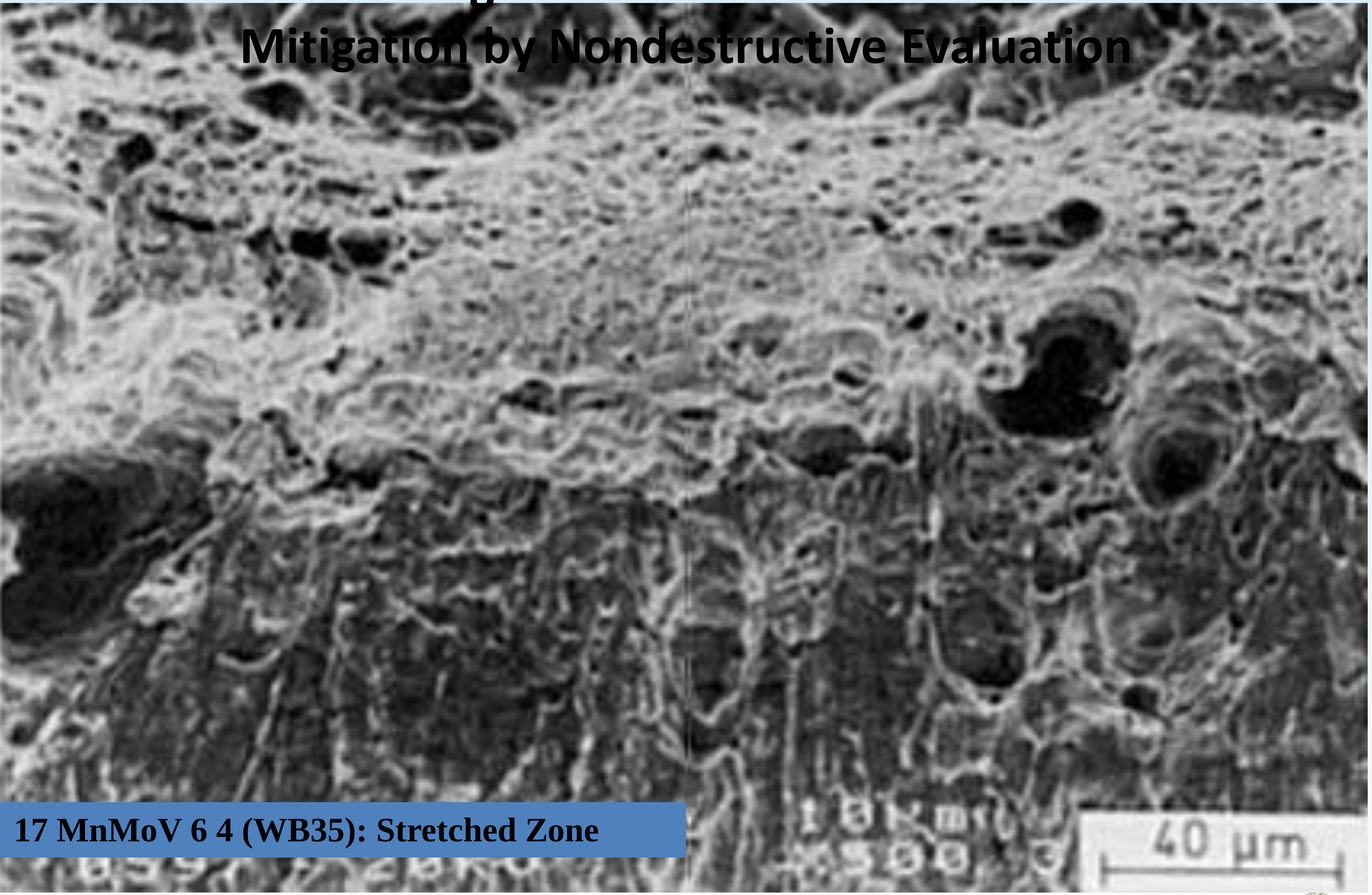
Material Degradation of Nuclear Structures
Mitigation by Nondestructive Evaluation



17 MnMoV 6 4 (WB35): Stretched Zone

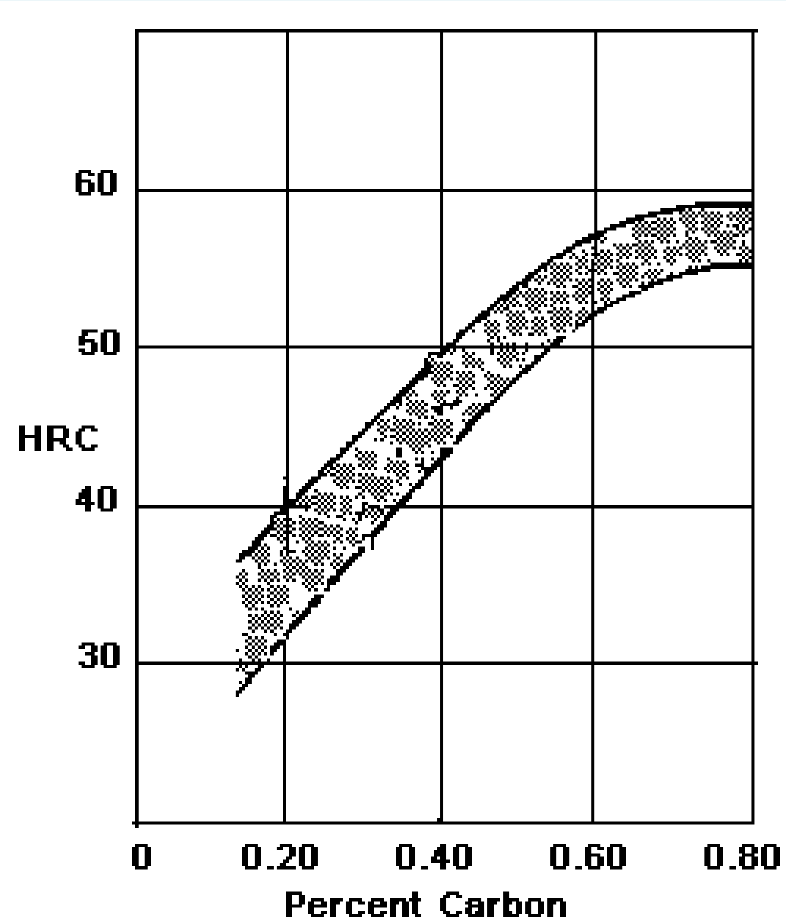
Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

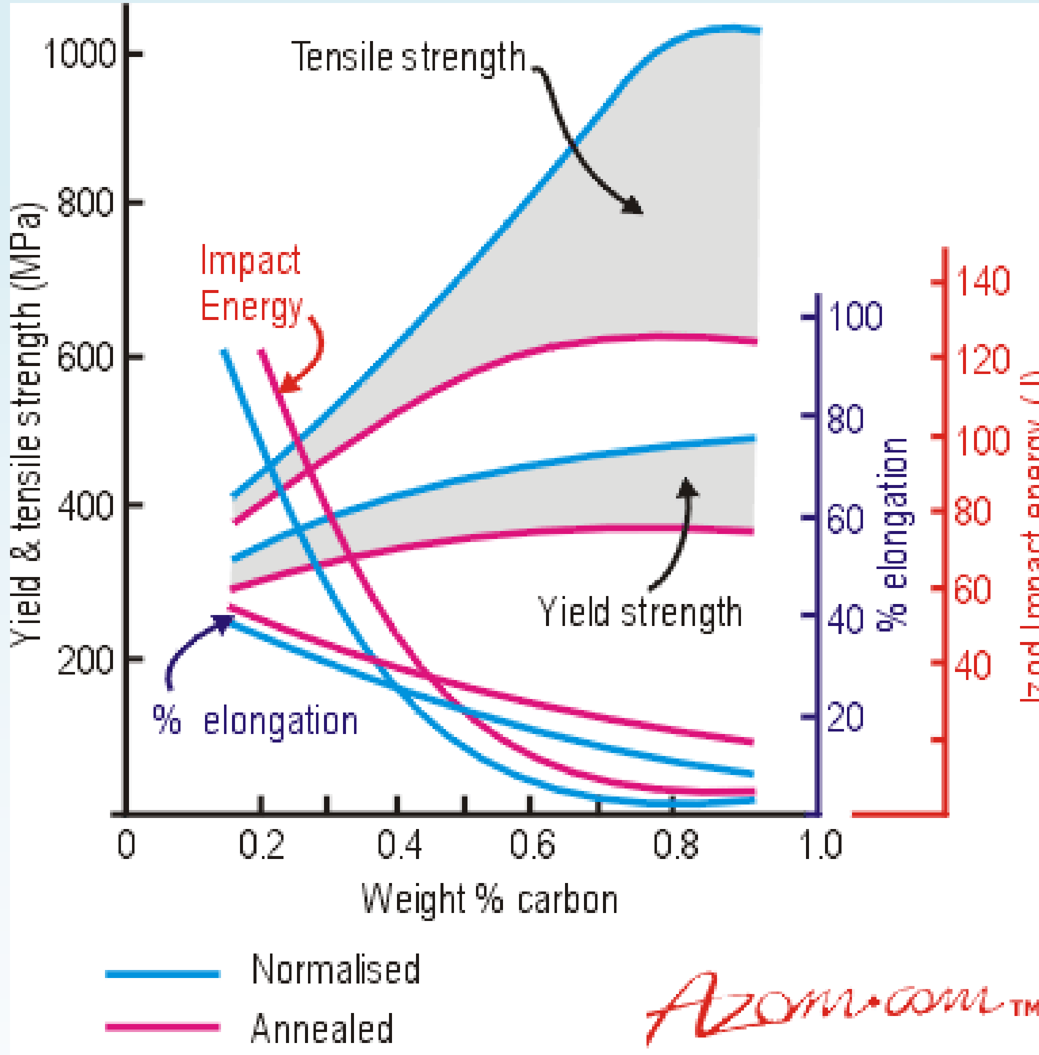
3.	**Focus on Steel – Carbon Steels**
3.1.	Basic Characteristics of Steel
3.2.	Steel Qualities and Characterization Methods
3.3.	**Carbon Steel Microstructures**
3.4.	Microstructure Transformation
3.5.	Transformation Diagrams
3.6.	Localized Hardening
3.7.	Steel Alloys

The Metallurgy & Weldability of Carbon Steel

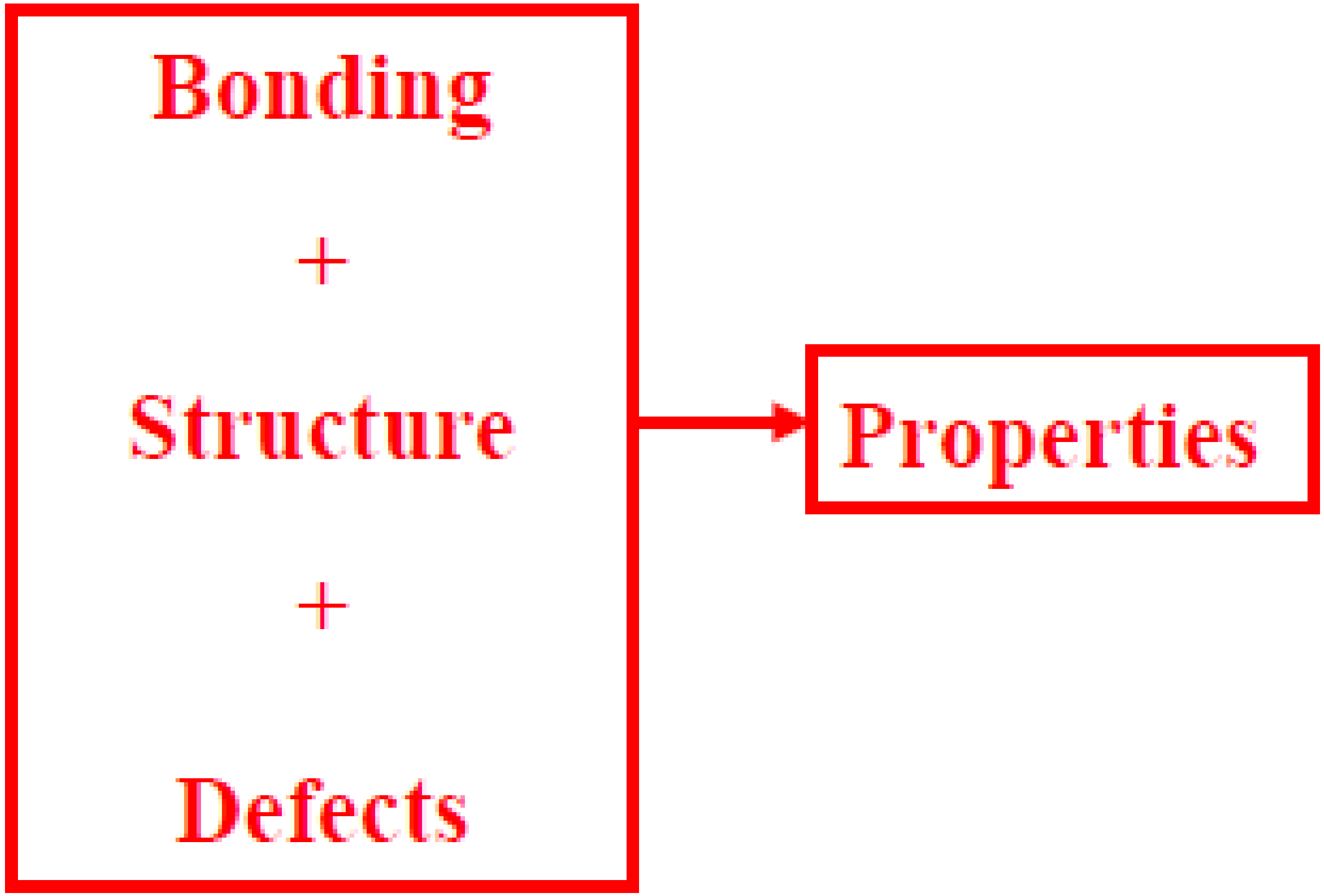
Focus on Steel – Carbon Steels

We know already: Effect of Carbon on Mechanical Properties





Focus on Steel – Properties of Steels



Defects have a profound impact on the macroscopic properties of steels

Focus on Steel – Carbon Steels

We learn:
Microstructure of Metals determines their Mechanical Properties

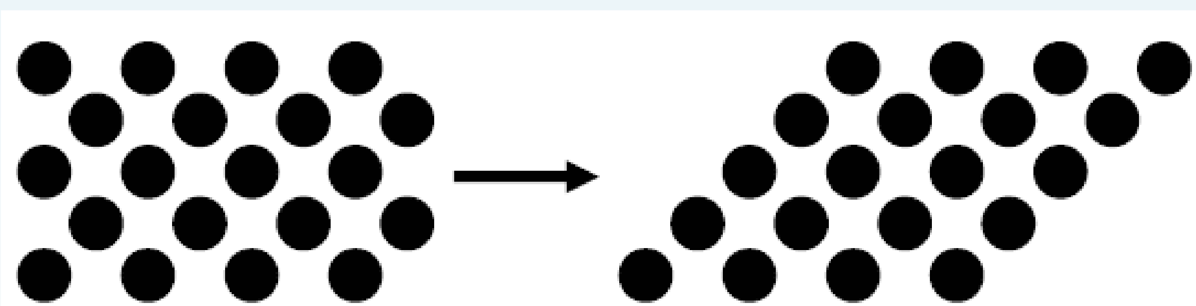
The microstructure is defined
by the type, crystal structure, number, shape and
topological arrangement of phases and defects
such as point defects, dislocations (line defects),
stacking faults or grain boundaries (planar defects)
in a crystalline material.

