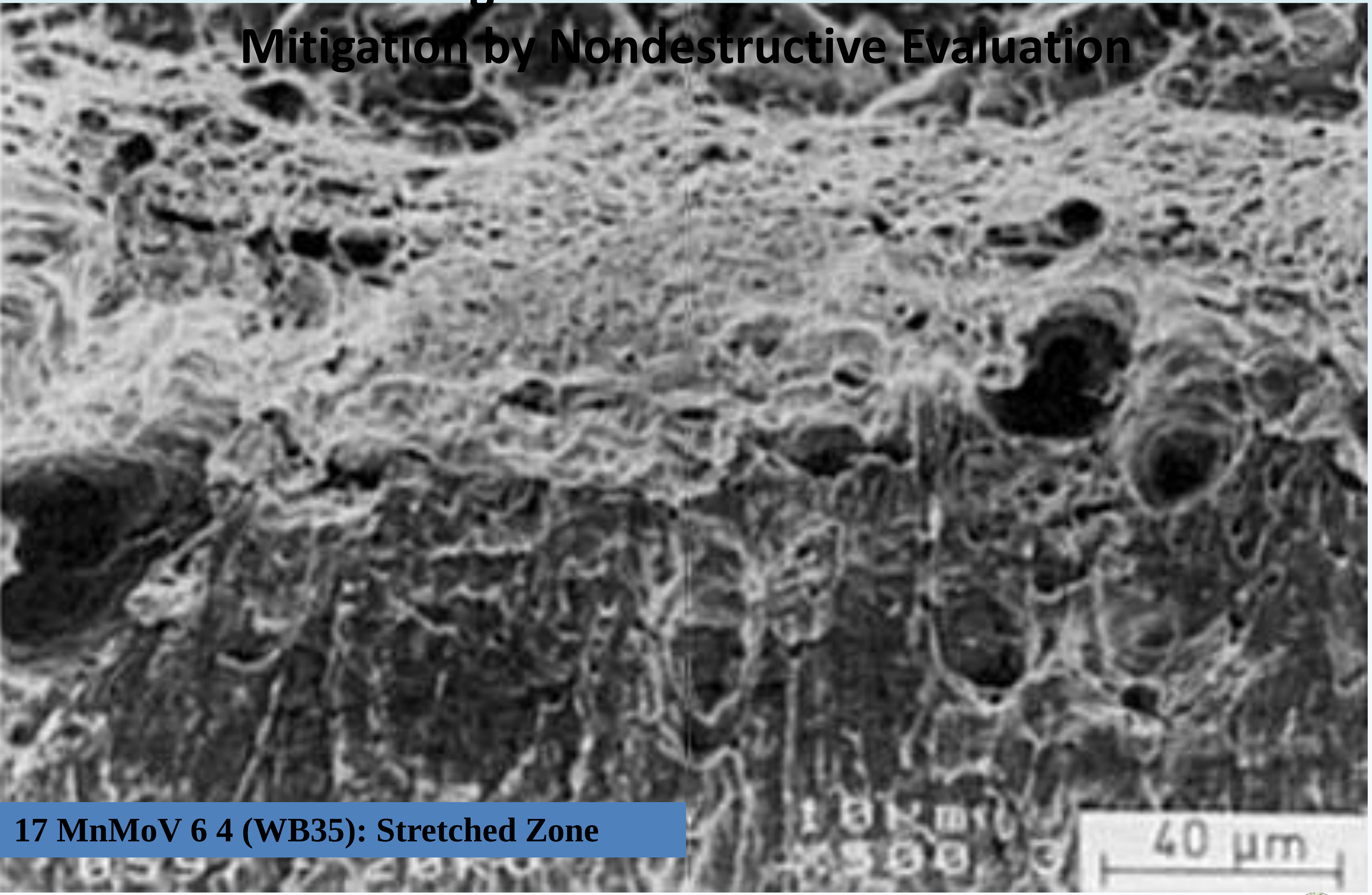
Material Degradation of Nuclear Structures
Mitigation by Nondestructive Evaluation



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

Making of Steel Properties

MICROSTRUCTURE

HEAT TREATMENT

changes the mechanical properties, usually ductility, hardness, yield strength, or impact resistance

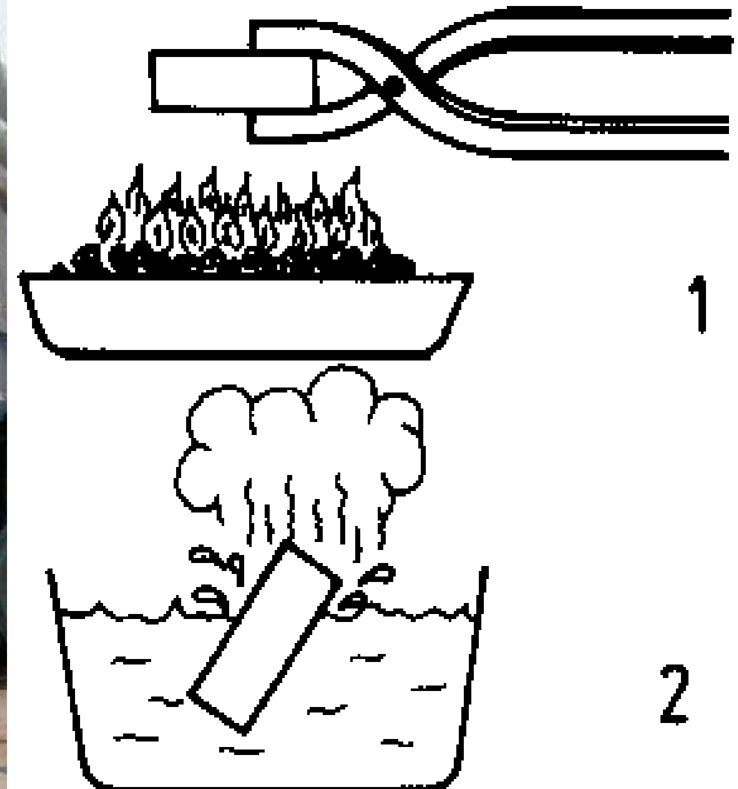
+

ALLOYING

enables the significant complexity of steel alloys by specific effects of various alloying elements

Tough & Strong

Focus on Steel – Carbon Steels



Heat treatment is a systematic sequence of various processes of "heating" and "cooling"

PURPOSE OF HEAT TREATING CARBON STEEL

Thermal treatment of steel is done for a variety of reasons, but these can generally be divided into three categories:

1. Reduce and relieve internal stresses
2. Reduce hardness and/or create a more uniform grain structure
3. Achieve specific mechanical properties

PURPOSE OF HEAT TREATING CARBON STEEL

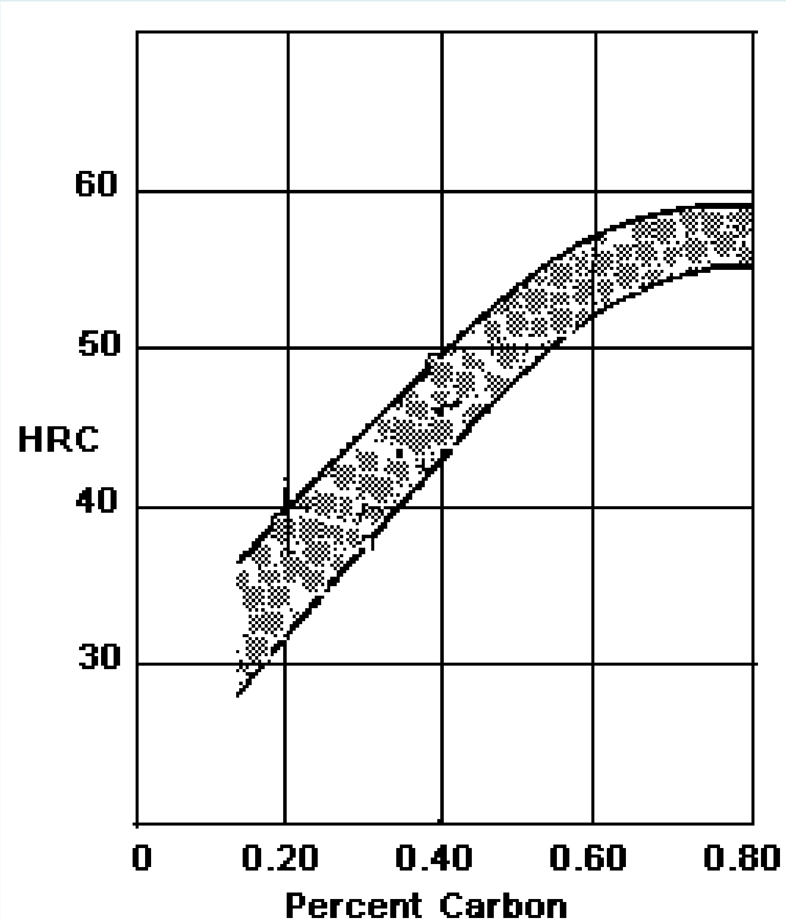
changing the mechanical properties of steel

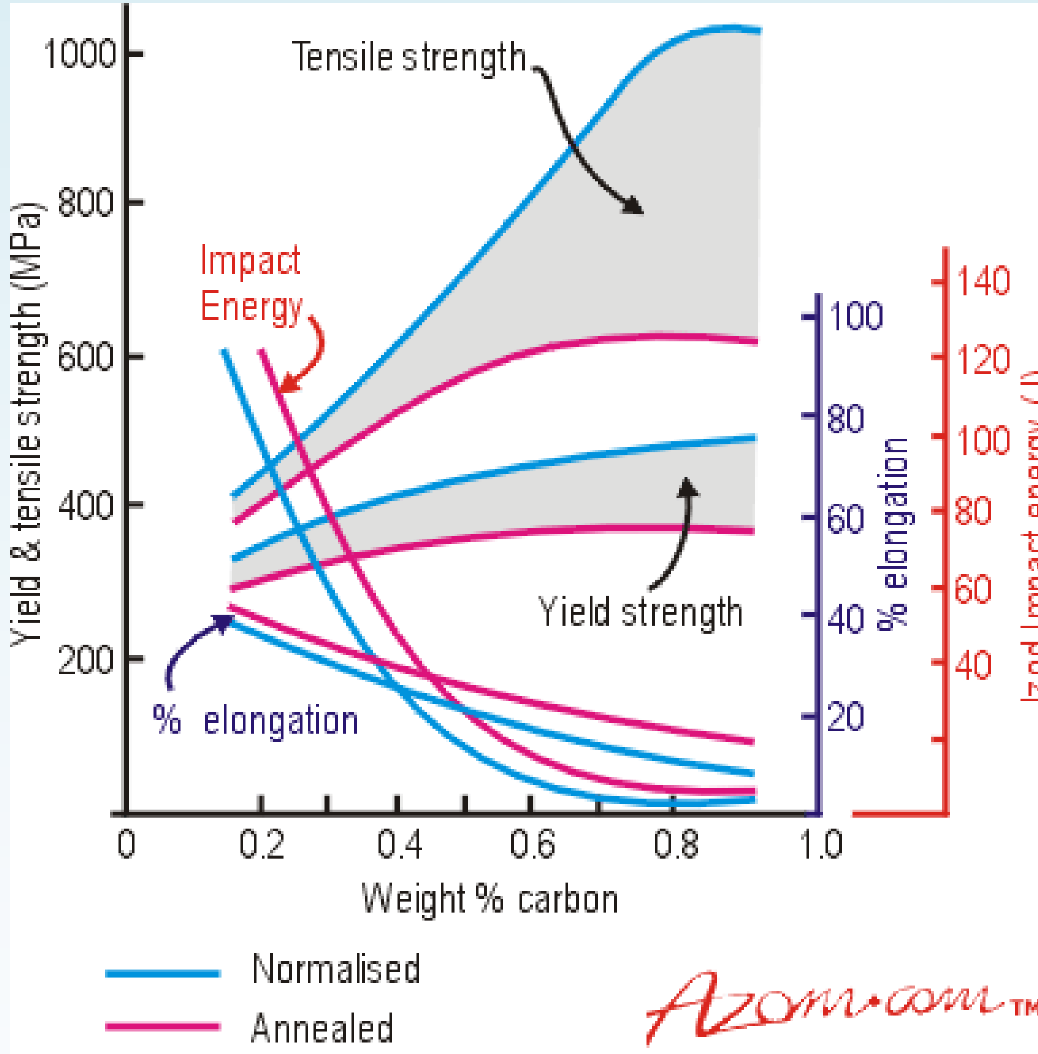
- **Ductility**
- **Hardness**
- **Yield Strength**
- **Impact Resistance**
- **Wear Resistance**