Microstructure & Ductility

fcc & bcc lattice structures of some metals

fcc	bcc
Cu, Ag, Au, Al, Ni, Pb, Pt	Li, Na, K, Cr, Mo, Ta, W
γ-Fe	α-Fe
ductile	brittle

$$\gamma\text{-Fe} \underset{1390°C}{\overset{910°C}{\rightleftarrows}} \alpha\text{-Fe}$$

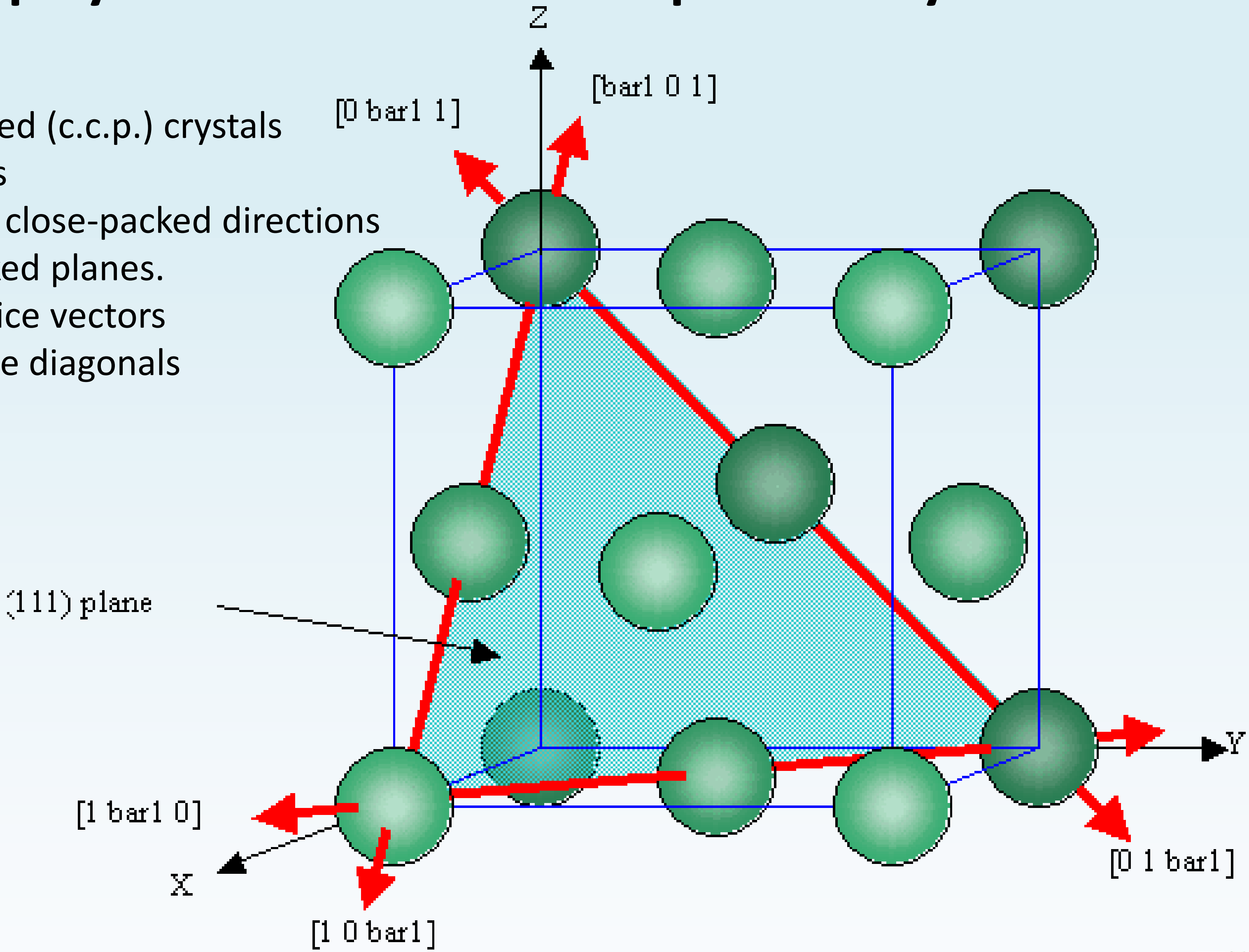


Highly occupied lattice plains like the (1,1,1) plane of fcc crystals are slipping more easily.

Metals with fcc structure are more ductile

Slip Systems of Cubic close –packed Crystals

Cubic close-packed (c.c.p.) crystals have slip systems consisting of the close-packed directions in the close-packed planes. The shortest lattice vectors are along the face diagonals of the unit cell



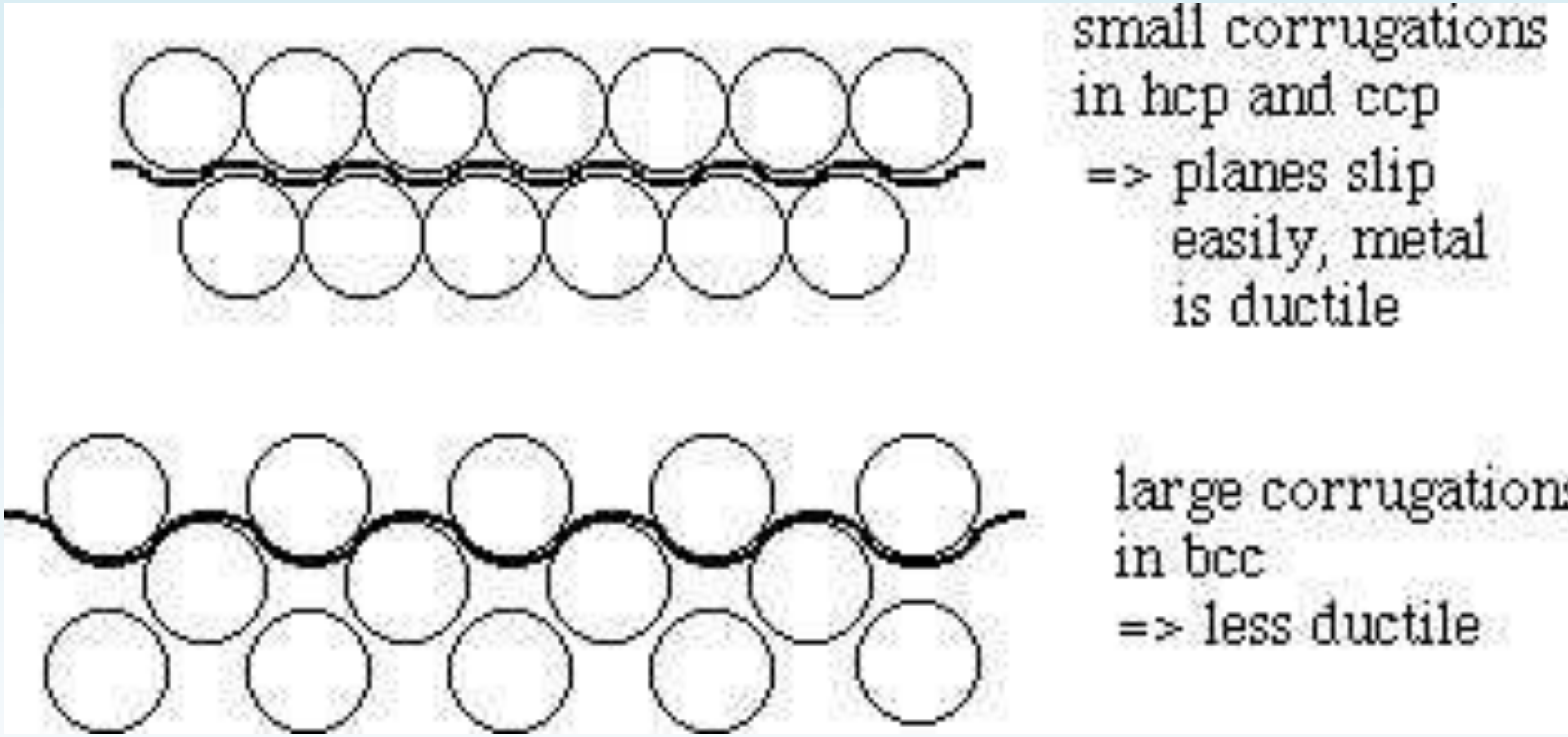
Slip Systems in C.C.P. Crystals

There are 3 distinct slip directions lying in the (111) plane
There are 3 other planes of the {111} type,
making 12 distinct slip systems of the <1 bar1 0>{111} type.

The cubic symmetry requires that there be many distinct slip systems,
using all <1 bar1 0> directions and {111} planes.
There are 12 such <1 bar1 0>{111} systems,
five of which are independent.

Note that on a given slip system,
slip may occur in either direction along the specified slip vector.

CRYSTAL TYPE MAKES SLIPPING EASIER OR MORE DIFFICULT



JUST AN OBSERVATION:

The yield stresses of normal (polycrystalline) metal samples are by a factor of 1000 lower than they are in perfect single crystals.

Normal crystals are not perfect,
There are defects:

- ***POINT DEFECTS***
- ***LINEAR DEFECTS***
- ***PLANAR DEFECTS***
- ***BULK DEFECTS***

These imperfections influence the mechanical properties.
Dislocation movements reduce the yield stress , for example

Microstructure: Point Defects

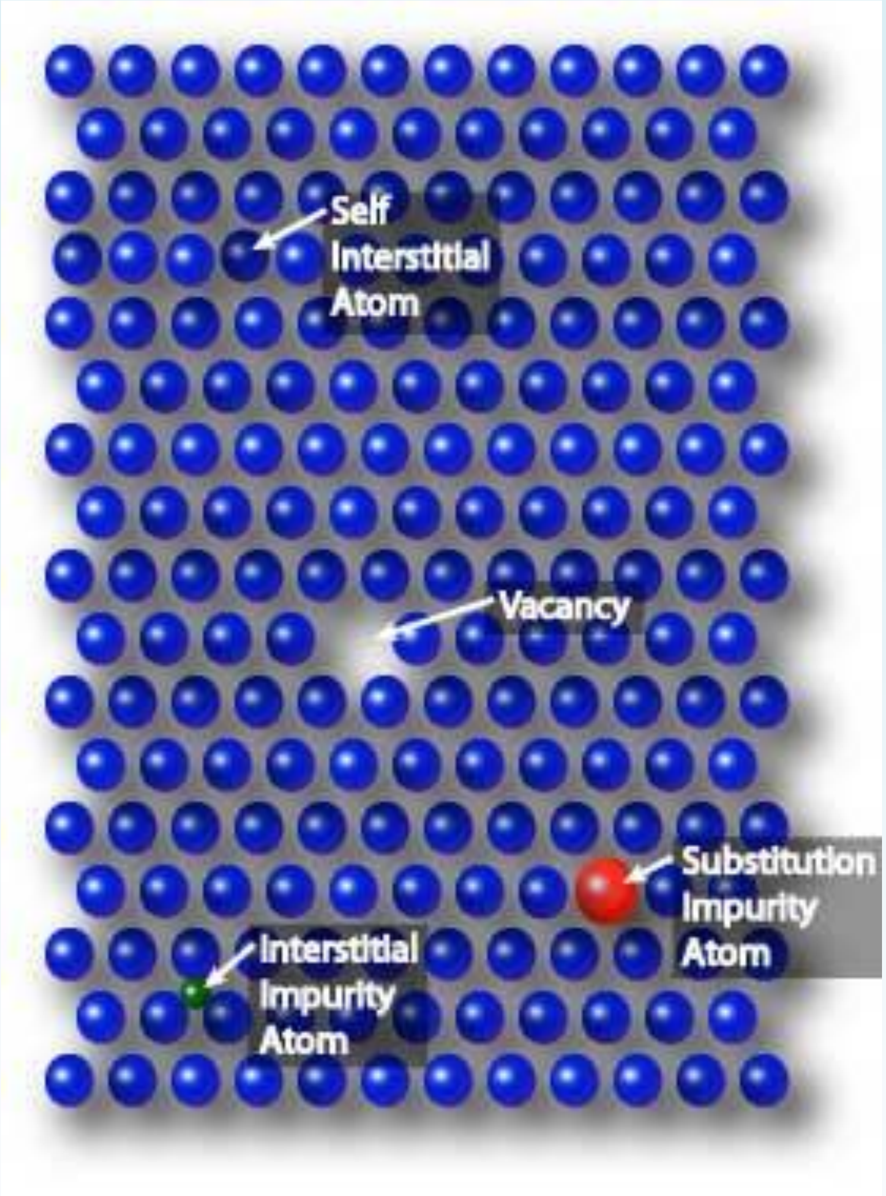
Point defects:

an atom is missing (vacancy)
or is in an irregular place
in the lattice structure.

A self interstitial atom:
an extra atom that has moved into
an interstitial void in the crystal structure.

A substitutional impurity atom:
an atom of a different type than the bulk atoms,
which has replaced one of the bulk atoms
in the lattice. They are usually close in size
(within approximately 15%) to the bulk atom.

Interstitial impurity atom:
It is much smaller than the bulk atoms.
It fits into the open space between
the bulk atoms of the lattice structure.
Carbon atoms, with a radius of 0.071 nm,
fit nicely in the open spaces
between the larger (0.124 nm) iron atoms.



Vacancies

are empty spaces in the lattice.
They are common,
especially at high temperatures.

Vacancies occur naturally
in all crystalline materials.
At any given temperature,
there is an equilibrium concentration
(ratio of vacant lattice sites
to those containing atoms).
Vacancies are formed
during solidification
due to vibration of atoms,
local rearrangement of atoms,
plastic deformation and ionic bombardments.

Frenkel defect (Frenkel Pair)

consists in the displacement of an atom
from its lattice position to an interstitial site,
creating a vacancy at the original site
and an interstitial defect at the new location.
This compound defect was discoverd by
the Russian scientist Yakov Frenkel in 1926.

Remind: Neutron irradiation
Wigner energy

Diffusion

(mass transport by atomic motion)
occurs mainly because of vacancies.

Dislocations and Plastic Deformation

Materials

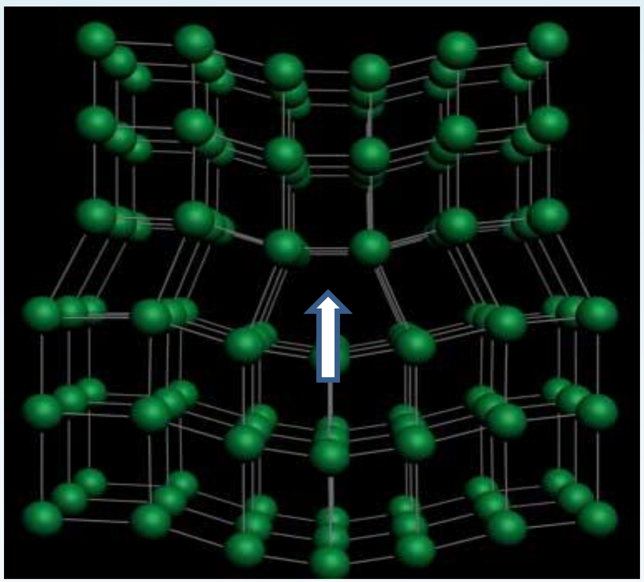
University of Colorado Boulder

Organized by textbooks at www.learncheme.com

Microstructure: Dislocations

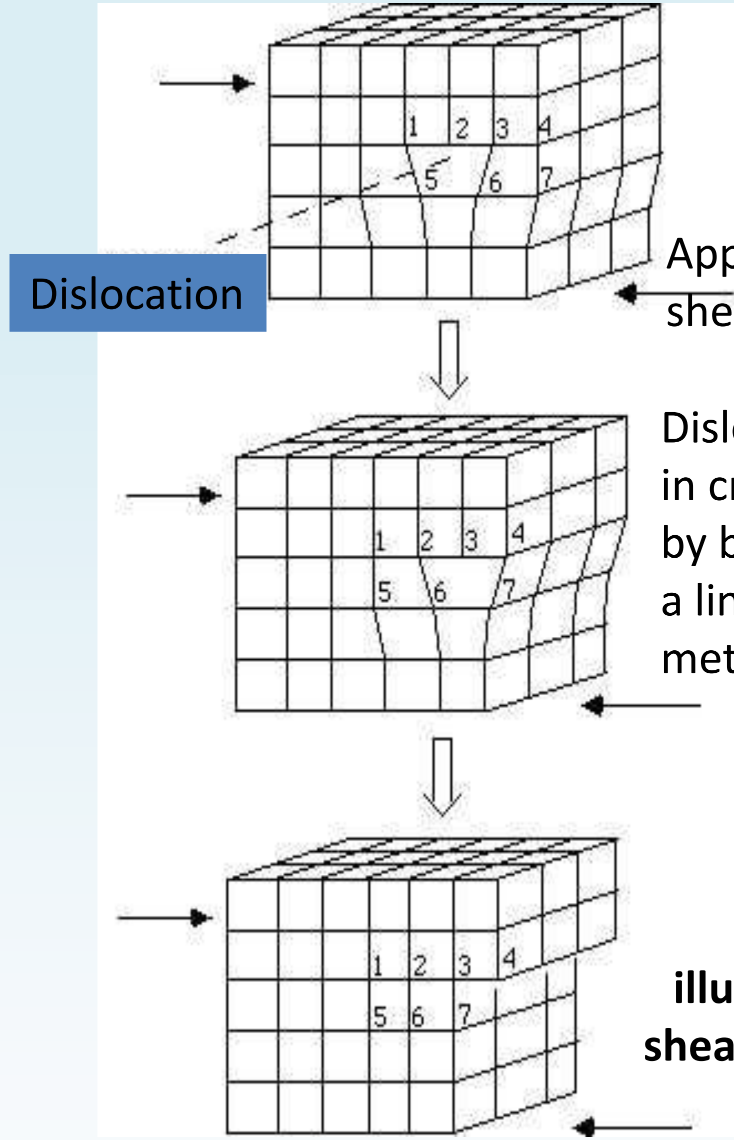
LINEAR DEFECTS:
Edge & Screw Dislocations

In the late 1950's,
the TEM allowed experimental evidence that the strength and ductility of metals are controlled by dislocations.



DISLOCATION:
extra plane of atoms

dislocation defect in metallic crystals

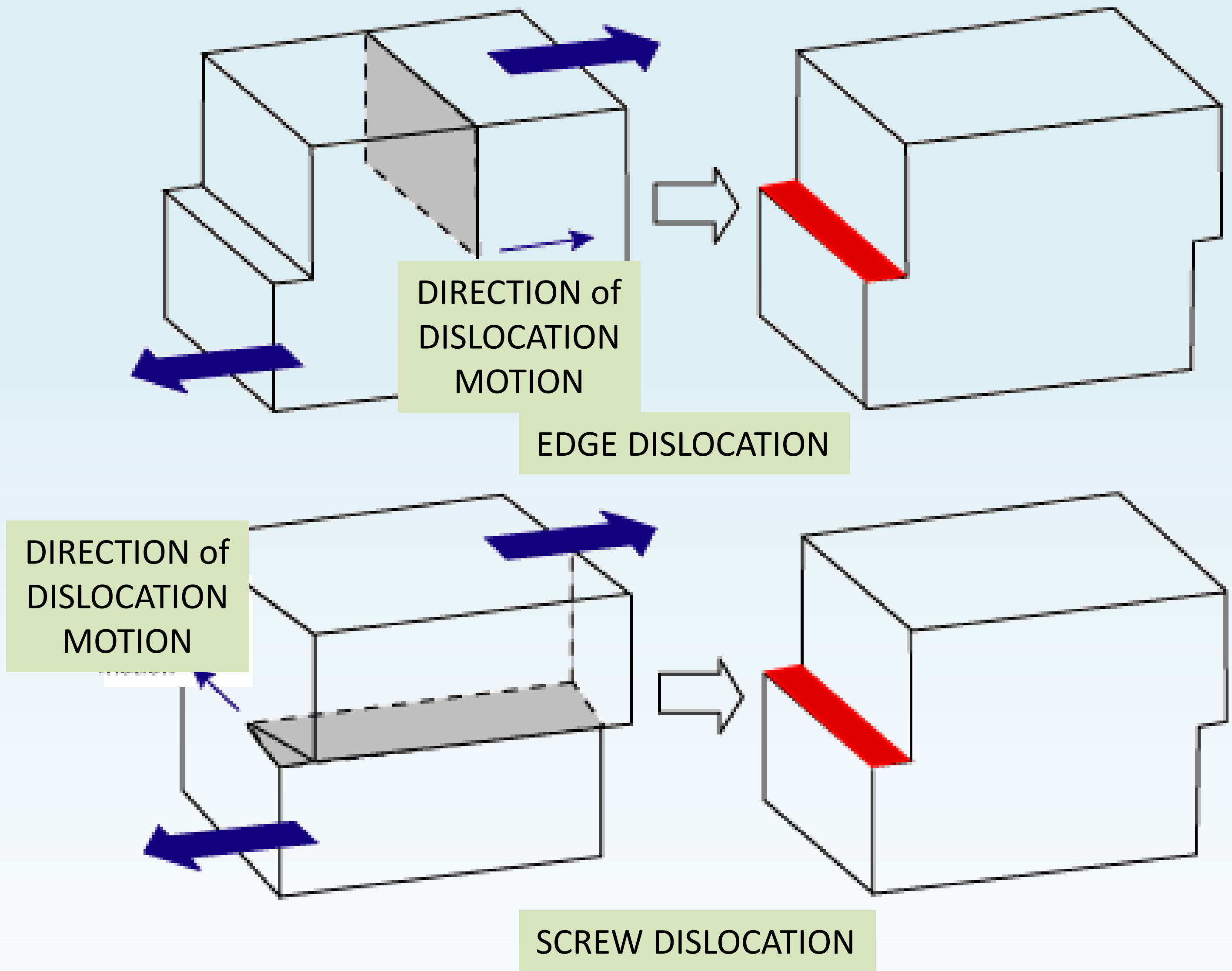


Applied shearing stress

Dislocation moves in crystal by breaking/making a line of metal-metal bonds

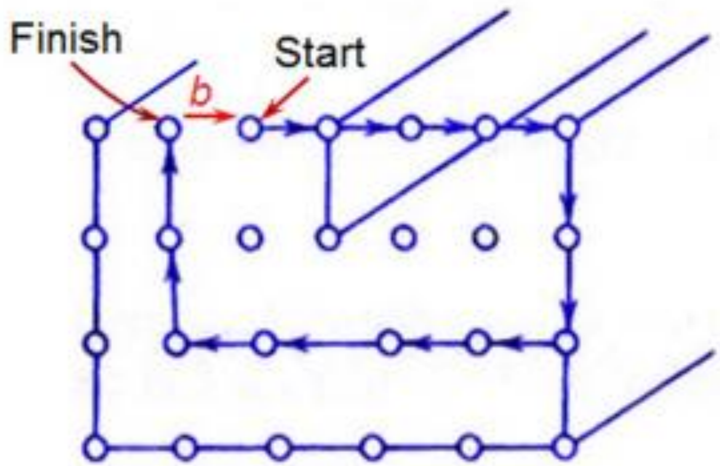
illustration of shear dislocation

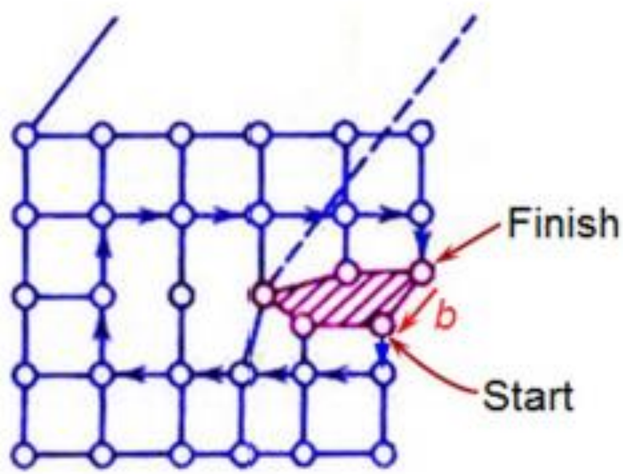
Microstructure: Dislocations



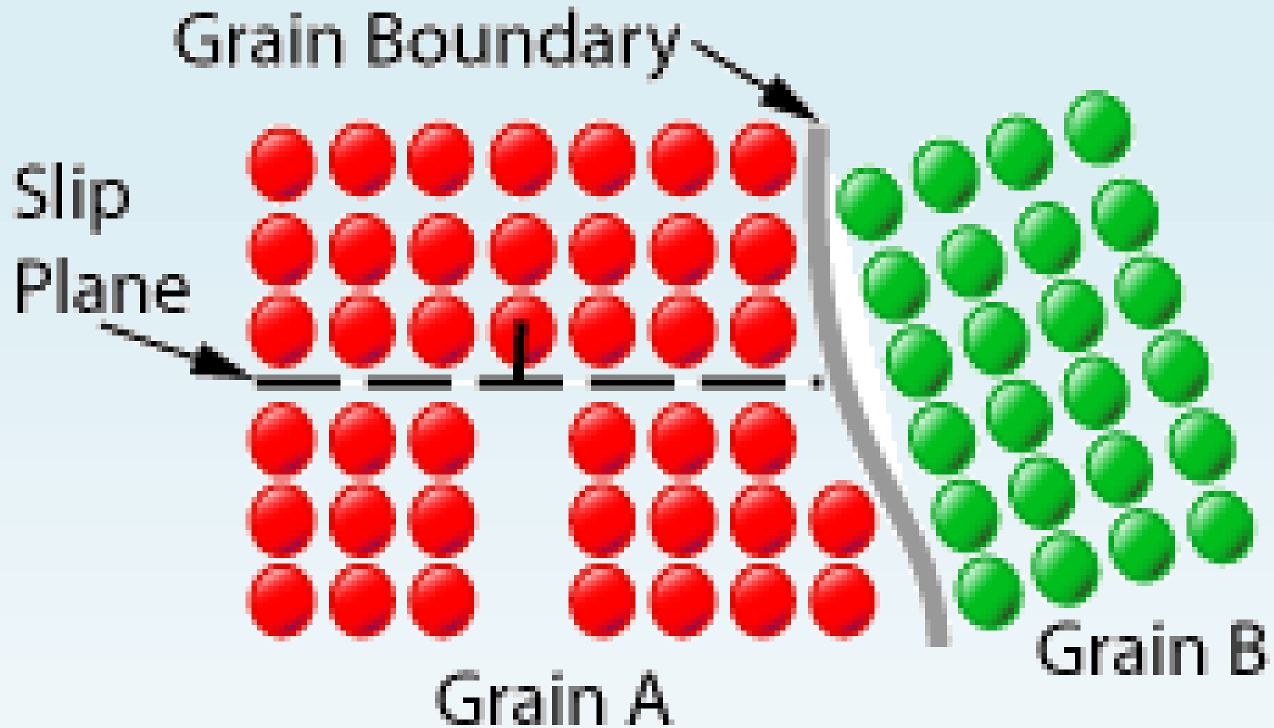
Burger Circuit

❖ The Burger vector can be found by the gap in the Burger circuit which is obtained by moving equal distances in each direction around the dislocation.





EFFECT OF GRAIN SIZE



Control of Grain Size

The size of the grains within a material has an effect on material strength.
The boundary between grains acts as a barrier to dislocation movement
The smaller the grains, the shorter the distance
atoms can move along a particular slip plane.

Therefore, smaller grains improve the strength of a material.