Note:

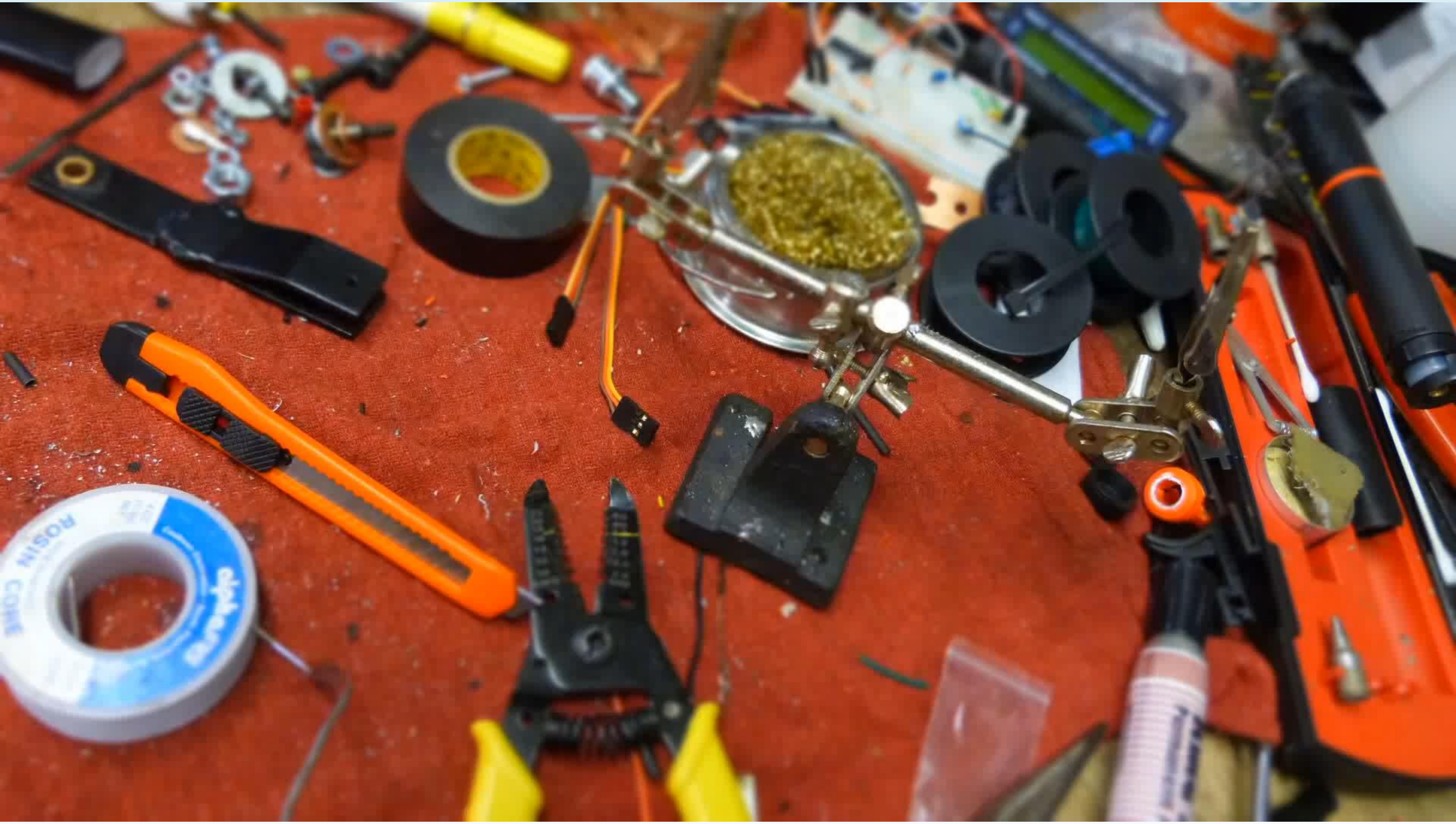
Electrical and thermal conductivity are only slightly altered.
Young's modulus (elasticity) is unaffected (Sound Velocity).
All treatments of steel trade ductility for increased strength and vice versa.

We know already: Effect of Carbon on Mechanical Properties





Heat Treatments
Transformation Diagrams



Heat Treatments
Transformation Diagrams

Heat treatments cause changes of microstructure by phase transformations

The changes depend on the way of heating/cooling;
Phase transformations do not occur instantaneously.
Diffusion-dependent phase transformations can be rather slow and the final structure often depend on the rate of cooling/heating.

We can assess microstructure changes by transformation diagrams but we need to consider the time dependence or kinetics of the phase transformations

Heat Treatments
Microstructural Transformations

PHASE TRANSFORMATIONS → **MICROSTRUCTURAL TRANSFORMATIONS**

Phases

Phases can transform

Phase Transformation

Geometrical
Structural

Physical
Property

Defects

Defect structures can change

Defect Structure Transformation

Residual stress

Stress state can be altered

Stress-State Transformation

Heat Treatments

Based on Mass transport

PHASE TRANSFORMATIONS

- **Diffusional** — Involves long range mass transport
- **Diffusionless** — E.g. Martensitic

Based on order

PHASE TRANSFORMATIONS

- 1^{nd} order — *nucleation & growth*
- 2^{nd} (& higher) order — *Entire volume transforms*

Three Categories of Phase Transformations:

Diffusion-dependent

no change in phase composition or number of phases present

(melting, solidification of pure metal, allotropic transformations, recrystallization, etc.)

Diffusion-dependent

with changes in phase compositions and/or number of phases

(e.g. eutectoid transformations)

Diffusionless phase transformation

produces a metastable phase
by cooperative small displacements of all atoms in structure

(e.g. martensitic transformation)

UNDERSTAND THE DIFFERENCE:

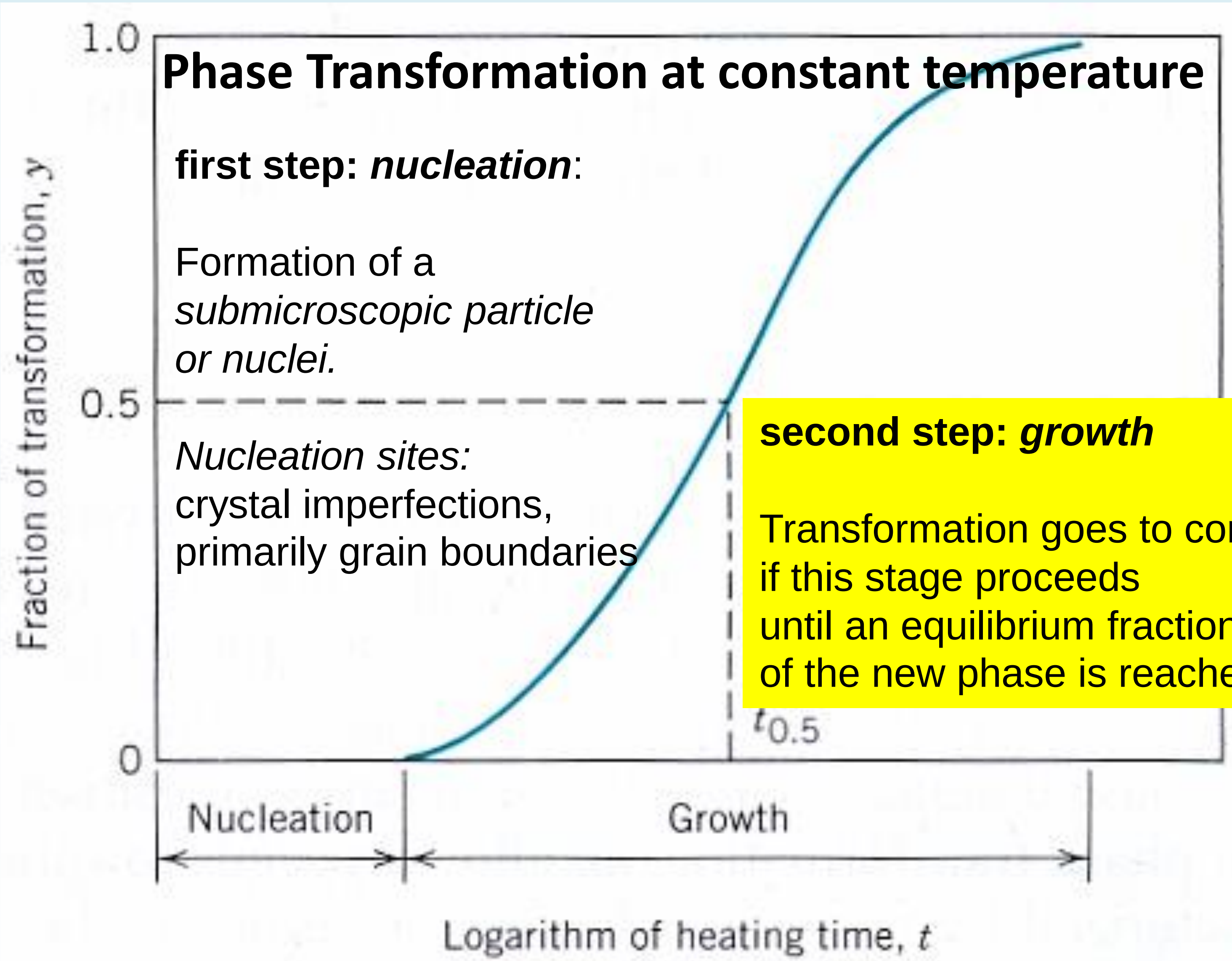
CRYSTALS	MICROSTRUCTURE
Ferrite	Pearlite
Austenite	Bainite
Cementite	Ledeburite
Graphite	Tempered martensite
Martensite	Widmanstätten structure

Products of Austenitic Transformations

Microconstituents	Description
• Pearlite	•Transformation rate increases with decreasing temperature • Coarse pearlite: alternating ferrite and cementite layers are relatively **thick** • Fine pearlite: alternating ferrite and cementite layers are relatively **thin** •Formed between 540 °C to 727 °C (above the nose)
Bainite	•Forms at temperatures between those at which pearlite and martensite transformation occurs • microstructure consists of α-ferrite and fine dispersion of cementite •Formed between 215 °C to 540 °C (below the nose)
Spheroidite	•Steel alloy composed of either pearlitic or bainitic microstructures is heated and held at a temperature below the eutectoid point for a long time (example: ≈700 °C for 18 – 24 h) •Sphere-like particles
Martensite	•A metastable iron phase supersaturated in carbon that is the product of a diffusionless transformation from austenite •Quenched to a relatively low temperature