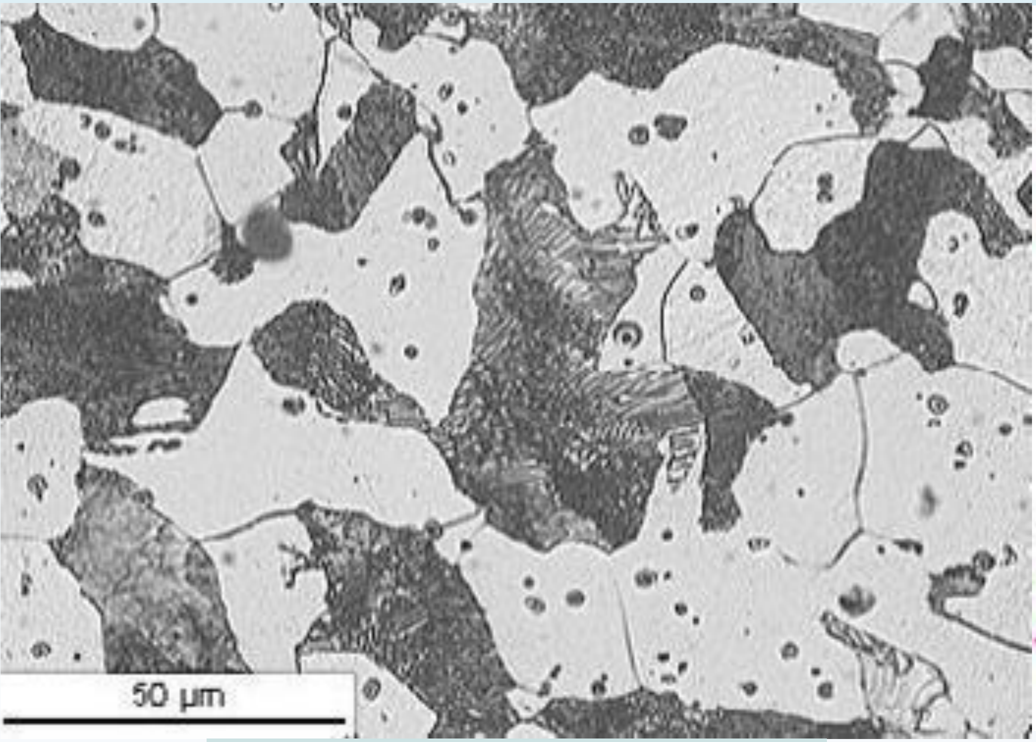
SUMMARY

The dislocations move along the densest planes of atoms,
because the stress needed to move the dislocation
increases with the spacing between the planes.
FCC and BCC metals have many dense planes,
so dislocations move relatively easy
and these materials have high ductility.

Metals are strengthened
by making it more difficult for dislocations to move.
This may involve the introduction of obstacles,
such as interstitial atoms or grain boundaries,
to “pin” the dislocations.

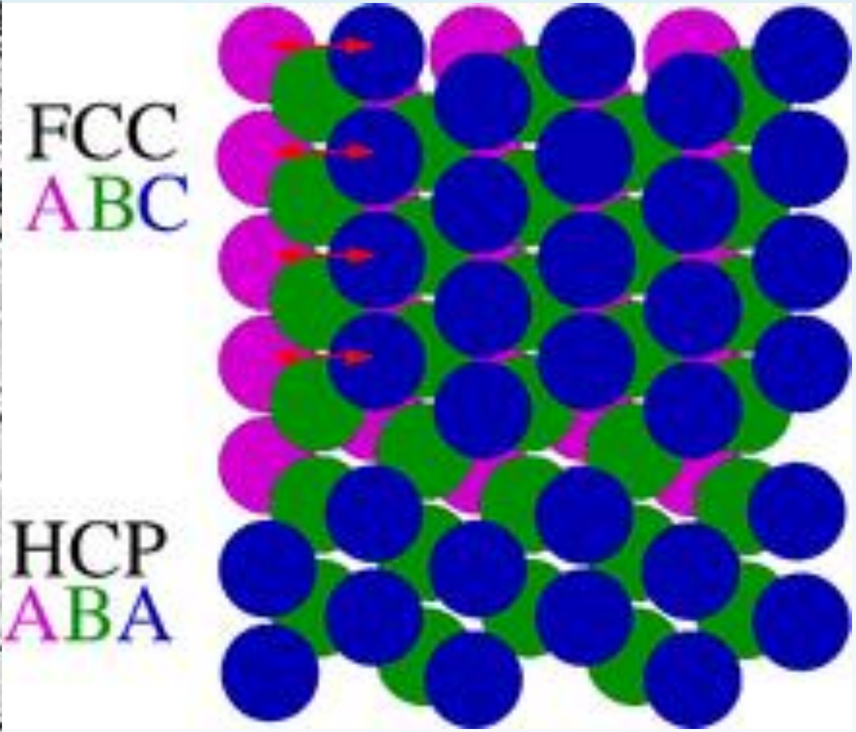
Also, as a material plastically deforms,
more dislocations are produced
and they will get into each others way and impede movement.
This is why strain or work hardening occurs.

Grain boundary
a two-dimensional interface
between two different crystal grains.
This usually occurs when two crystals
begin growing separately and then meet



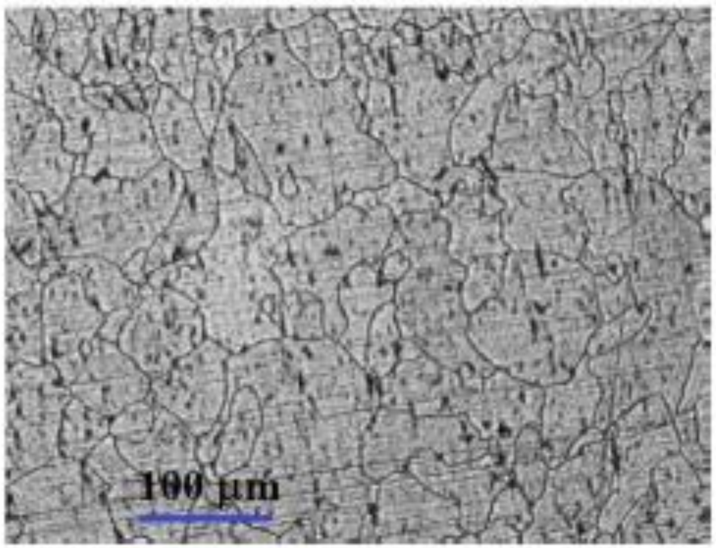
Low Carbon Steel 0.1% C

Stacking fault
(common in close-packed structures)
one or two layer interruptions
in the stacking sequence, for example,
if the sequence ABCABABCAB
were found in an fcc structure

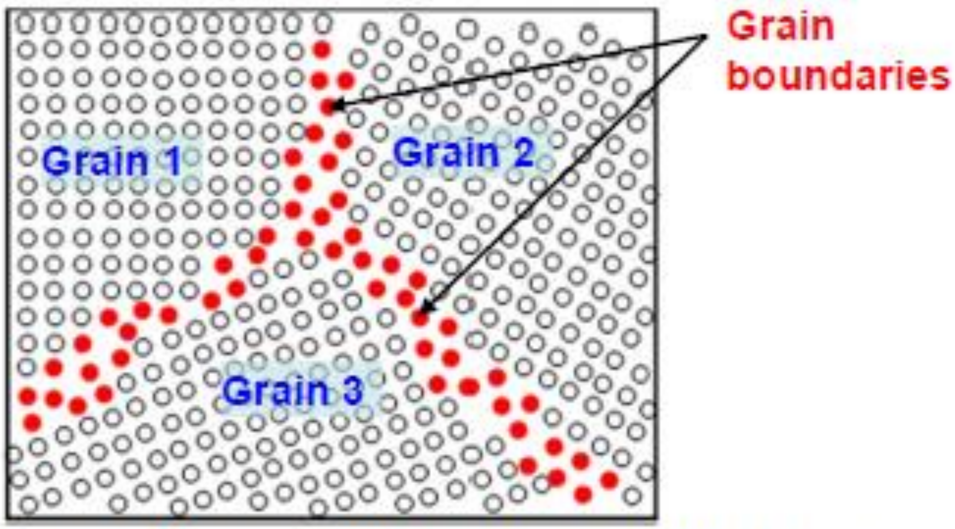


Stacking fault in FCC material

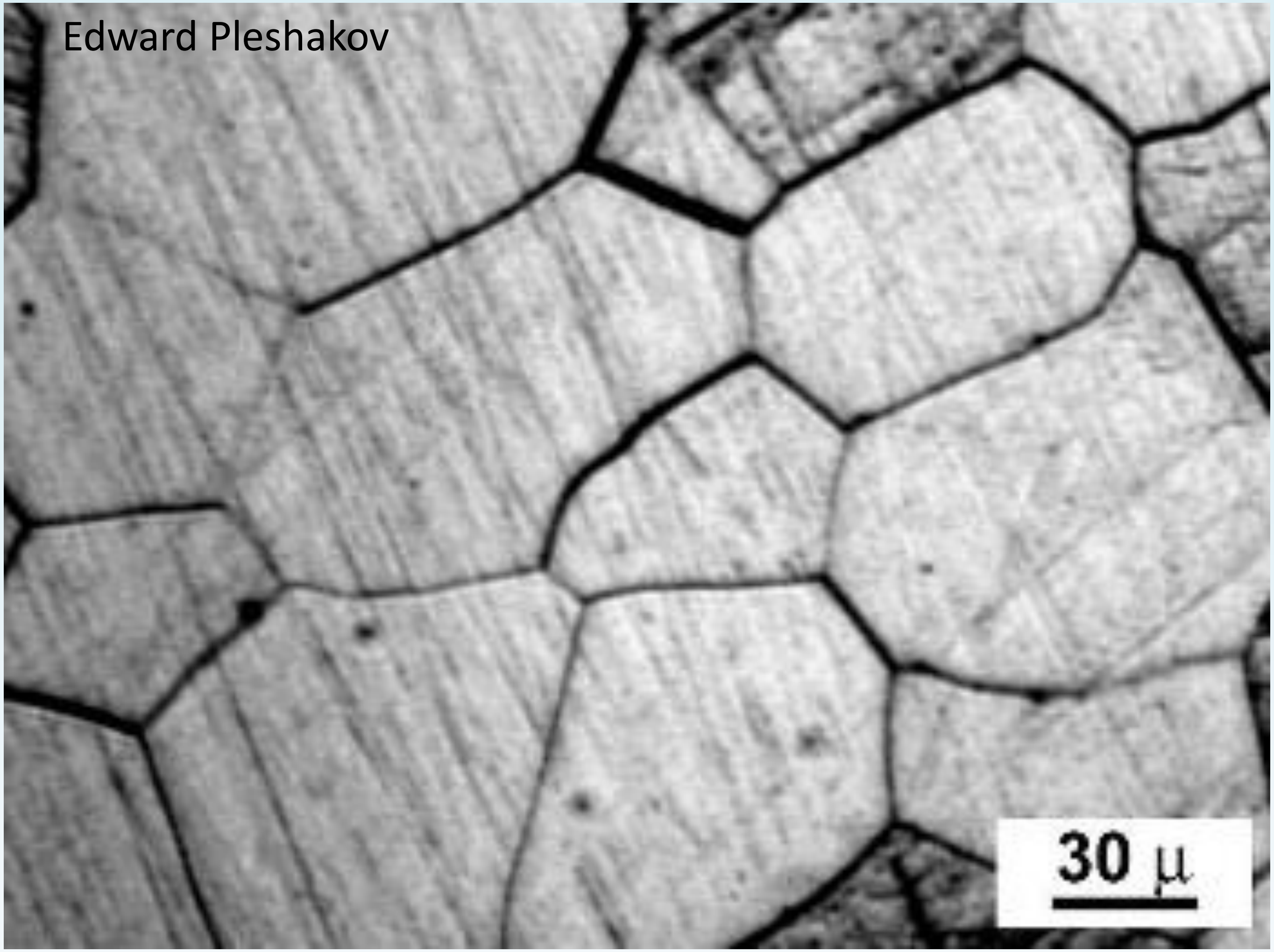
Grain boundaries



(a) Optical micrograph of a polycrystalline material



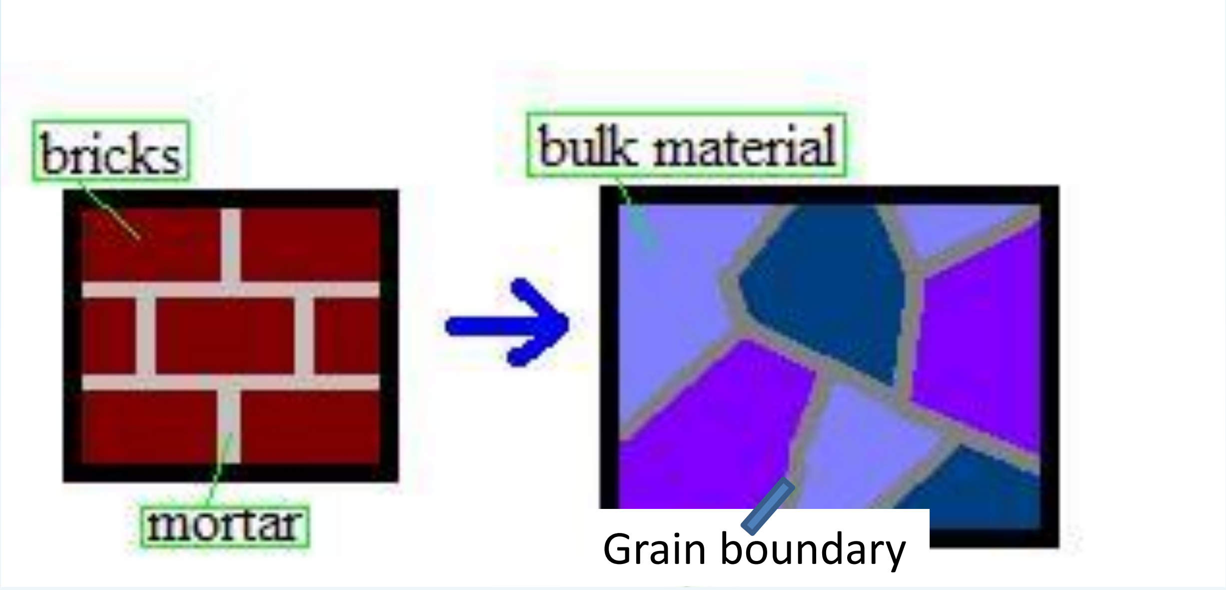
(b) Schematic of orientation change across the grain boundary



Micrograph of a polycrystalline metal; grain boundaries evidenced by acid etching.
Microstructure of VT22 (Ti5Al5Mo5V1,5Cr) after quenching

Grain boundaries are important structural components of polycrystalline materials

Because grain boundaries form a continuous network throughout such materials, their properties may limit their practical use.



One of the serious phenomena which evoke these limitations is the grain boundary segregation of impurities. It results in the loss of grain boundary cohesion and consequently, in brittle fracture of the materials.

Segregation in Materials
refers to the enrichment of a material constituent
at a free surface or an internal interface of a material.
In a polycrystalline solid, a segregation site can be

- a dislocation,
- a grain boundary,
- a stacking fault,
- or an interface with a precipitate or secondary phase within the solid.

There are two recognized types of segregation:

- equilibrium segregation (lowest energy state) and
- non-equilibrium segregation (stress or temperature change).