Microconstituent	Phases Present	Arrangement of Phases	Mechanical Properties (Relative)
Spheroidite	α Ferrite + Fe_3C	Relatively small Fe_3C sphere-like particles in an α -ferrite matrix	Soft and ductile
Coarse Pearlite	α Ferrite + Fe_3C	Alternating layers of α -ferrite and Fe_3C that are relatively thick	Harder and stronger than spherodite, but not as ductile as spherodite
Fine Pearlite	α Ferrite + Fe_3C	Alternating layers of α-ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in a α-ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered Martensite	α Ferrite + Fe_3C	Very small Fe_3C sphere-like particles in an α-ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

Heat Treatments
Kinetics of Solid–State Reactions



Phase Transformation at constant temperature

first step: *nucleation*:

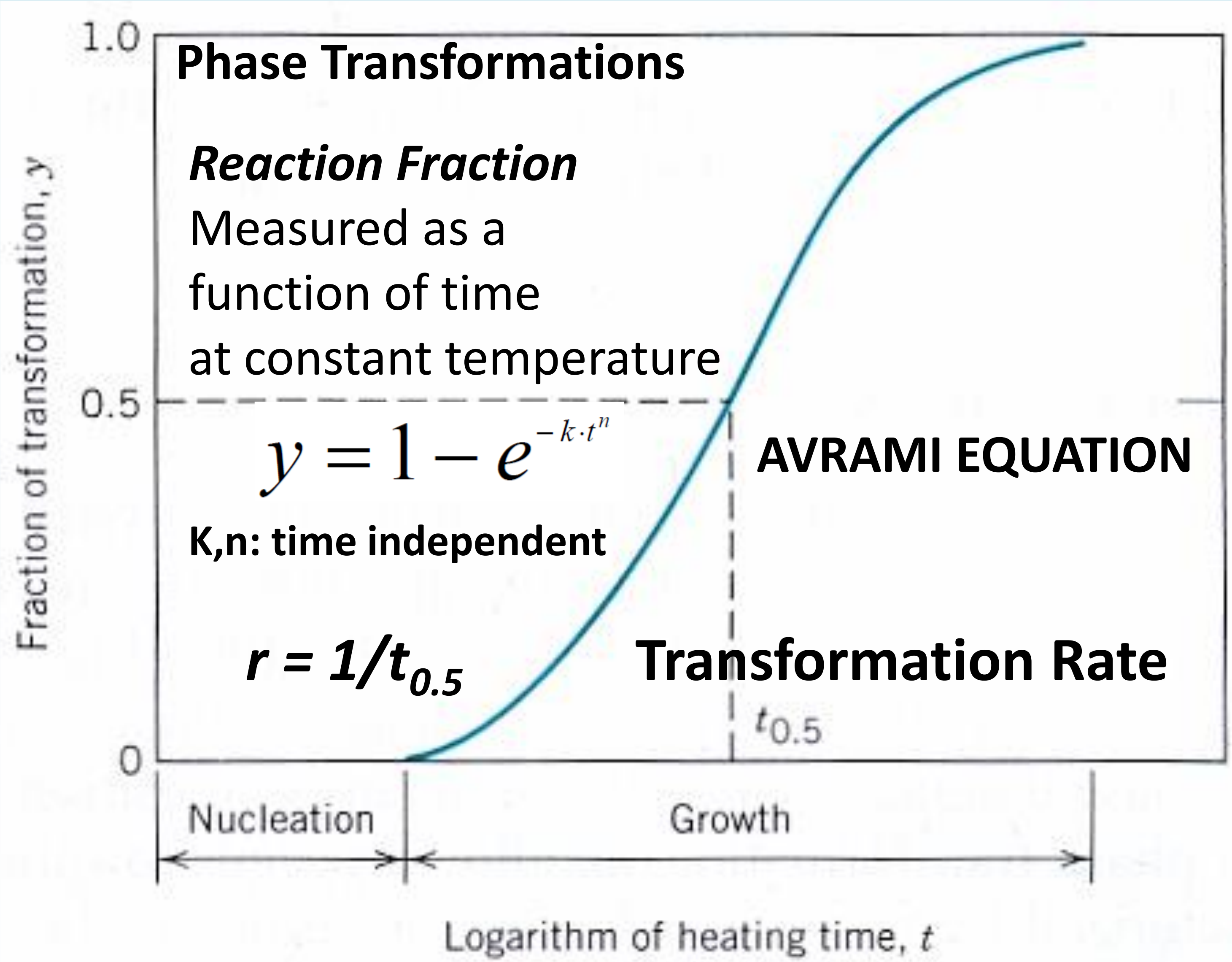
Formation of a
*submicroscopic particle
or nuclei.*

Nucleation sites:
crystal imperfections,
primarily grain boundaries

second step: *growth*

Transformation goes to completion
if this stage proceeds
until an equilibrium fraction
of the new phase is reached..

Heat Treatments
Kinetics of Solid –State Reactions



Heat Treatments
Kinetics of Solid –State Reactions

Thermally Activated Transformation Rate

$$r = A\, e^{-Q/RT}$$

(similar to the temperature dependence of the diffusion constant D)

Diffusion Constant D in Solids

$$D = D_0 \cdot \exp\left(-\frac{E}{R \cdot T}\right)$$

Arrhenius Equation

Diffusion Constants for Iron

System	Temperature (°C)	Diffusion Constant (m^2s^{-1})
Hydrogen	10	$1{,}66 \times 10^{-13}$
	50	$11{,}4 \times 10^{-13}$
	100	124×10^{-13}
Carbon	800	15×10^{-13}
	1100	450×10^{-13}

The diffusion coefficient in solids at different temperatures is generally found to be well predicted by :

$$D = D_0 e^{-E_A/(RT)}$$

ARRHENIUS EQUATION

Where

D	**the diffusion coefficient (m^2 / s)**
D_0	the maximum diffusion coefficient (at infinite temperature; m^2 / s)
E_A	the activation energy for diffusion (J mol^{-1})
T	the temperature (K)
R	the gas constant (J K^{-1} mol^{-1})

Gibbs Free Energy: $G = U - TS$

where U = Internal Energy, T = Absolute Temperature, and S = Entropy

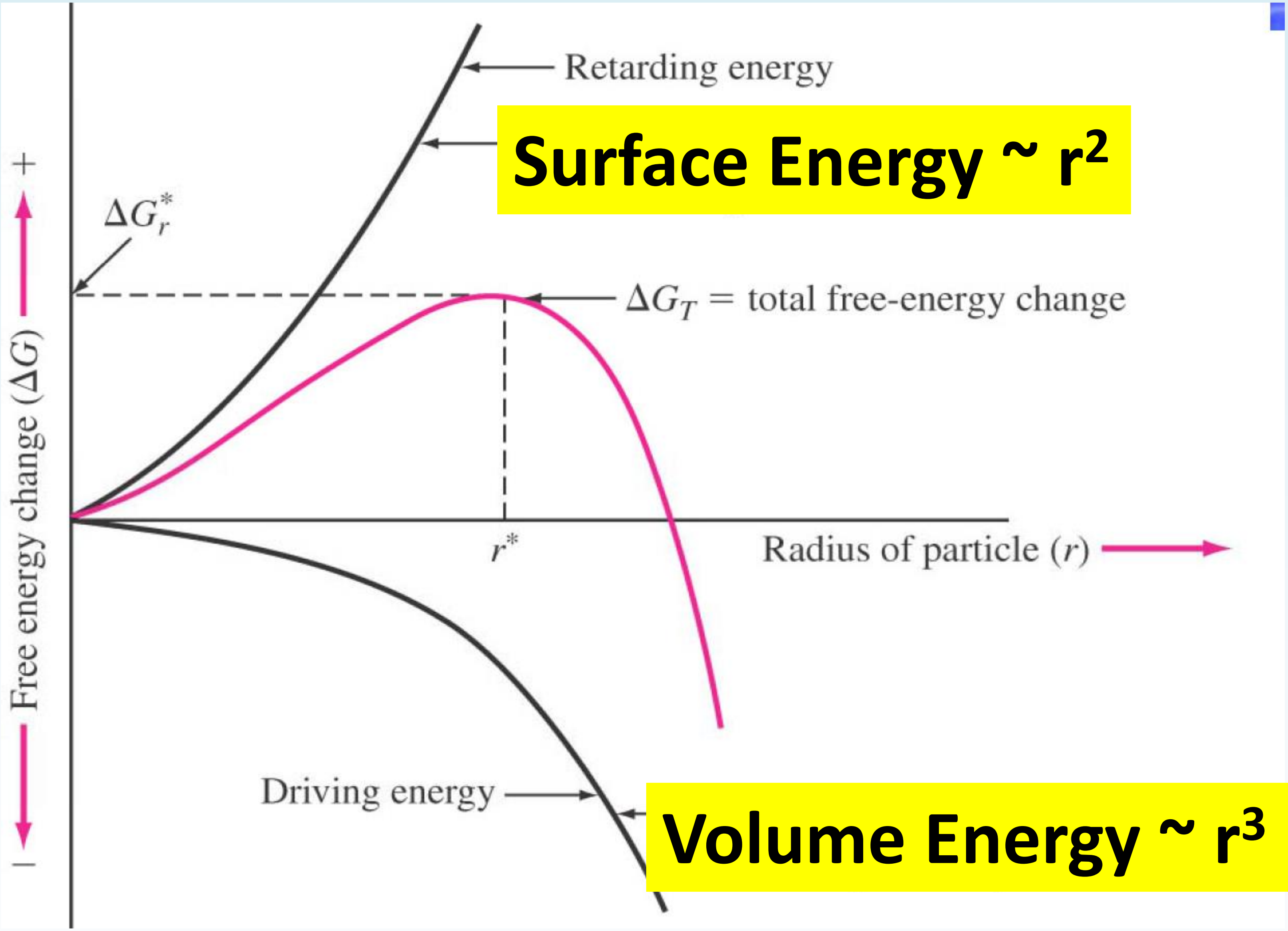
driving "force" for the phase transformation: difference in G between the old and new phases

Note:

The release of heat when a metal solidifies indicates that the crystalline phase has a lower Gibbs Free Energy, G, than the liquid.

At the equilibrium freezing temperature the Gibbs Free Energy of the liquid and the crystalline phase are equal.

Heat Treatments
Kinetics of Solid –State Reactions



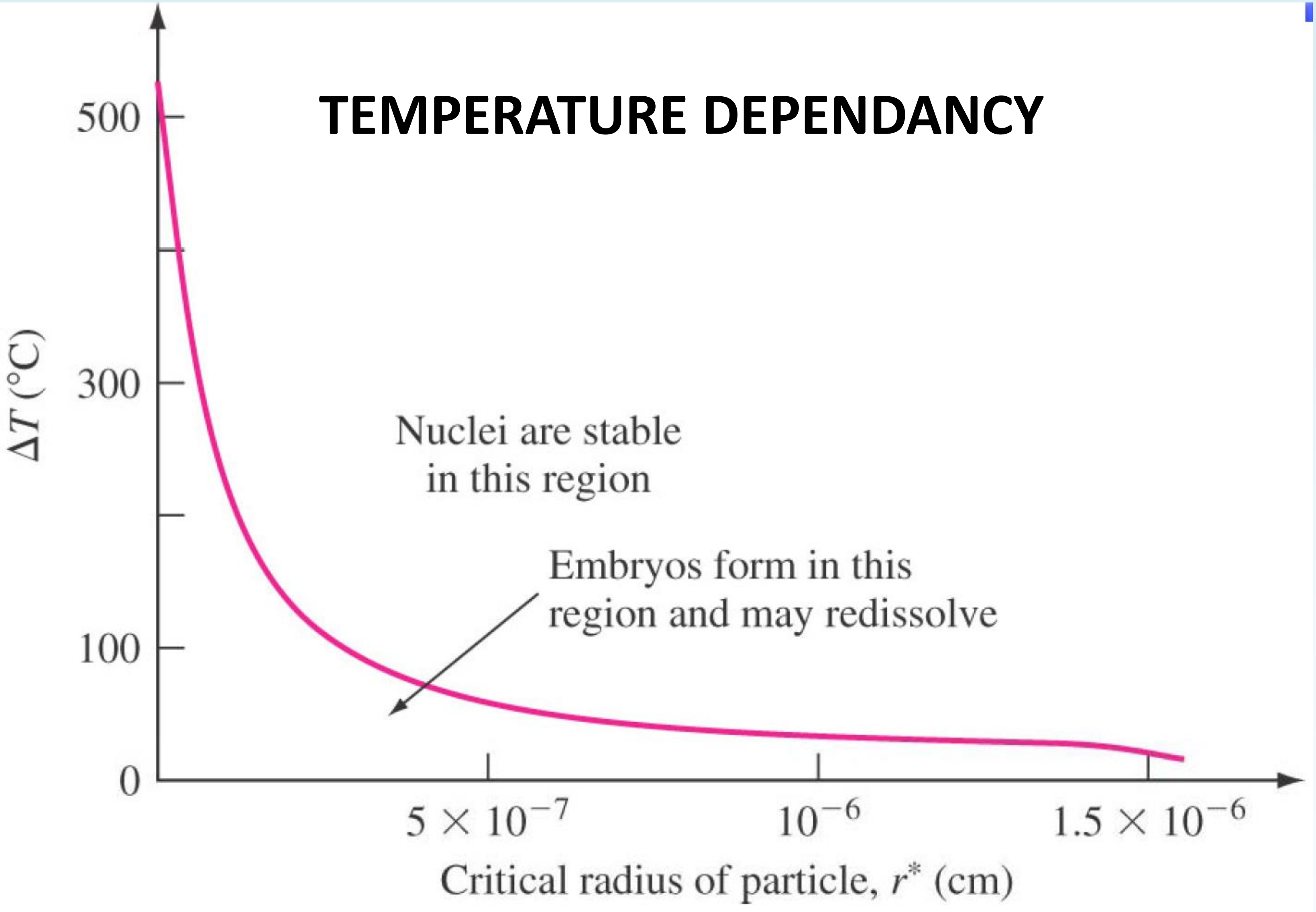
Critical Nucleus Radius r*

$$\frac{d(\Delta G)}{dr} = 0!$$

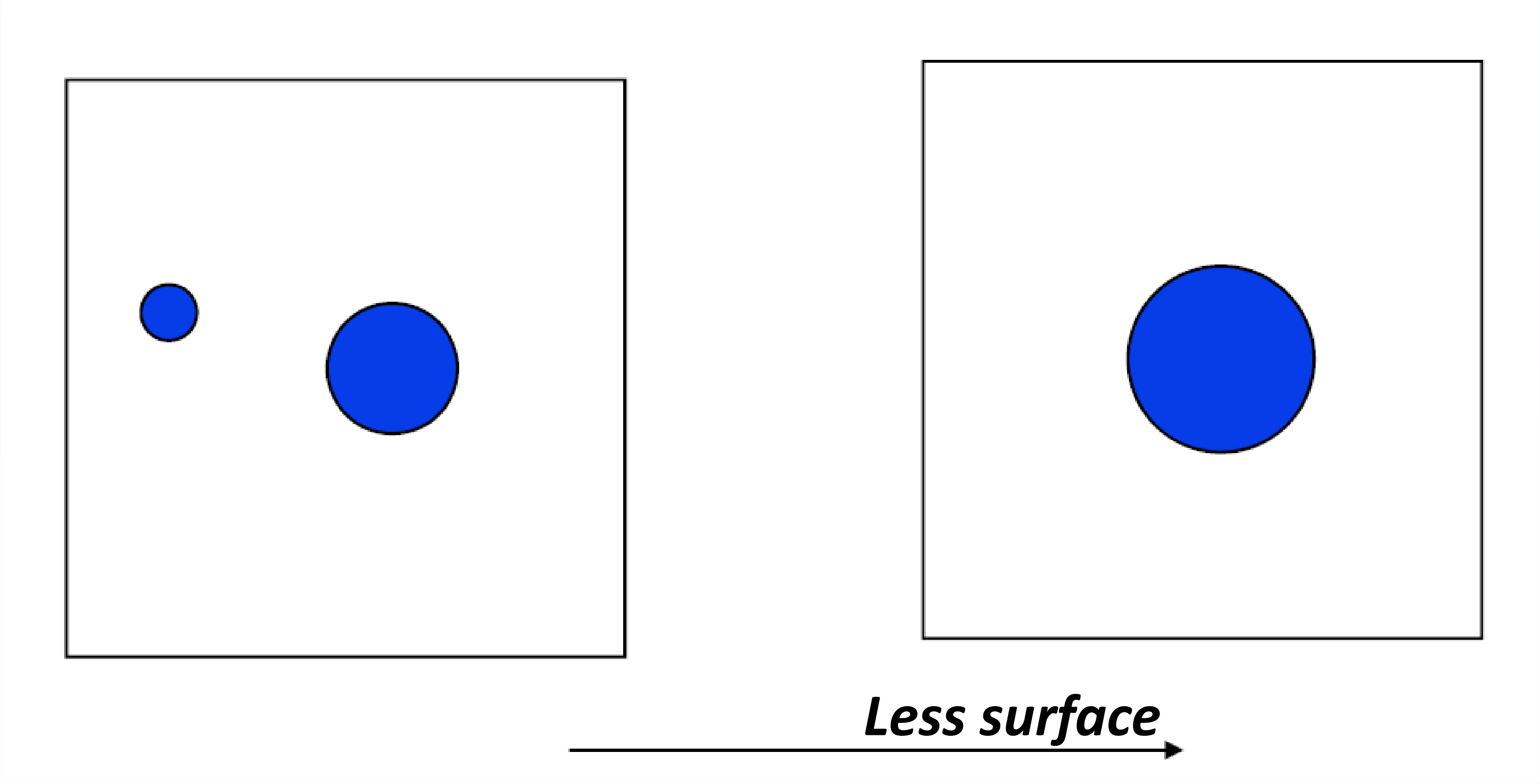
with

$$\Delta G = \frac{4}{3}\pi r^3 G_V - 4\pi r^2 \gamma$$

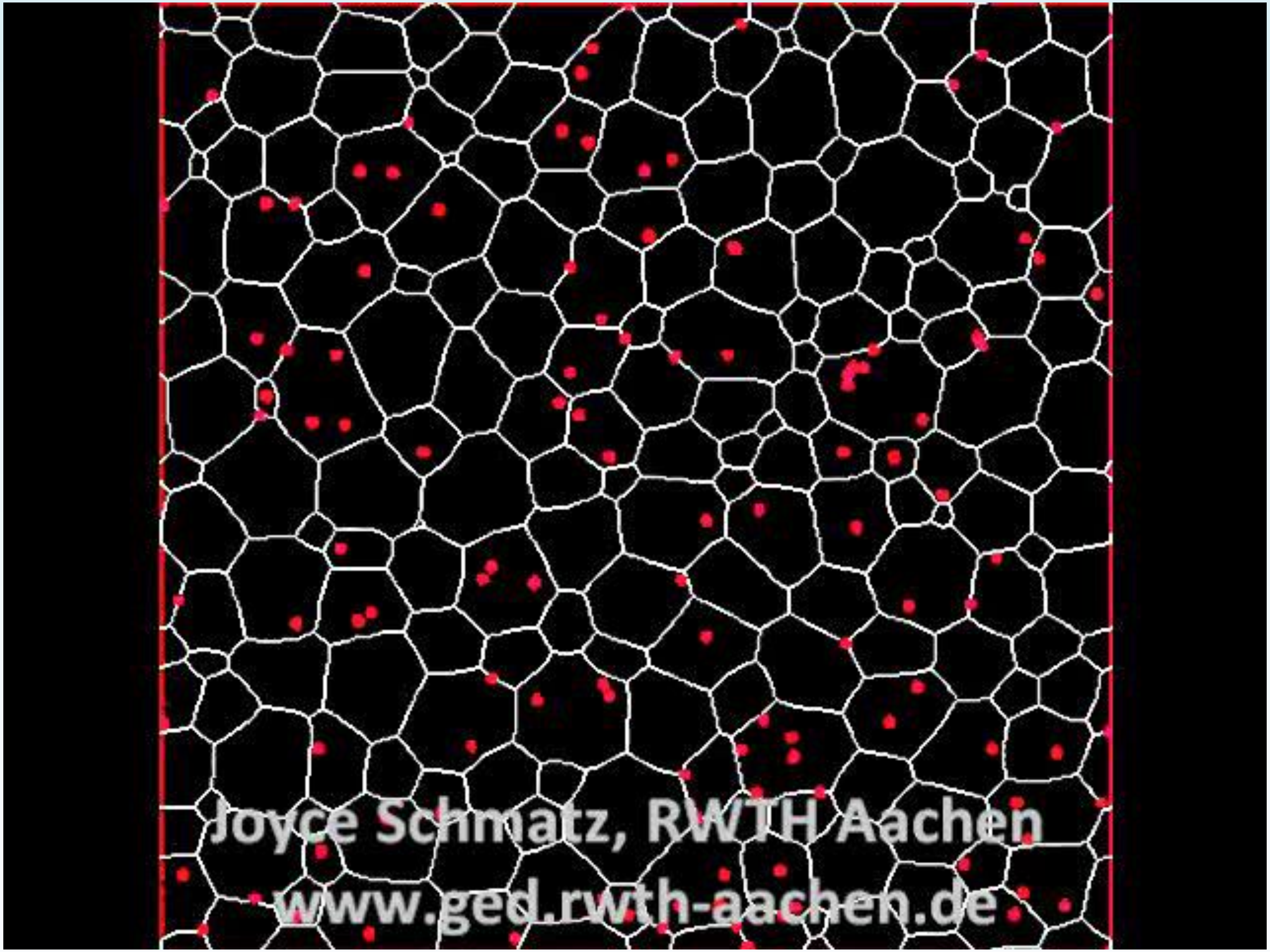
$$r^* = -\frac{2\gamma}{\Delta G}$$


TEMPERATURE DEPENDANCY
500
300
100
0
ΔT (°C)
Nuclei are stable in this region
Embryos form in this region and may redissolve
5 × 10⁻⁷
10⁻⁶
1.5 × 10⁻⁶
Critical radius of particle, r* (cm)