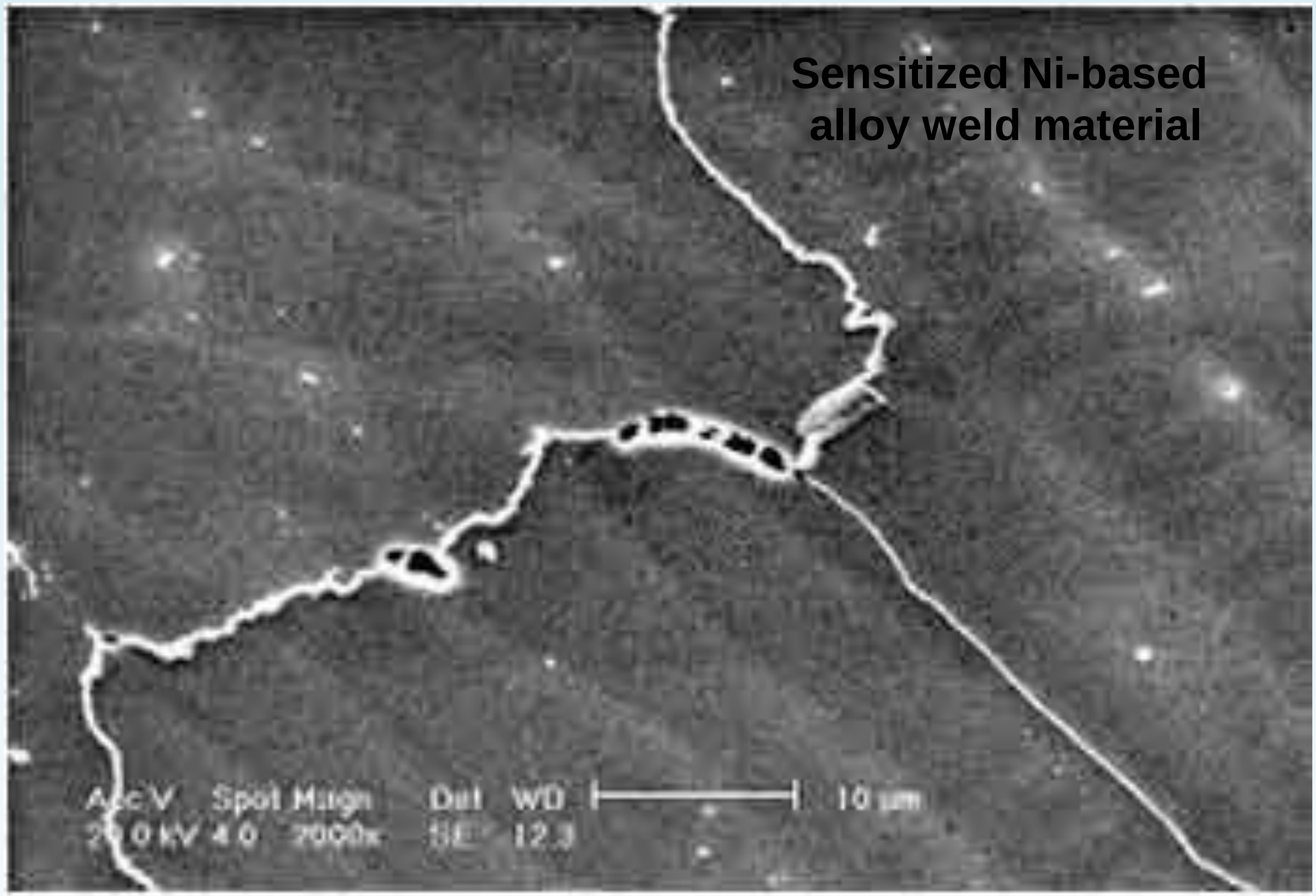
Segregation of a solute to surfaces and grain boundaries in a solid produces a section of material with a discrete composition and its own set of properties that can have important (and often deleterious) effects on the overall properties of the material.

Focus on Steel – Steel Qualities

Equilibrium segregation is associated with the lattice disorder at interfaces, where there are sites of energy different from those within the lattice at which the solute atoms can deposit themselves. The equilibrium segregation is so termed because the solute atoms segregate themselves to the interface or surface in accordance with the statistics of thermodynamics in order to minimize the overall free energy of the system.

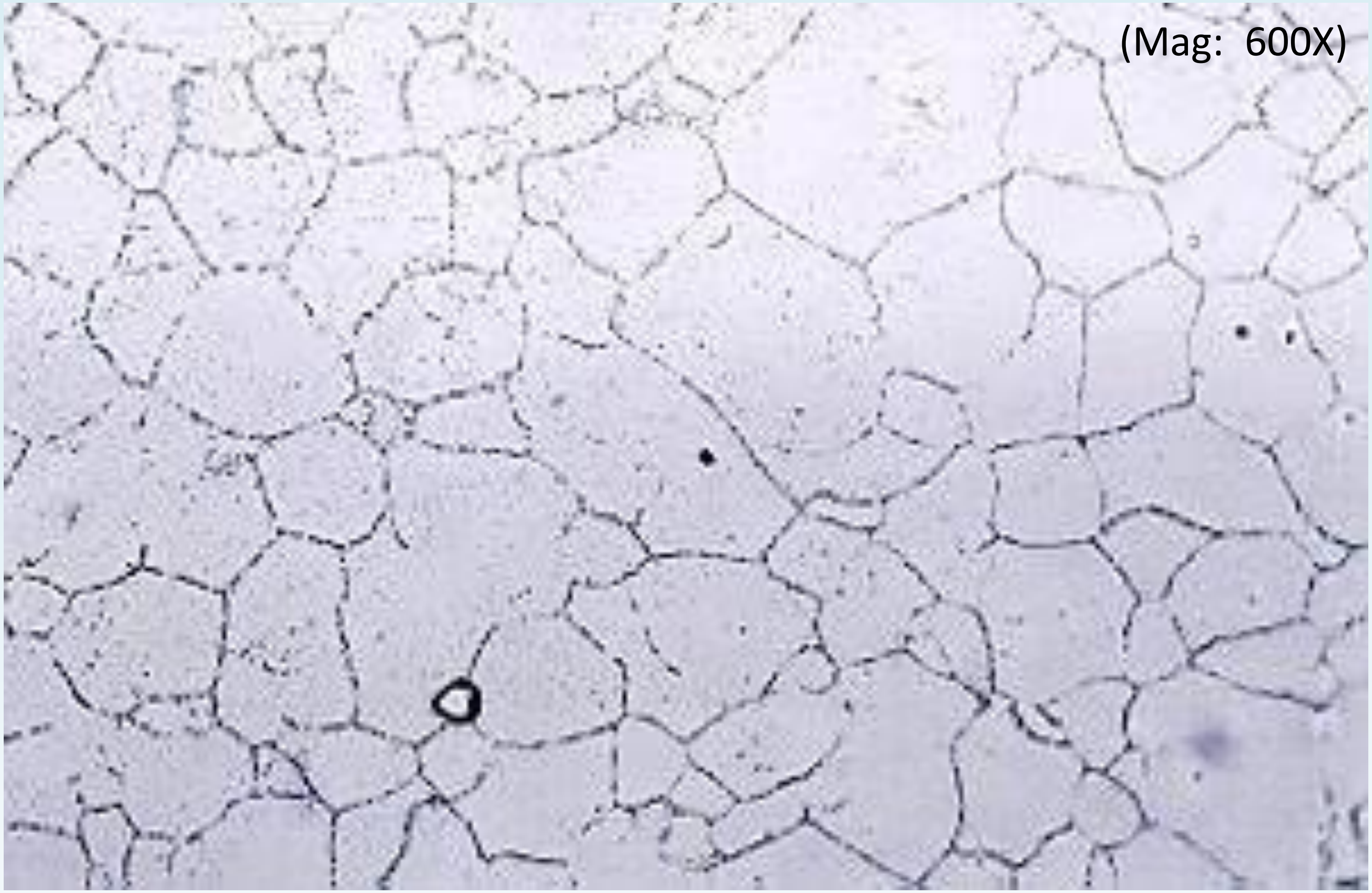
This sort of partitioning of solute atoms between the grain boundary and the lattice was predicted by McLean in 1957. Non-equilibrium segregation, first theorized by Westbrook in 1964, occurs as a result of solutes coupling to vacancies which are moving to grain boundary sources or sinks during quenching or application of stress. It can also occur as a result of solute pile-up at a moving interface. There are two main features of non-equilibrium segregation, by which it is most easily distinguished from equilibrium segregation. In the non-equilibrium effect, the magnitude of the segregation increases with increasing temperature and the alloy can be homogenized without further quenching because its lowest energy state corresponds to a uniform solute distribution. In contrast, the equilibrium segregated state,by definition, is the lowest energy state in a system that exhibits equilibrium segregation, and the extent of the segregation effect decreases with increasing temperature.

Grain Boundary – Ductility Dip Cracking



Inititation of ductility dip crack by void formation
at the interface of the matrix and grain boundary carbide (Cr23C6)

Grain Boundary – Intergranular Stress Corrosion



Microstructure evaluation of the heat-affected zone
of a welded stainless steel piping flange etched to reveal the carbide distribution.
Fine carbide particles outline the grain boundaries, indicating a "sensitized" condition resulting in susceptibility to intergranular corrosion.

Grain Boundary – Intergranular Stress Corrosion

View of intergranular stress corrosion cracking (IGSCC) in an Inconel heat exchanger tube.

MICROSTRUCTURE: BULK DEFECTS

Voids

small regions where there are no atoms; They can be thought of as clusters of vacancies.

Impurities

can cluster together to form small regions of a different phase. These are often called precipitates

Weld defect

Casting defect

Shrinkage cavity

- Casting blow holes, porosity – Gas entrapment during melting and pouring. Improper welding parameters/practice
- Shrinkage cavity due to improper risering
- Non-metallic inclusions – Slag, oxide particles or sand entrapment
- Cracks – Uneven heating/cooling, thermal mismatch, constrained expansion/contraction all leading to stress development

Impediments to easy dislocation movement

- Impurity atoms (“solute hardening”)
- Intersection with other dislocations

  (entanglement) (“work hardening”)
- Grain boundaries (dislocations “pile up”)
- Small dispersed inclusions (“precipitation hardening”)
- All of these affect ductility and yield strength of a metals

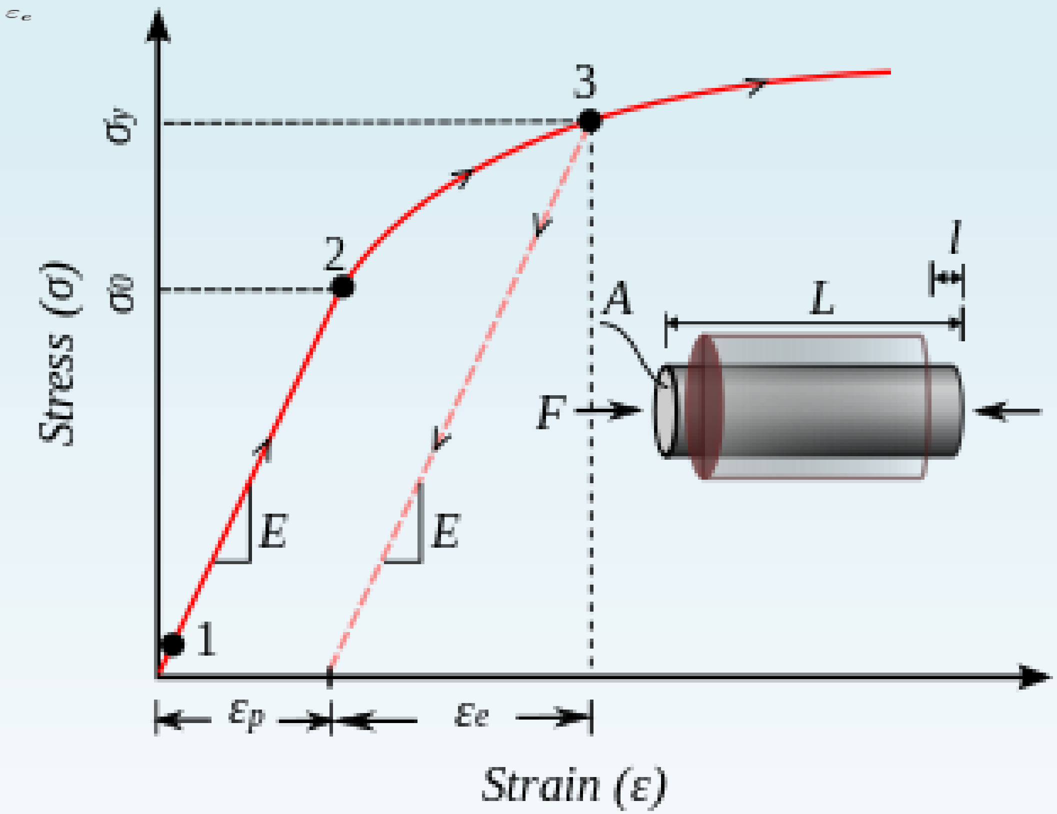
Impediments to easy dislocation movement

through

- Cold Working
- Heat Treatment
- Alloying

WORK HARDENING – STRAIN HARDENING – COLD WORKING

the strengthening of a metal by plastic deformation



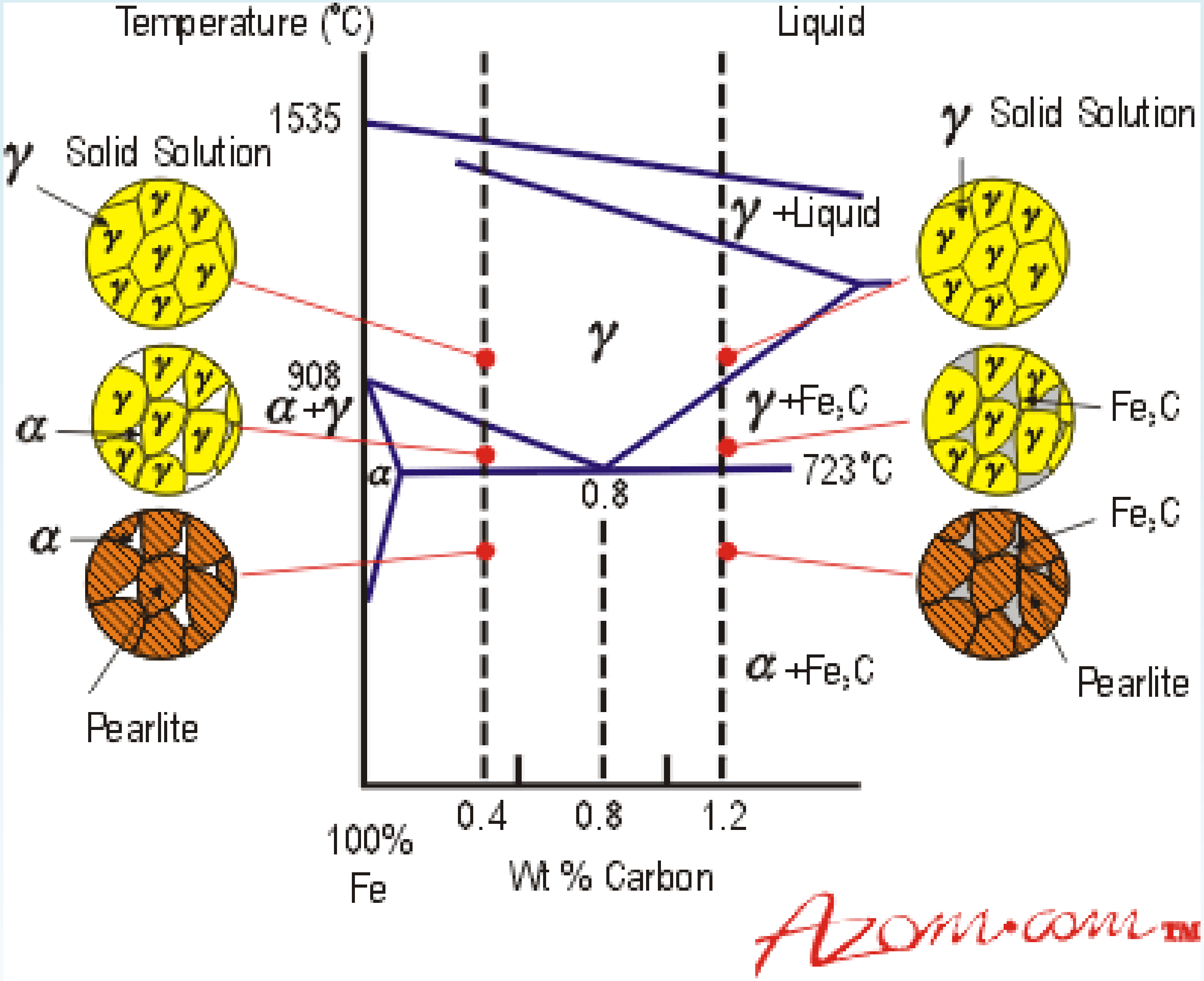
For work hardening materials the yield stress increases with increasing plastic deformation. The strain can be decomposed into a recoverable elastic strain and an inelastic strain

a grain boundary is a planar defect much less responsive to stress than a line defect.

DISLOCATION MOVEMENT TO GRAIN BOUNDARIES

Plastic Deformation → **&** → **Work Hardening**

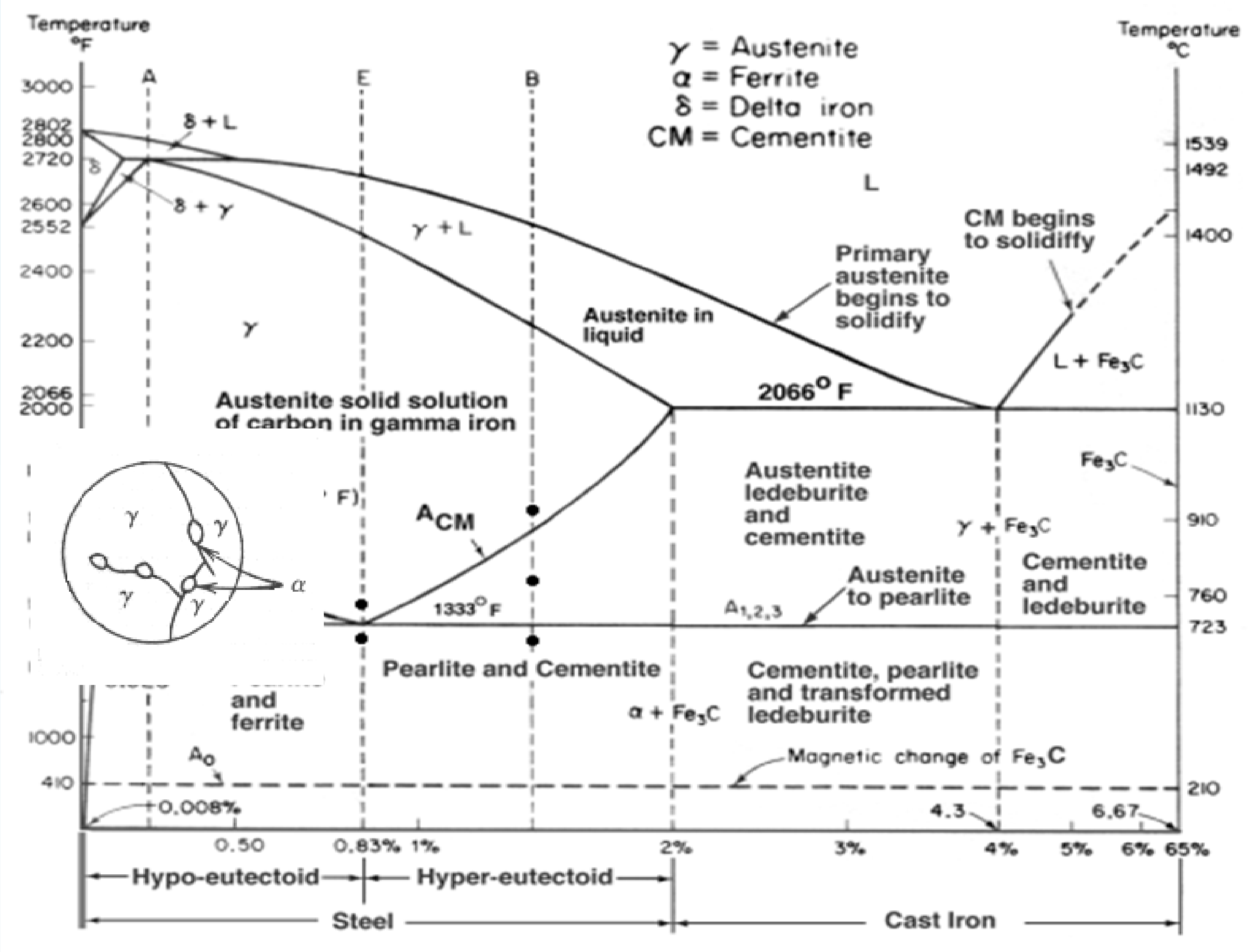
DISLOCATION GENERATION



PHASE TRANSFORMATIONS DURING COOLING

Given all the time the constituents need

Focus on Steel – Carbon Steels

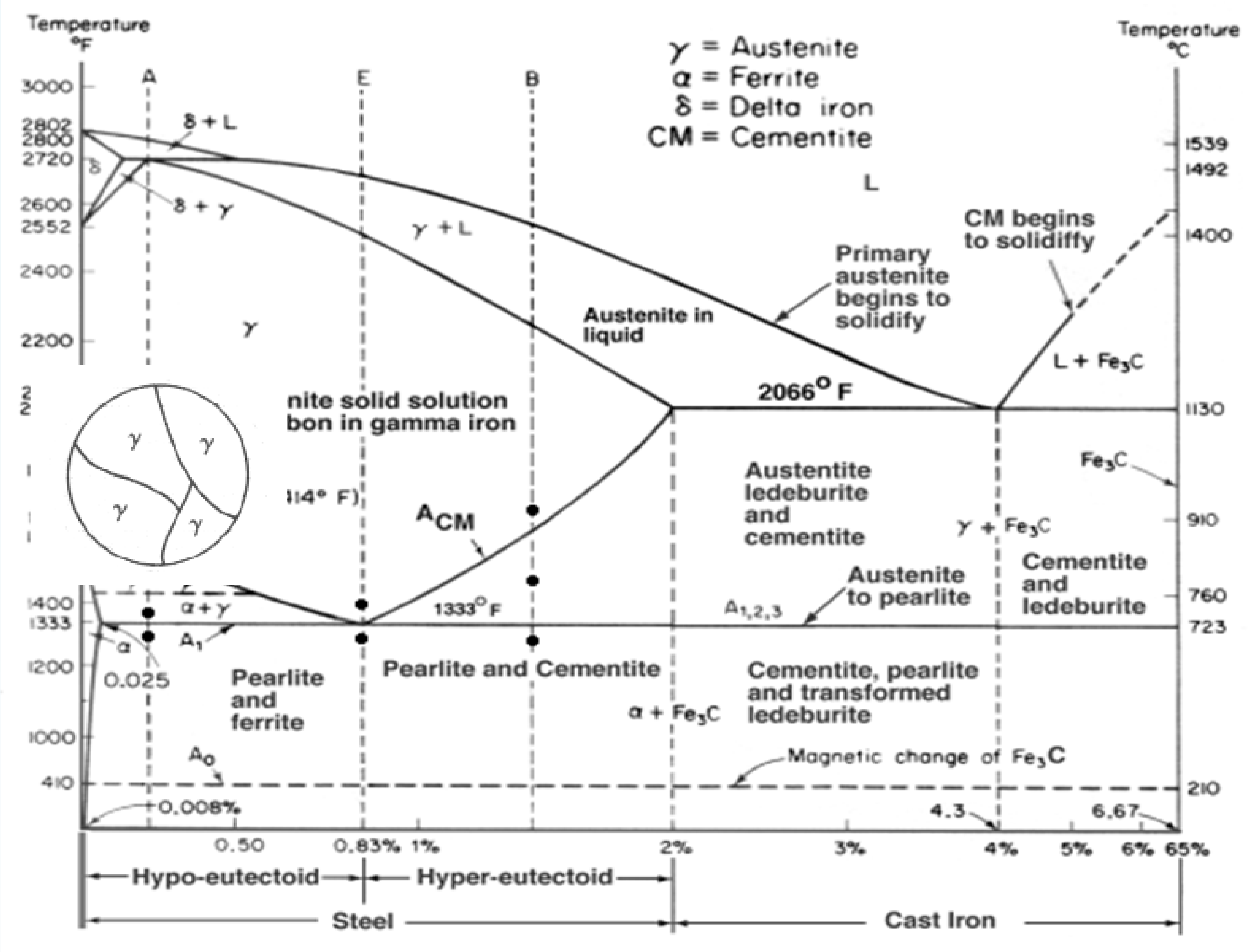


Fe-Fe_3C Phase Diagram (clickable),

Materials Science and Metallurgy, 4th ed., Pollack, Prentice-Hall, 1988

Fig 1:

Focus on Steel – Carbon Steels



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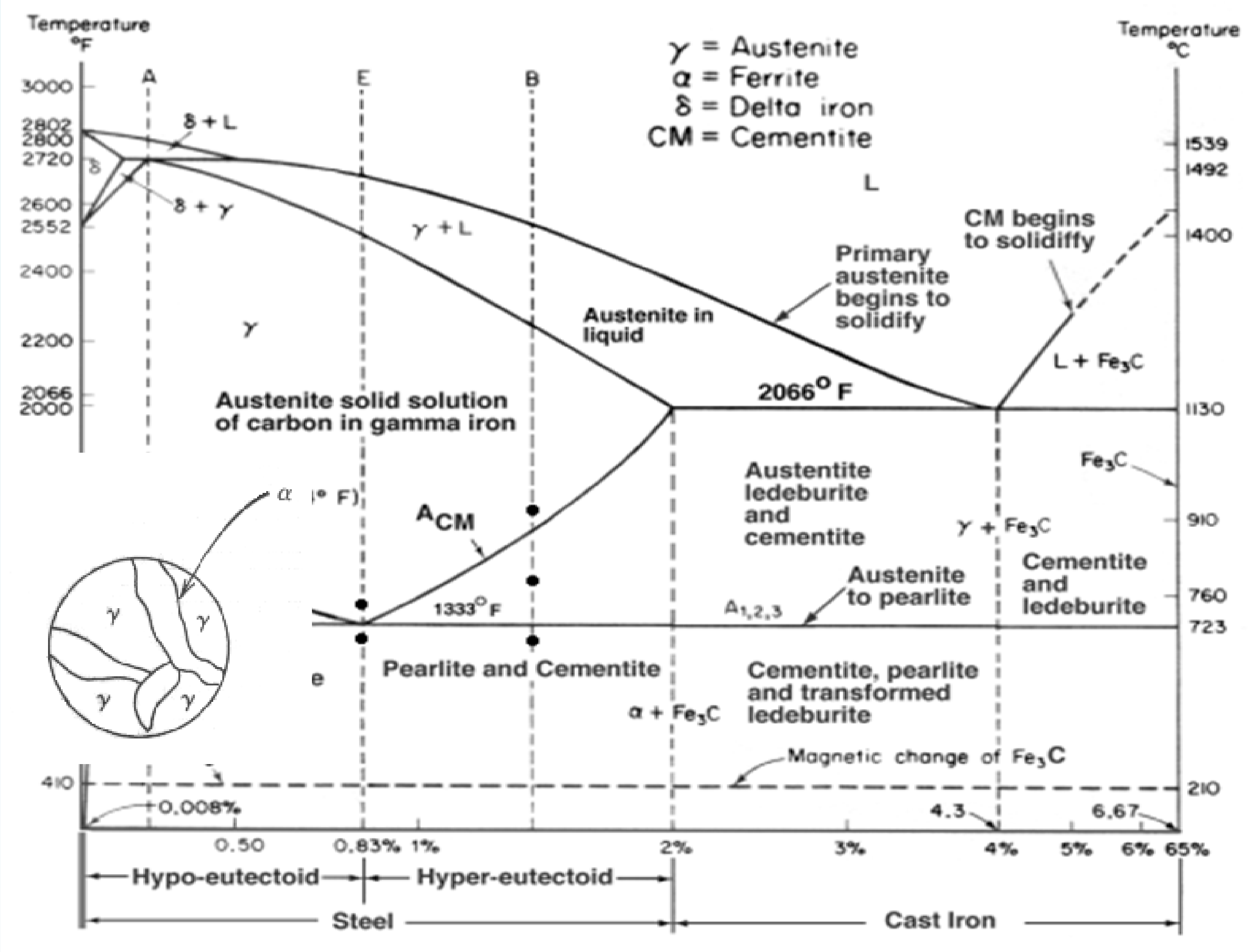