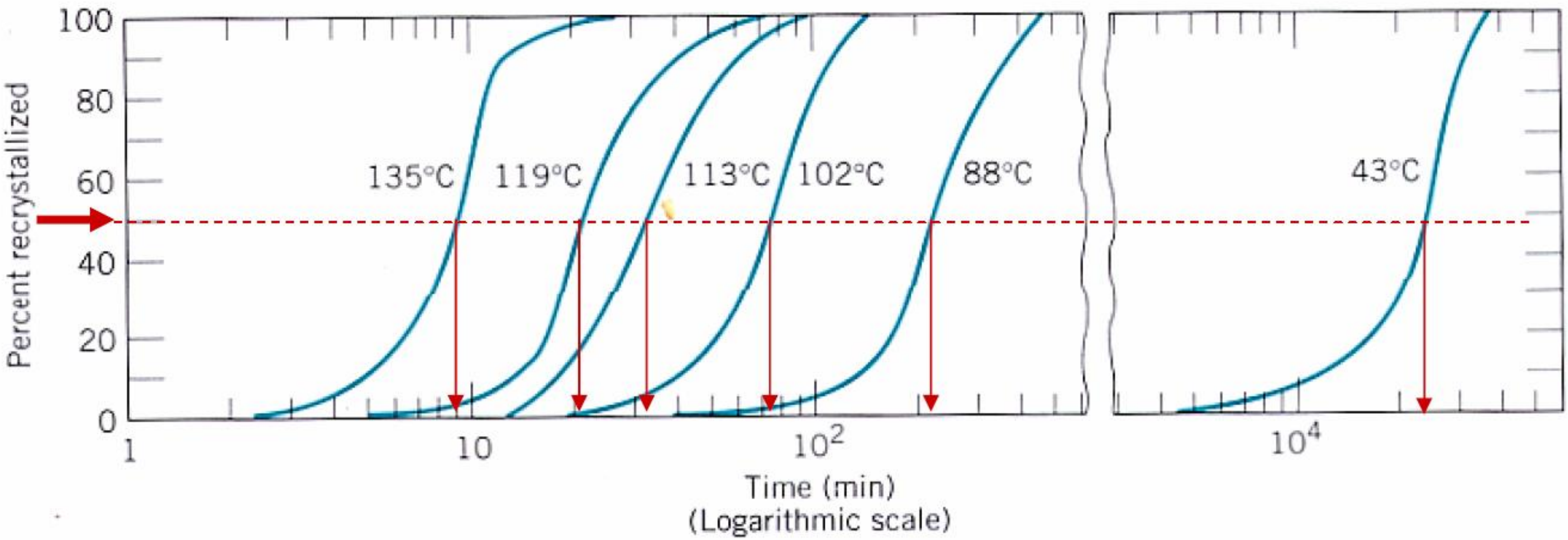
GRAIN COARSENING
An effect of minimization of the surface energy



Heat Treatments
Kinetics of Solid –State Reactions

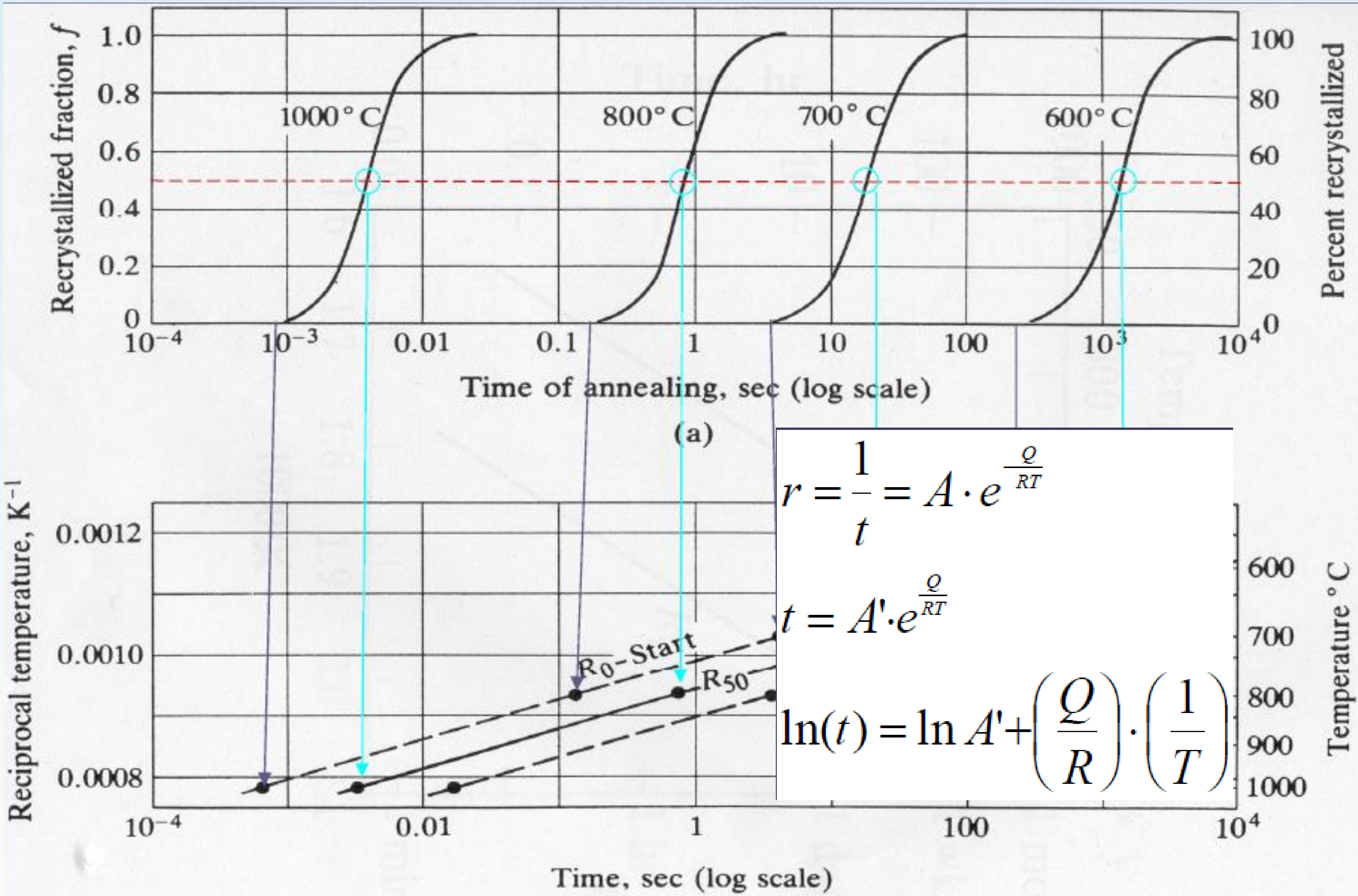


Temperature has an important impact on the kinetics of any solid state transformation.



TEMPERATURE DEPENDANCY

Heat Treatments
Kinetics of Solid –State Reactions



$$r = \frac{1}{t} = A \cdot e^{-\frac{Q}{RT}}$$

$$t = A' \cdot e^{\frac{Q}{RT}}$$

$$\ln(t) = \ln A' + \left(\frac{Q}{R}\right) \cdot \left(\frac{1}{T}\right)$$

Hardening

a metallurgical and metalworking process
used to increase the hardness of a metal

Grain Boundary Strengthening (Hall-Petch Method)

Grain boundary strengthening by fine grained microstructure. The increased number of dislocations running into grain boundaries form strong dislocation barriers. In general, smaller grain size will make the material harder

Work Hardening (Cold Working)

Plastic straining generate new dislocations. With increasing dislocation density, further dislocation movement becomes more difficult since they hinder each other. The material hardness increases.

Precipitation Hardening (Age Hardening)

A second phase in solid solution with the matrix metal is precipitated out of solution with the metal as it is quenched, leaving particles of that phase distributed throughout to cause resistance to slip dislocations

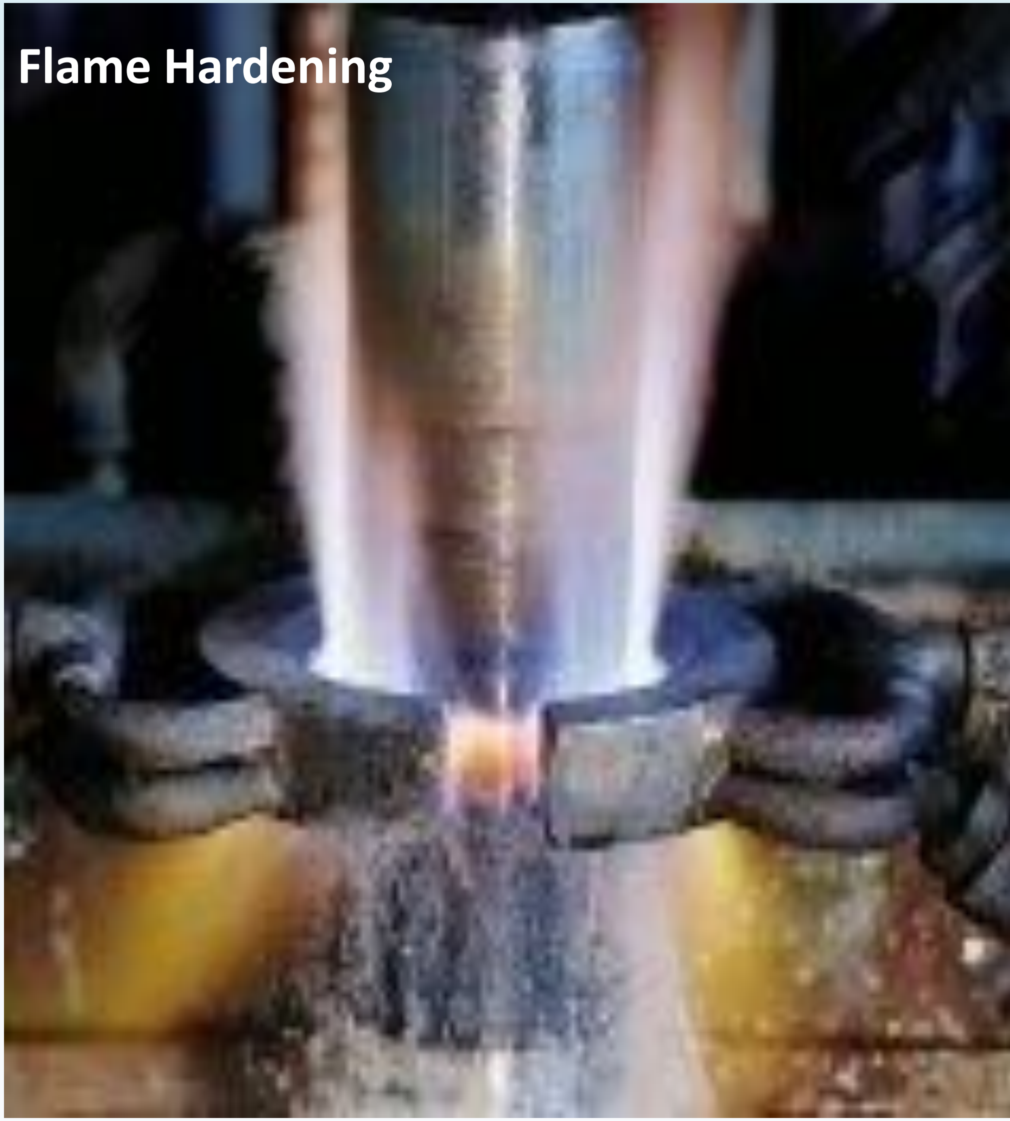
Martensitic Transformation (Quenching & Tempering)

Hardening by Martensitic Transformation

Steel hardening is performed
to impart strength and hardness.

Steel is heated up
to austenitic region
and held there
until its carbon is dissolved,
and then cooled rapidly.

The carbon does not get
sufficient time to escape
and get dissipated
in the lattice structure.
This helps in locking
the dislocation movements
when stresses are applied.



Quenching

Quenching is performed to cool hot metal rapidly by immersing it in brine*, water, oil, molten salt, air or gas.

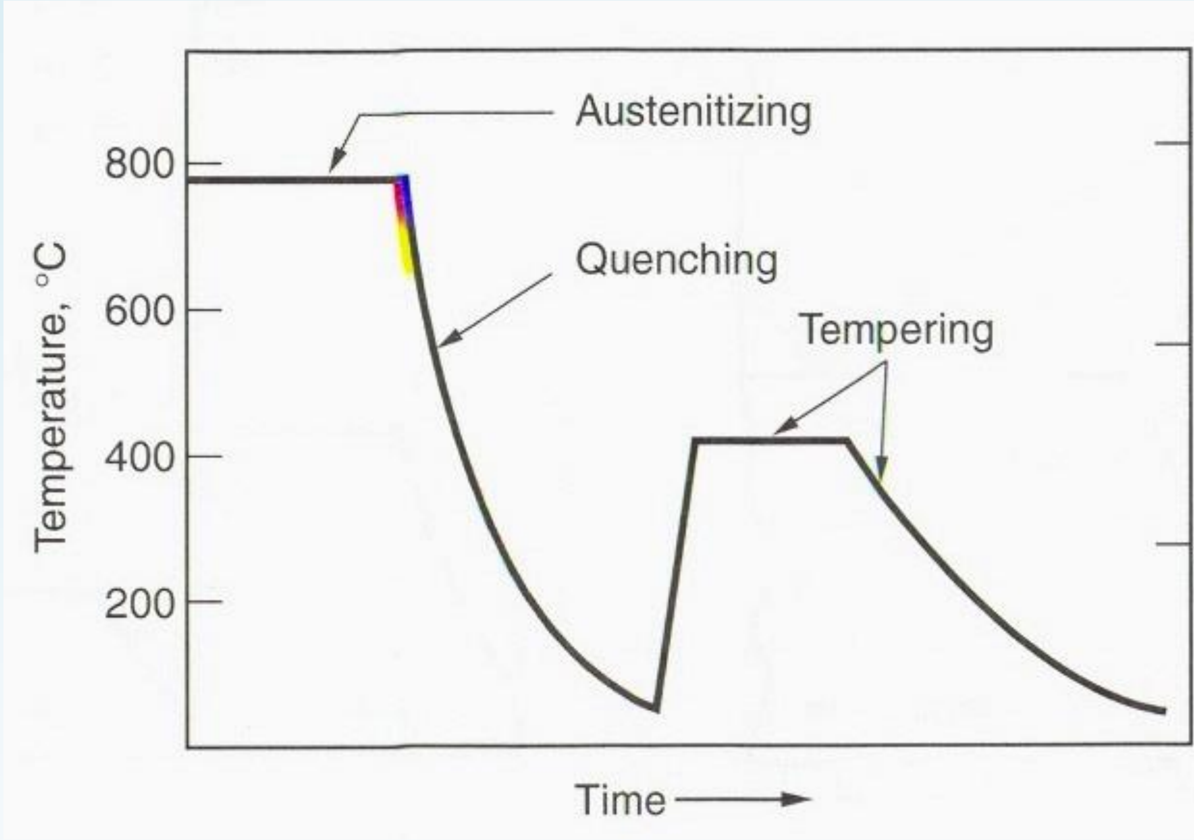
Brine: salt water

Quenching sets up residual stresses in the work piece and sometimes results in cracks.

Heat Treatments
Tempering

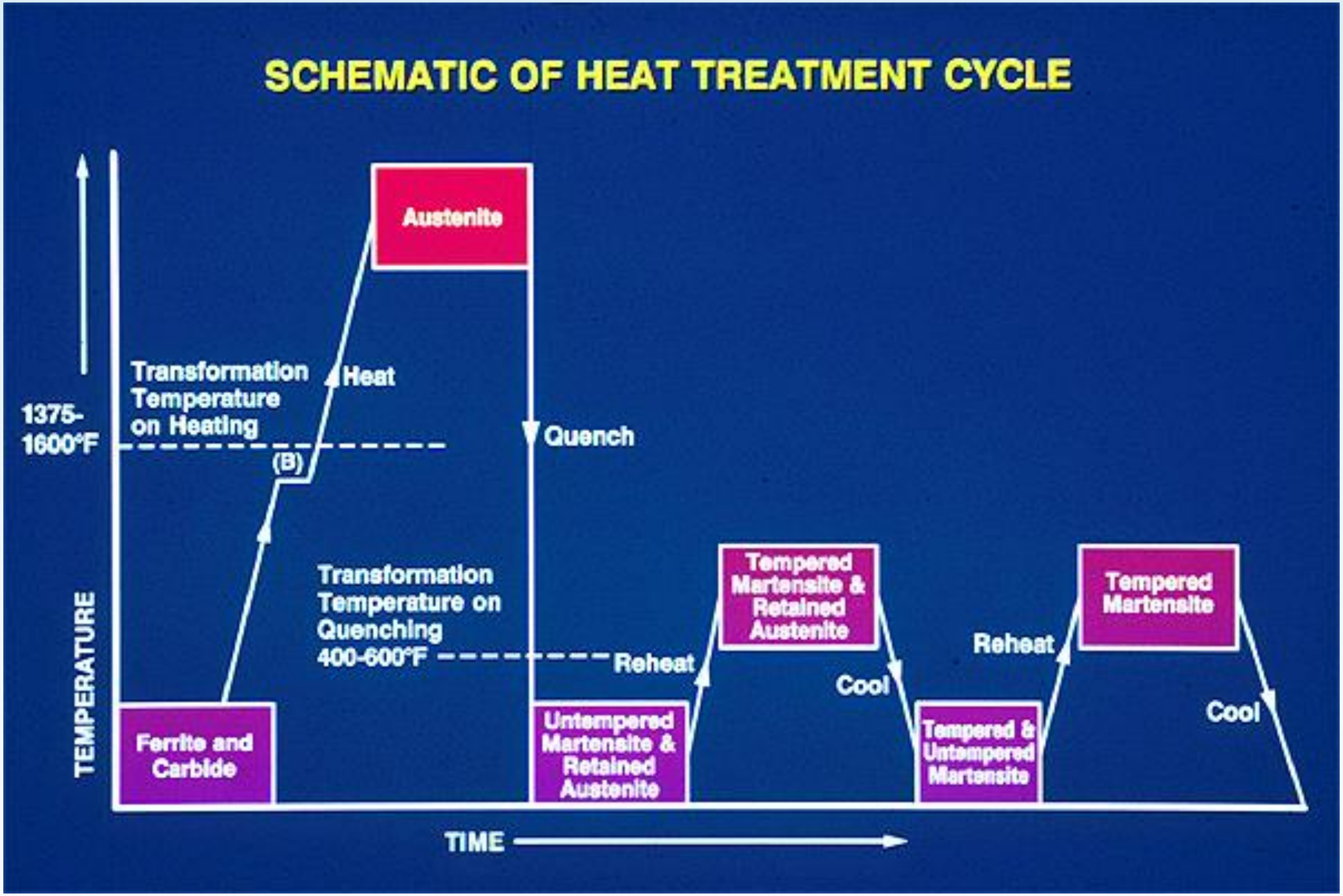
Tempering is applied
to hardened steel
to reduce brittleness,
increase ductility & toughness
and relieve stresses
in martensitic structure.

The steel is heated
to lower critical temperature
keeping it there
For about one hour
and then cooled slowly
at prescribed rate.



Tempering increases ductility and toughness but also reduces hardness, strength and wear resistance marginally. Increase in tempering temperature lowers the hardness.

Focus on Steel – Carbon Steels



Heat Treatments - Tempered Martensite

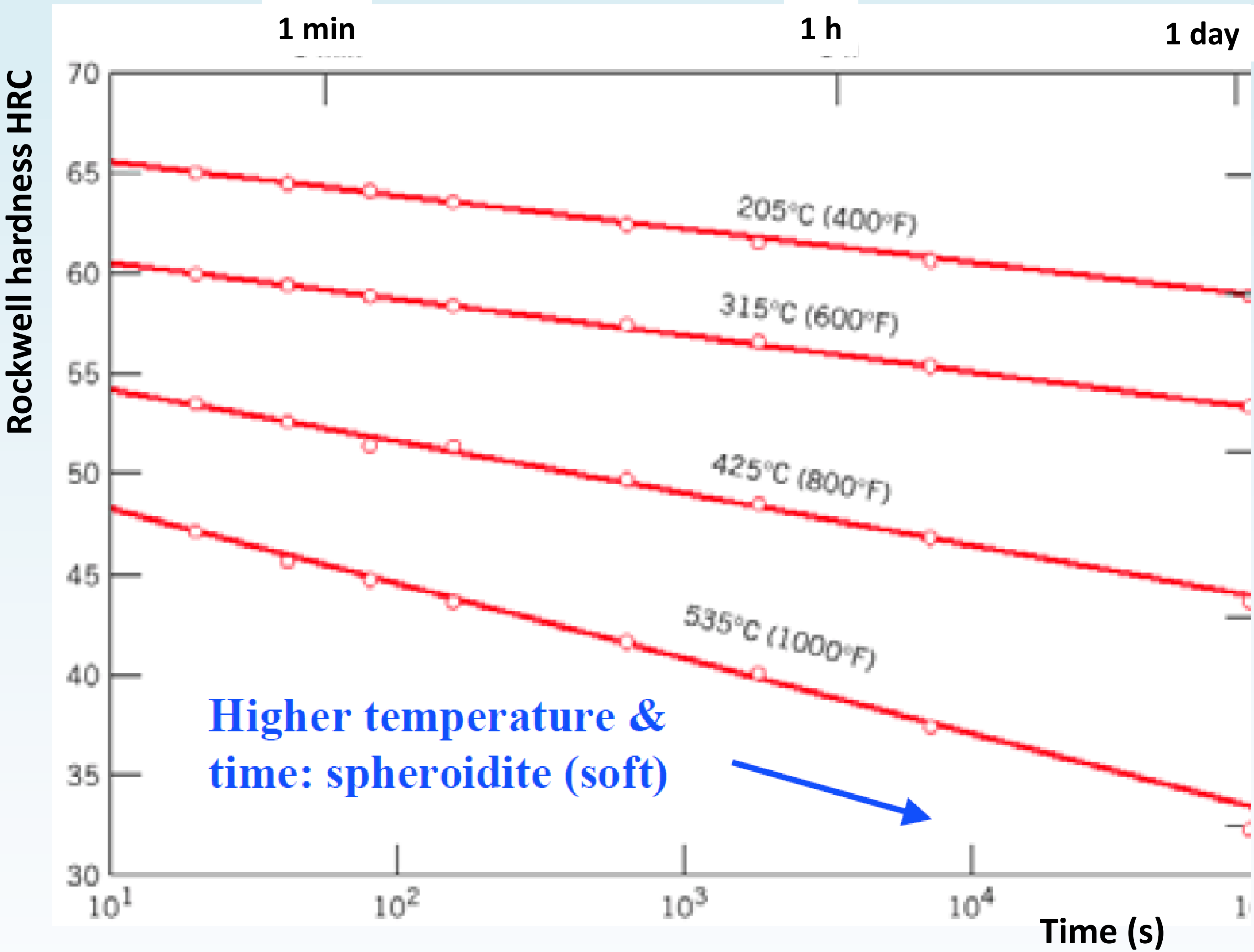
Tempering:
Heating to 250-650°C for some time