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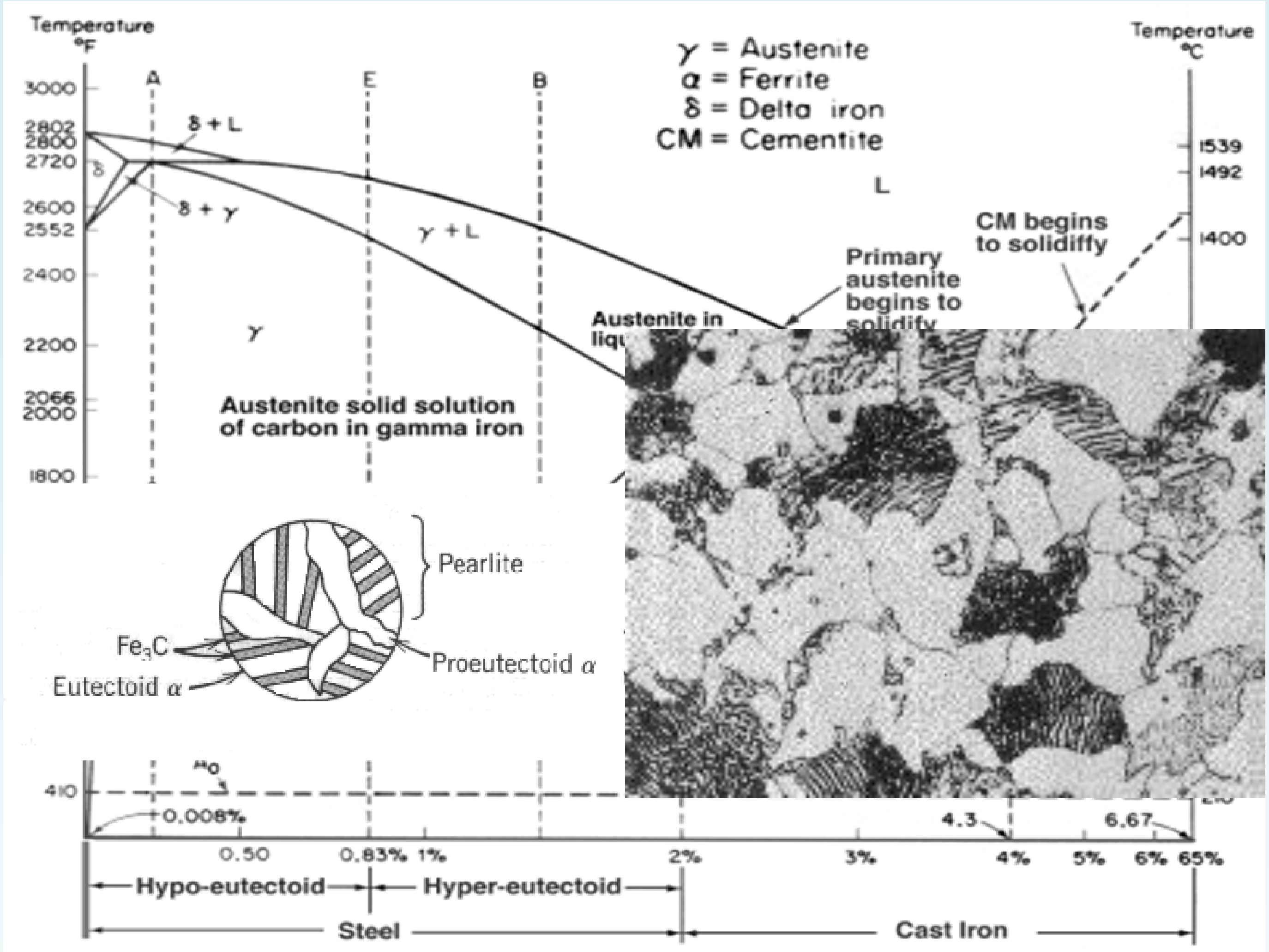

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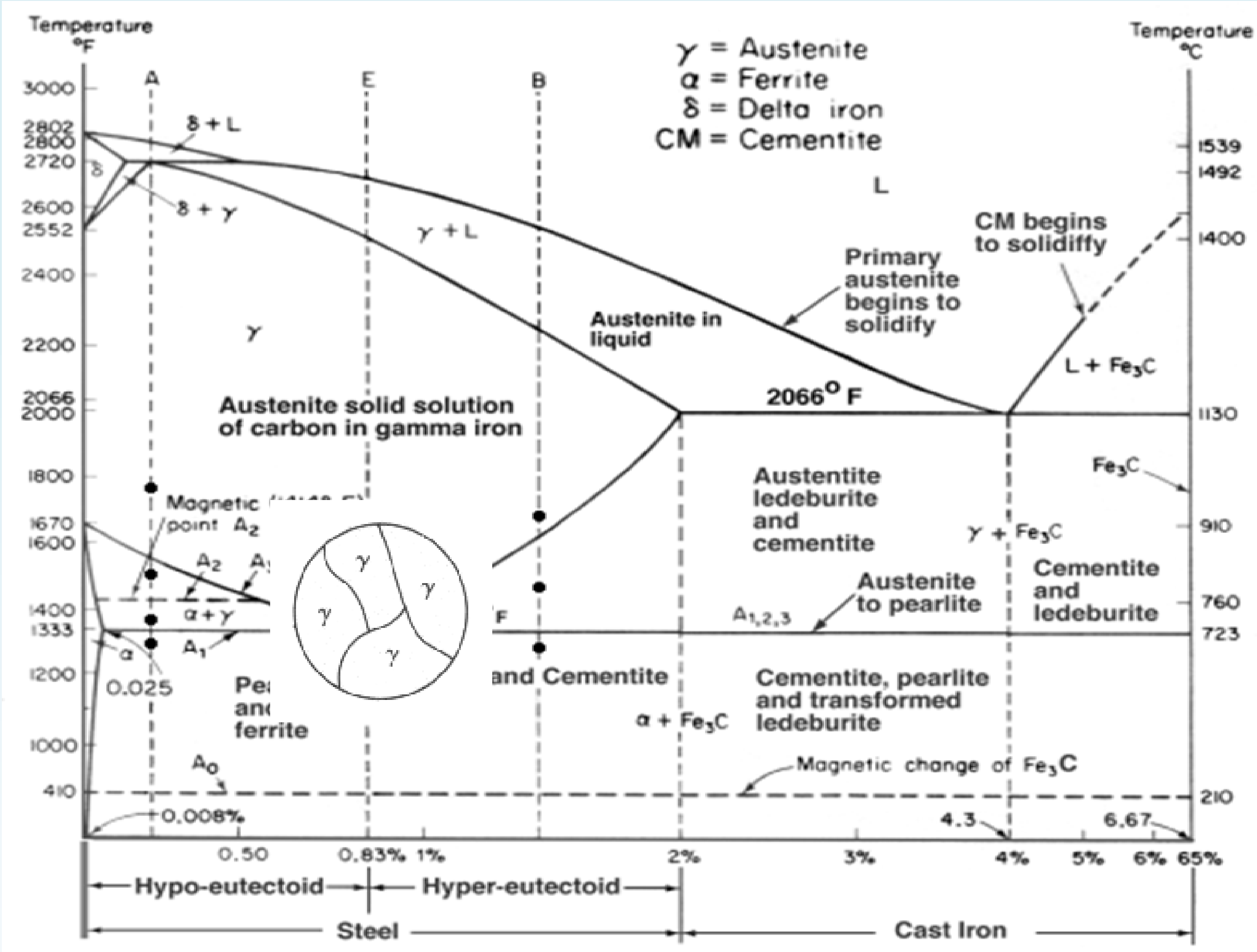

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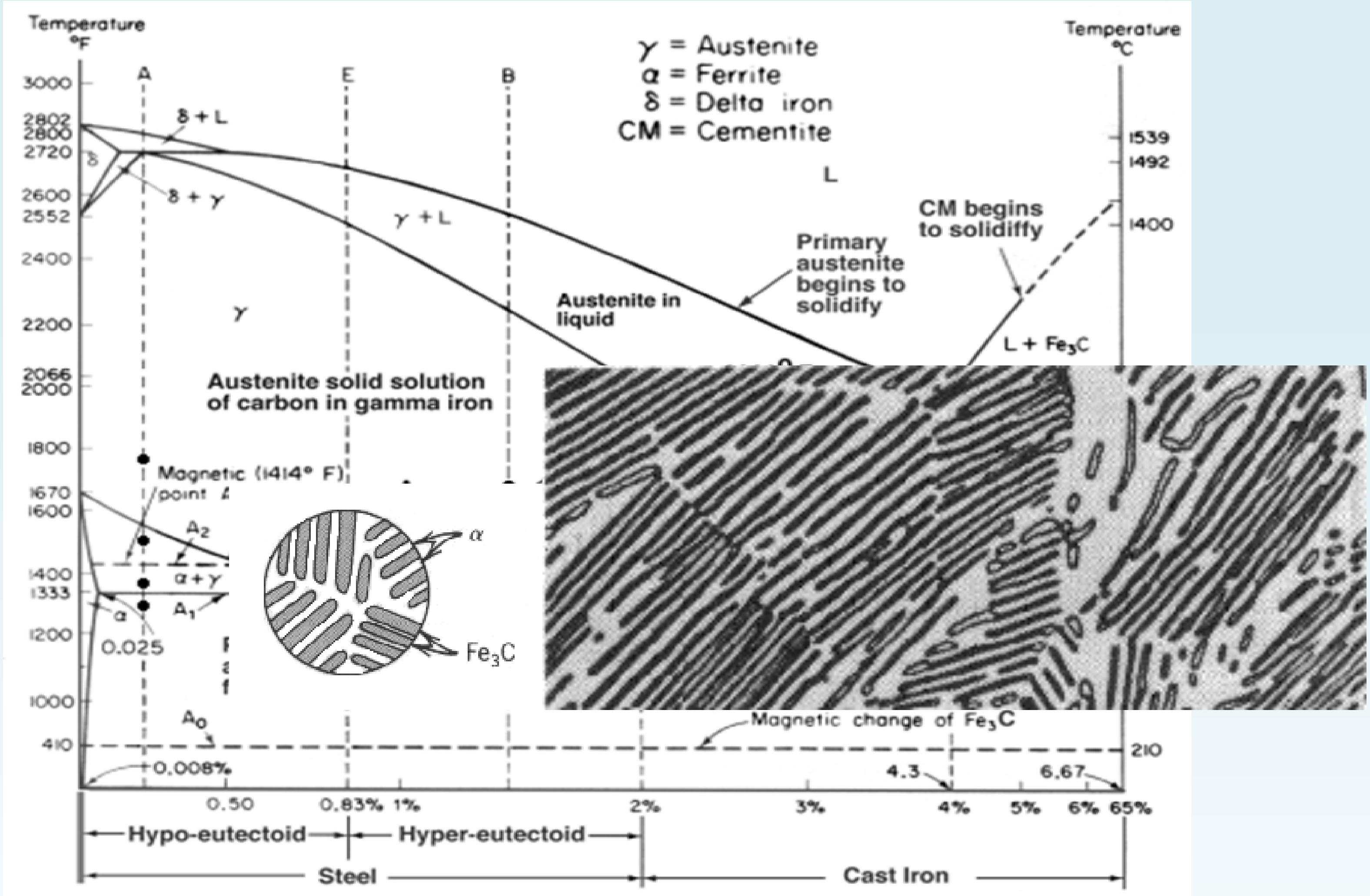

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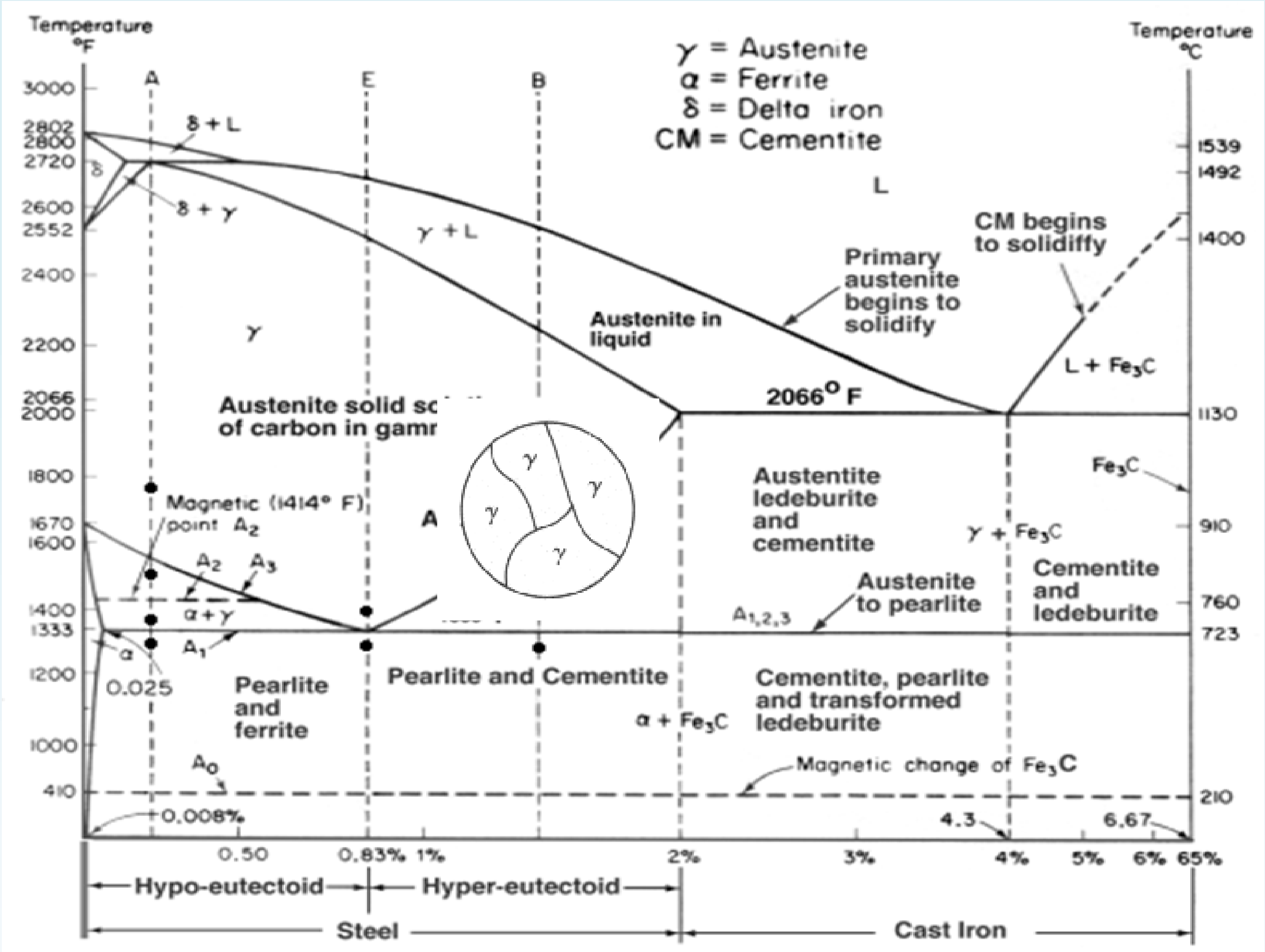