- ***Lower hardness/strength***
- ***Enhanced ductility (ferrite phase!)***

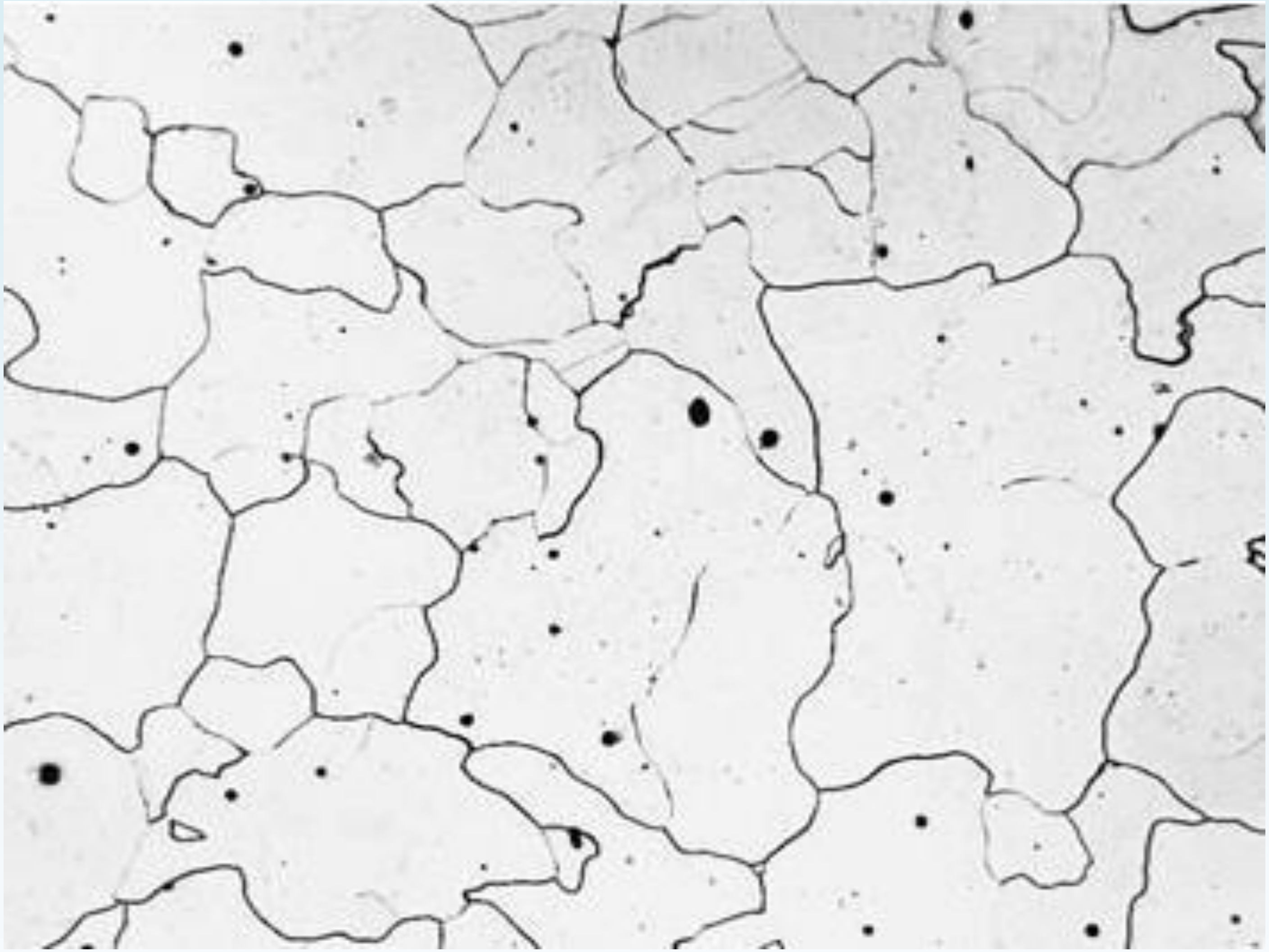
Mechanical properties depend on particle size of cementite

- ***Fewer, larger particles:***
  yield less boundary area
  produce softer, more ductile material
- ***Particle size increases***
  with higher temperature,
  longer time (more C diffusion)

Heat Treatments



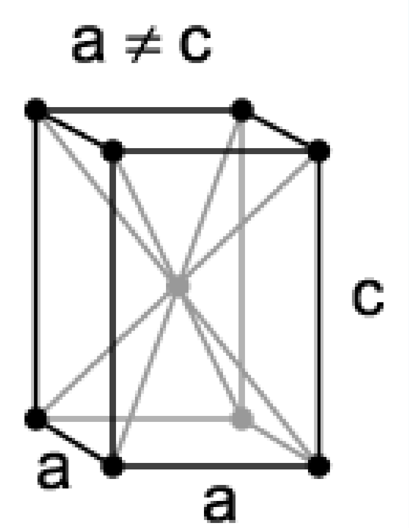
Focus on Steel – Crystals



Alpha Ferrite

Martensite

a body-centered tetragonal form of iron in which some carbon is dissolved.
Martensite forms during quenching,
when the face centered cubic lattice of austenite is distored
into the body centered tetragonal structure
without the loss of its contained carbon atoms into cementite and ferrite.
Instead, the carbon is retained in the iron crystal structure,
which is stretched slightly so that it is no longer cubic.
Martensite is more or less ferrite supersaturated with carbon.



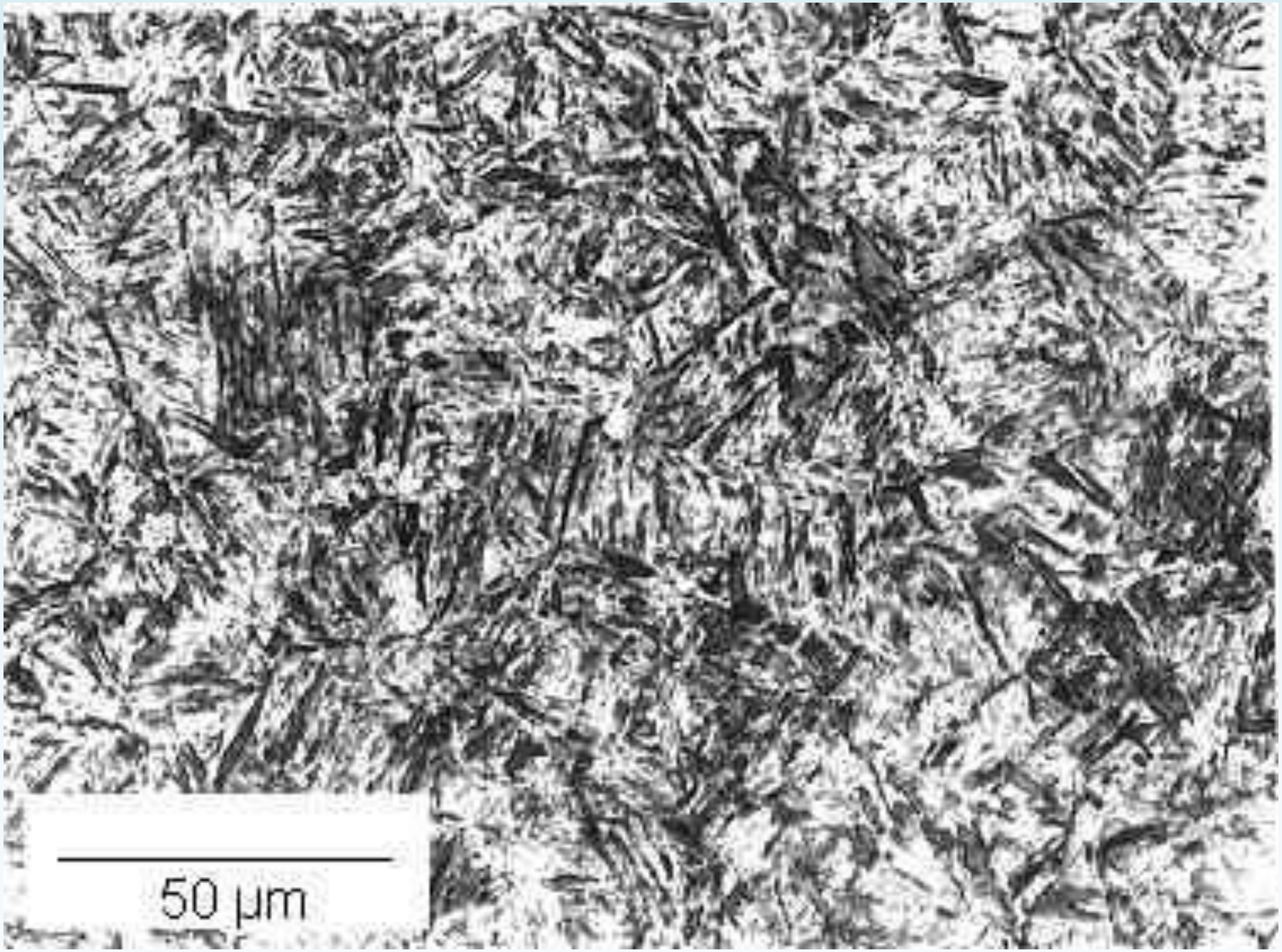
Body Centered Tetragonal Unit Cell

Martensite

A very hard needle-like structure of iron and carbon,
only formed by very rapid cooling from the austenitic structure.
Needs to be modified by tempering before acceptable properties reached.

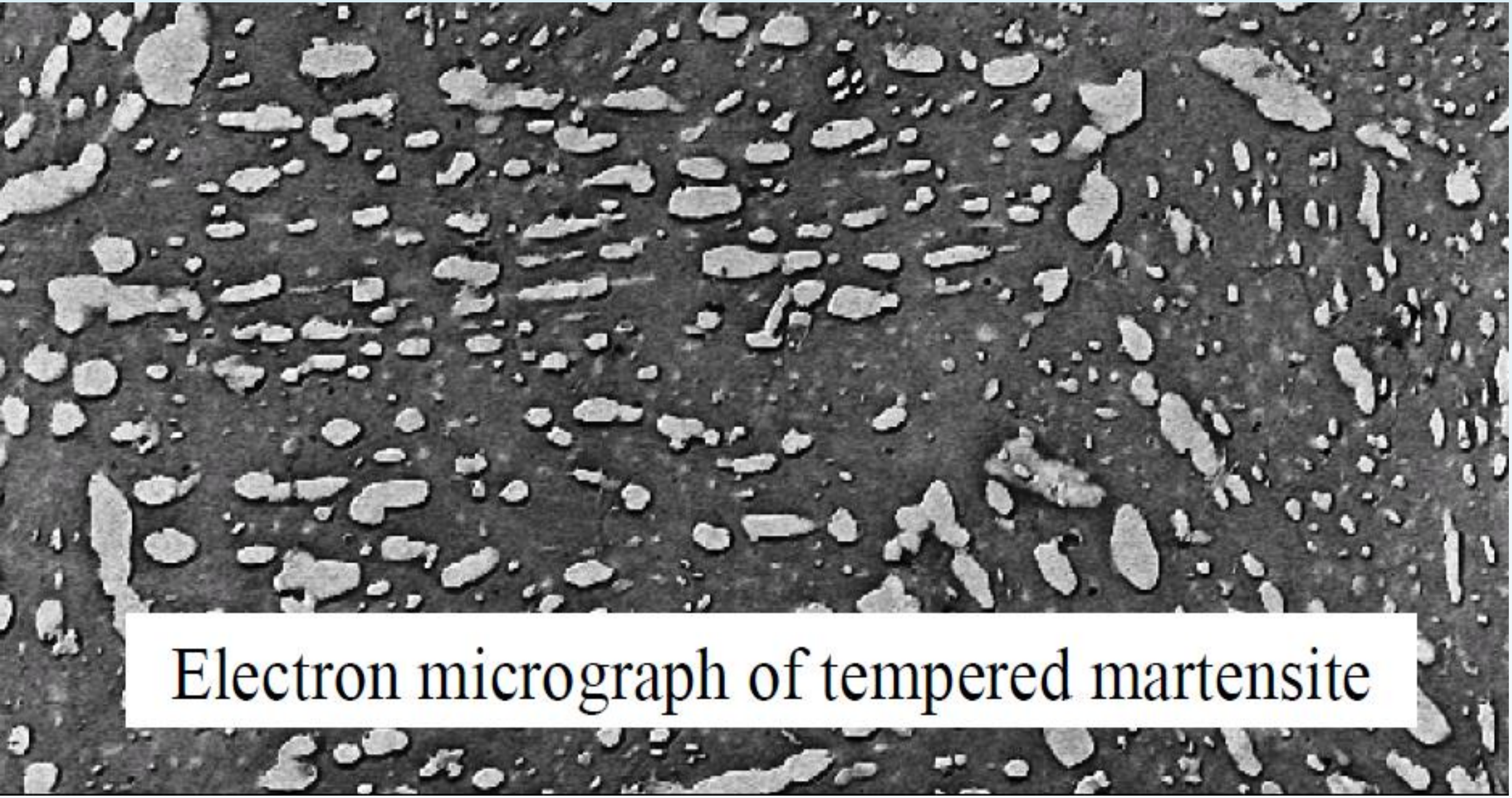
The needle-like structure of martensite, the white areas are retained austenite.