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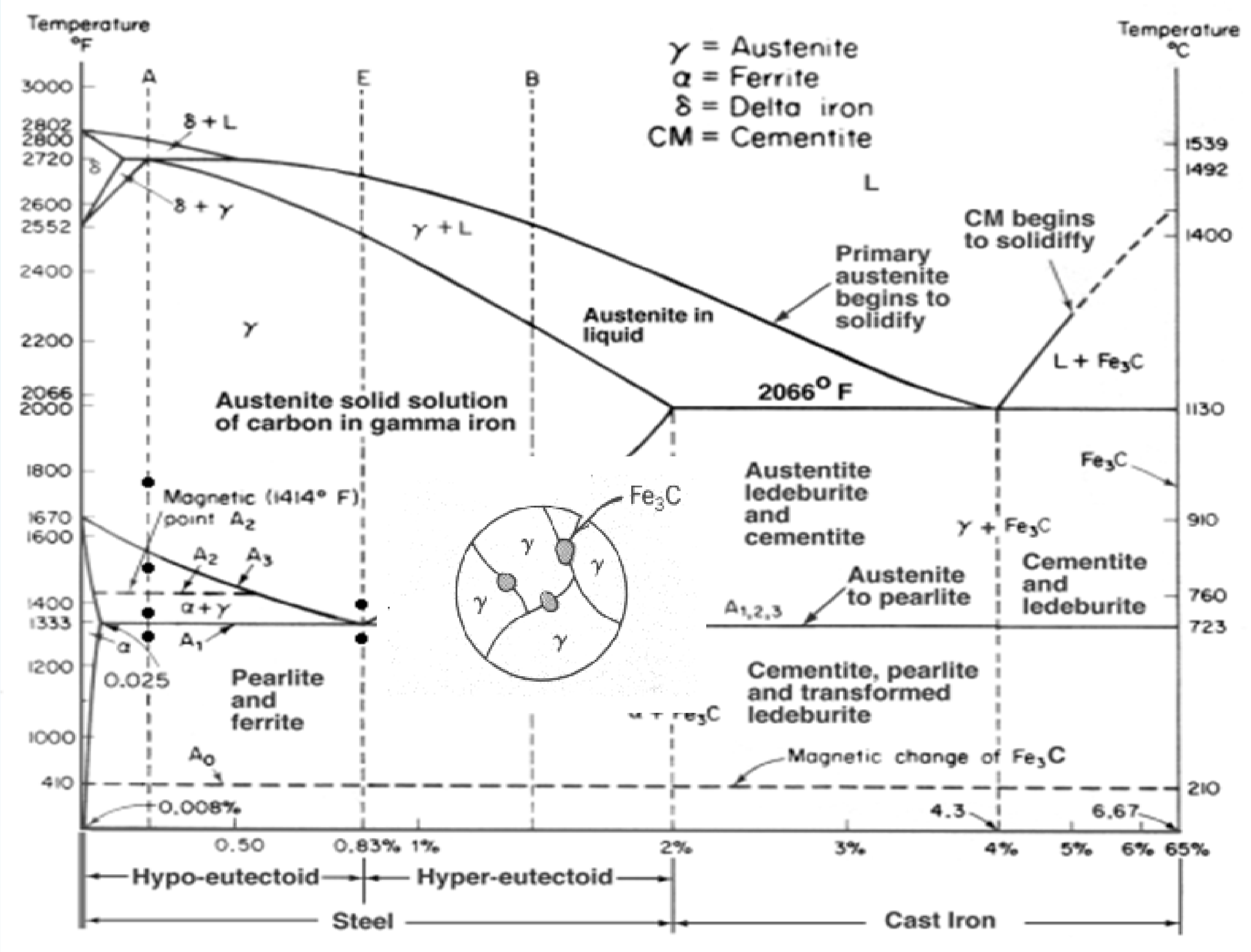

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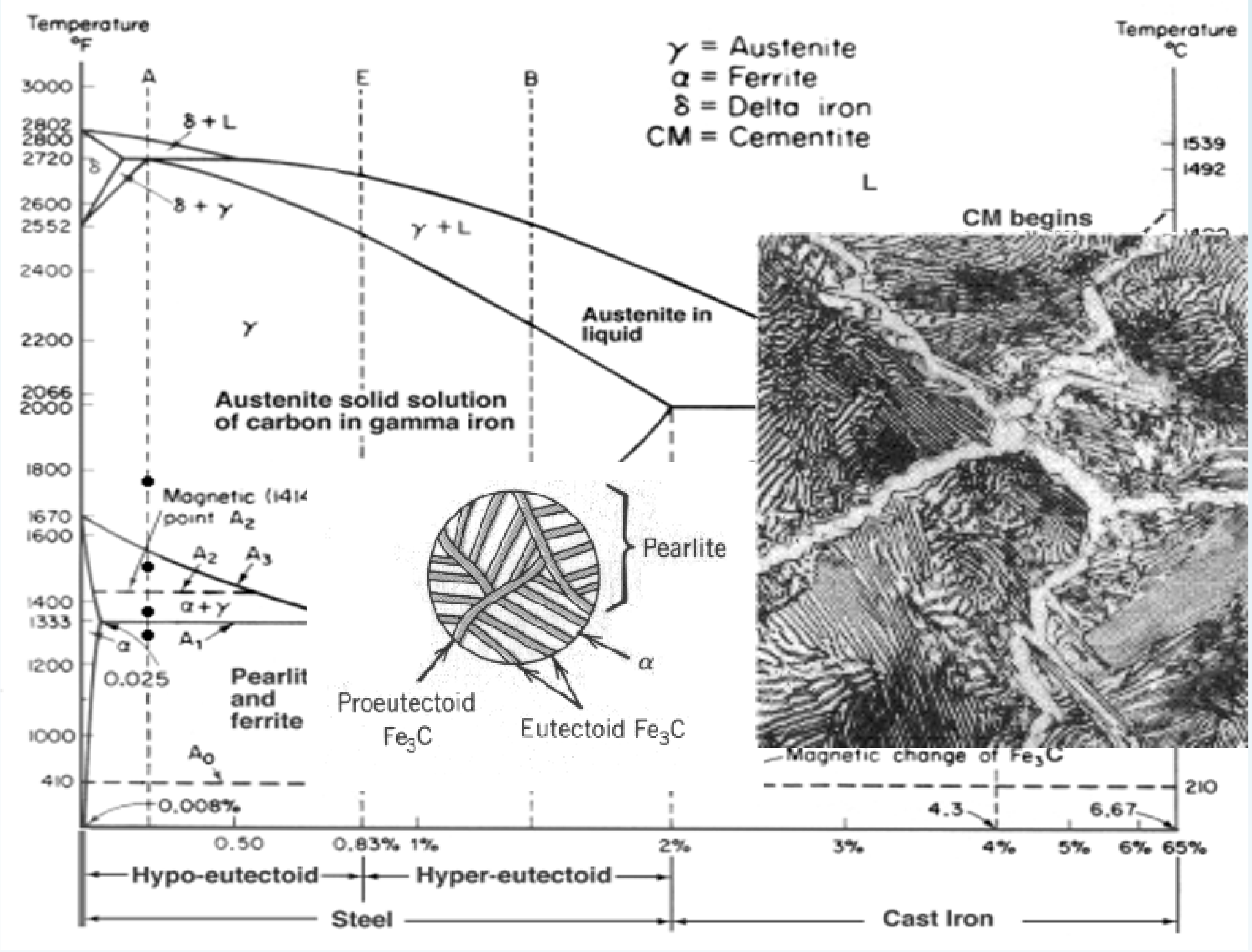


Fe-Fe$_3$C Phase Diagram (clickable),

Materials Science and Metallurgy, 4th ed., Pollack, Prentice-Hall, 1988

Fig 1:

Michael Kröning

Focus on Steel – Carbon Steels

The much larger phase field of gamma-iron (austenite) compared with that of alpha-iron (ferrite) indicates clearly the considerably greater solubility of carbon in gamma-iron (austenite).

At the low-carbon end of the metastable Fe-C phase diagram, ferrite (alpha-iron) can at most dissolve 0.028 wt. % C at 738 °C, austenite (gamma-iron), can dissolve 2.08 wt. % C at 1154 °C.

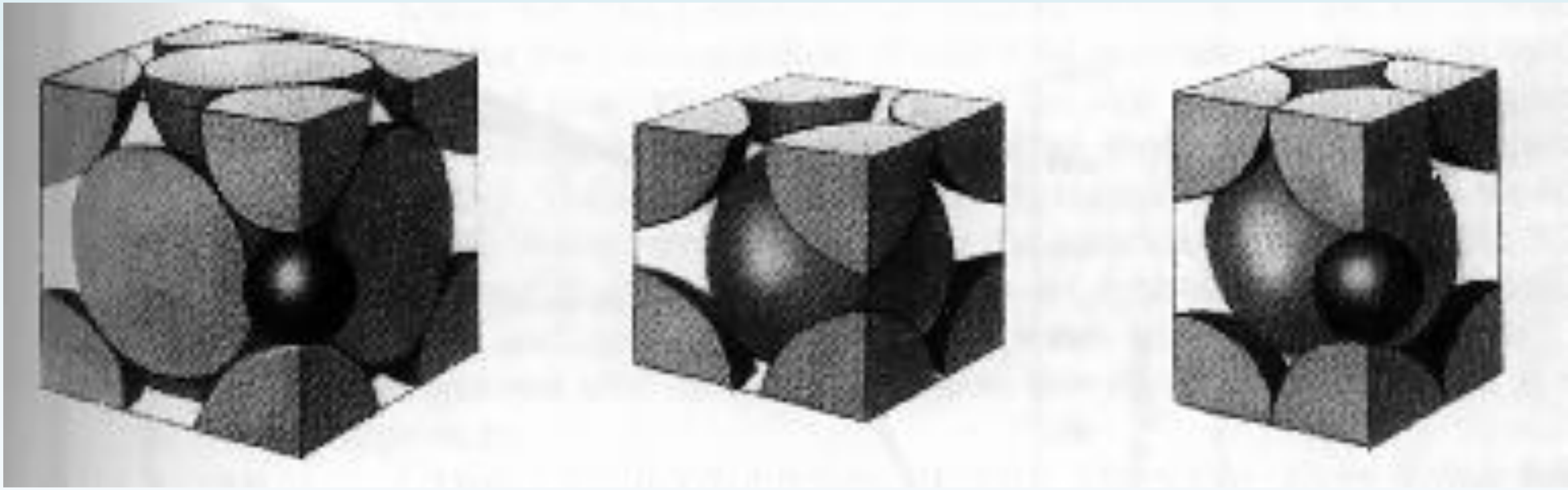
The hardening of carbon steels, as well as many alloy steels, is based on this difference in the solubility of carbon in alpha-iron (ferrite) and gamma-iron (austenite).

Focus on Steel – Carbon Steels

Gift of Nature

Only a small amount of carbon can be dissolved in ferrite; the maximum solubility is about 0.02 wt% at 723 °C and 0.005% carbon at 0 °C.

Carbon dissolves in iron interstitially, with the carbon atoms being about twice the diameter of the interstitial "holes", so that each carbon atom is surrounded by a strong local strain field



Carbon dissolved interstitially in bcc ferrite

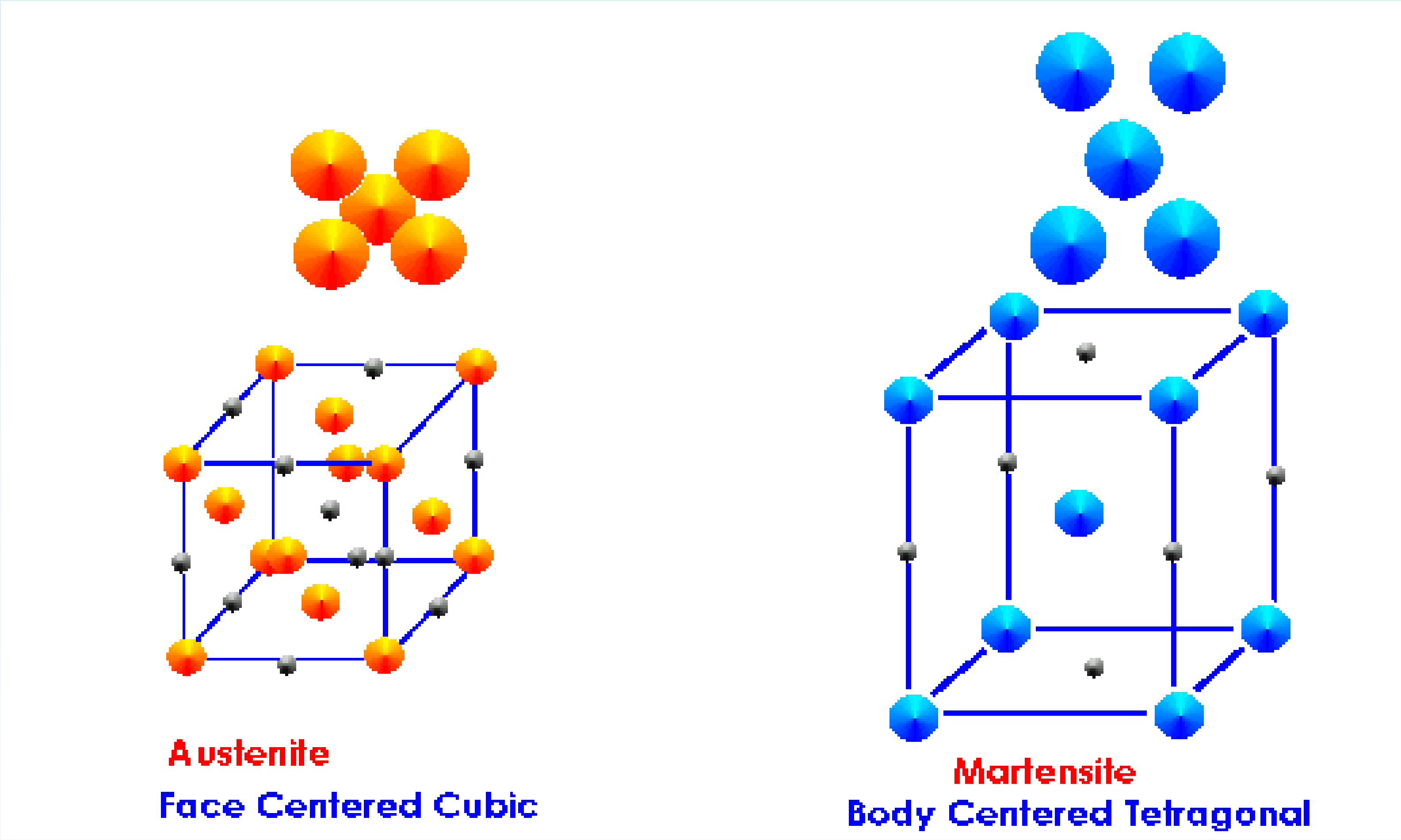
Diffusion needs time

What happens
when we don't give that time to Carbon atoms ?

Time Temperature Transformation Diagram (TTT-Diagram) will answer that question

Focus on Steel – Carbon Steels

2nd Gift of Nature: Martensite is 4.3% larger by Volume



Compressive Stress State

Literature

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2. Lejcek, Pavel. *Grain Boundary Segregation in Metals,* Springer Series in Materials Science, vol. 136, (2010), ISBN 978-3-642-12505-8
3. Ehrhart, P. *Properties and interactions of atomic defects in metals and alloys*, volume 25 of Landolt-Börnstein, New Series III, chapter 2, page 88, Springer, Berlin, 1991