Focus on Steel – Martensite Formation



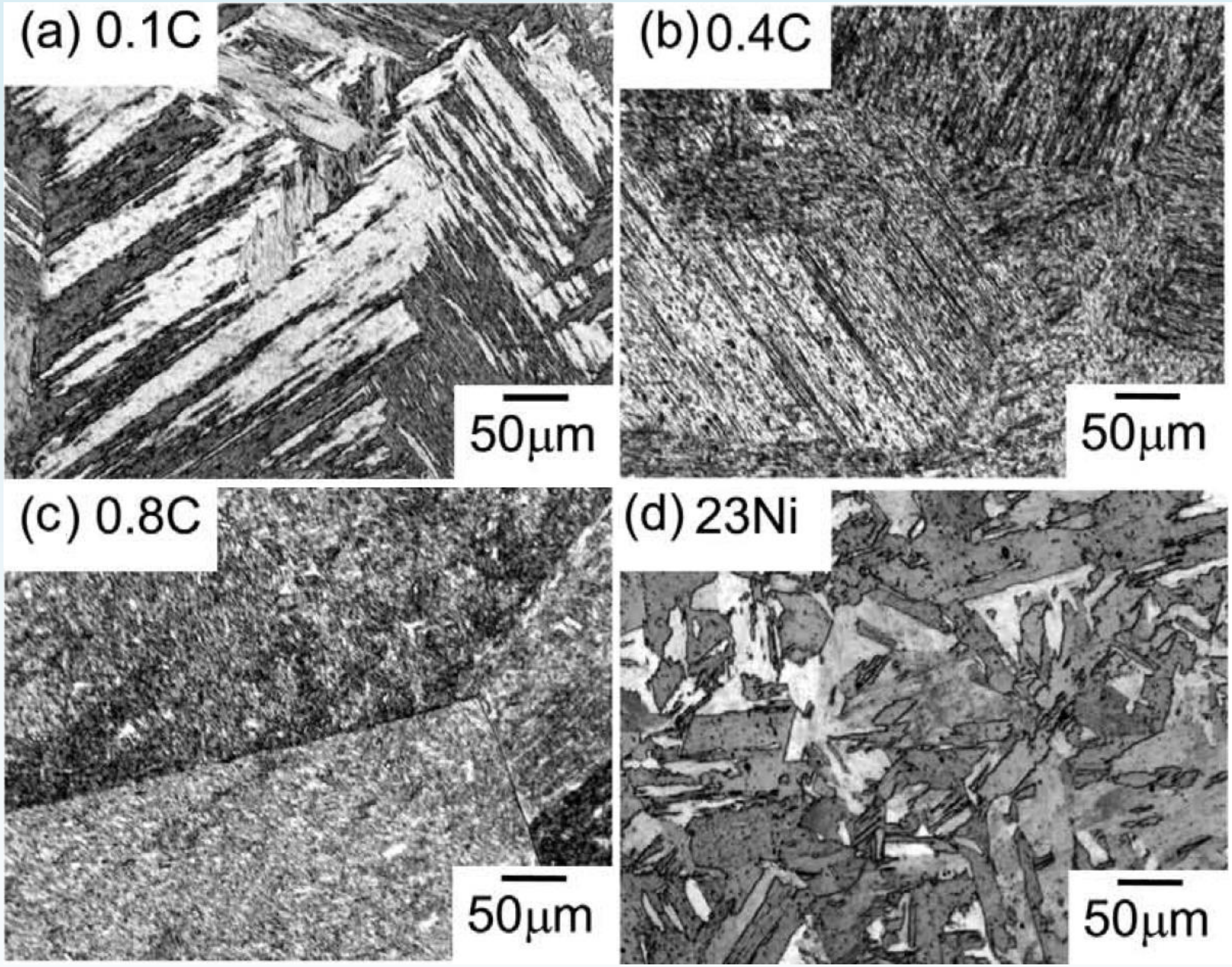
Photomicrograph of Martensite Structure

Heat Treatments



Electron micrograph of tempered martensite

Focus on Steel – Martensite



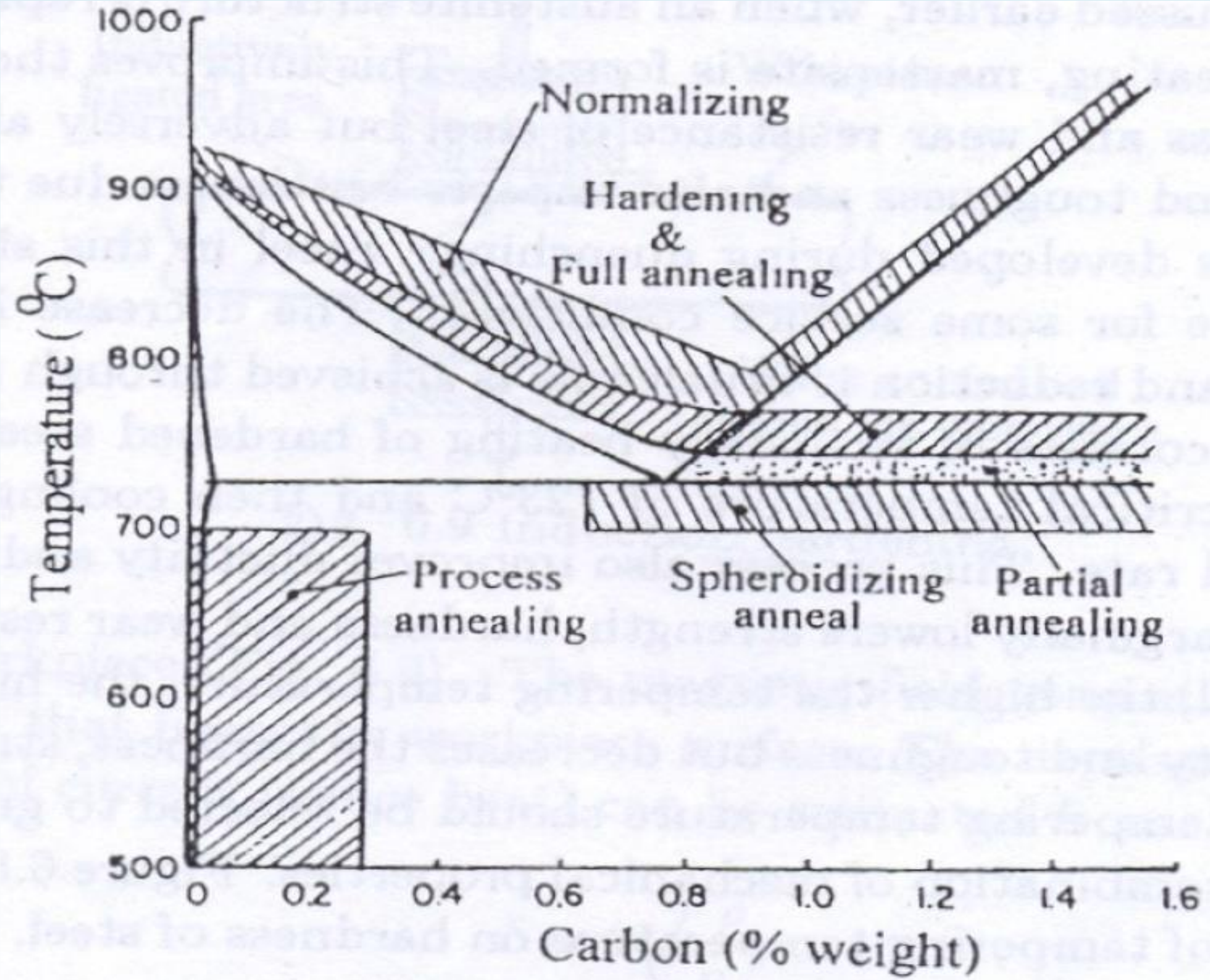
CARBON CONTENT

The block width decreases with an increase in the carbon content.

The block width of the Fe-23Ni alloy is much larger than that of the Fe-C alloys.

Optical micrographs of the Fe-C lath martensite

Heat treatments



Heat Treatments - Annealing

Annealing occurs by the diffusion of atoms within a solid material.
The material progresses towards its equilibrium state

Annealing involves

- *heating a material*
- *maintaining a suitable temperature,*
- *and then cooling.*

It alters the physical (and sometimes chemical properties)
of a material by refining its structure

- *to increase its ductility*
- *to relieve internal stresses*
- *and to make it more workable (cold working properties)*

Stages of the annealing process during heating:

- **recovery**

softening of the metal through removal of dislocations and related internal stresses; recovery occurs at the lower temperature stage before the appearance of new strain-free grains.

- **recrystallization**

New strain-free grains nucleate and replace those deformed by internal stresses

- **grain growth**

If annealing continues and recrystallization has completed, then grain growth occurs. The microstructure starts to coarsen, the metal looses a substantial part of its original strength

Normalization

Normalization is used on steels of less than 0.4% carbon.
It gives the material a uniform fine grained structure and make it less brittle.
transforming retained austenite into ferrite, pearlite and sorbite.

- **heating the steel to 20-50 Kelvin above its upper critical point**
- **soaking for a short period at that temperature**
- **cooling in air**

Smaller grains form that produce a tougher, more ductile material.
It eliminates columnar grains and dendritic segregation
that sometimes occurs during casting and welding.
Normalizing improves machinability of a component
and provides dimensional stability
if subjected to further heat treatment processes

Full Anneal

(LP Annealing – lamellar pearlite)

*A full anneal typically results
in the second most ductile state a metal can assume for metal alloy.
Steel is heated to 50°C above the austenite temperature
and held for sufficient time to allow the material
to fully form austenite or austenite-cementite grain structure.
The material is then allowed to cool slowly (e.g. in air)
so that the equilibrium microstructure is obtained.*

*The result is a more ductile material
but a lower yield and tensile strength.
Often the material to be machined is annealed,
and then subject to further heat treatment
to achieve the final desired properties.*

Heat Treatments – Specialized Cycles of Annealing

Process Annealing

(intermediate annealing, subcritical annealing, or in-process annealing)

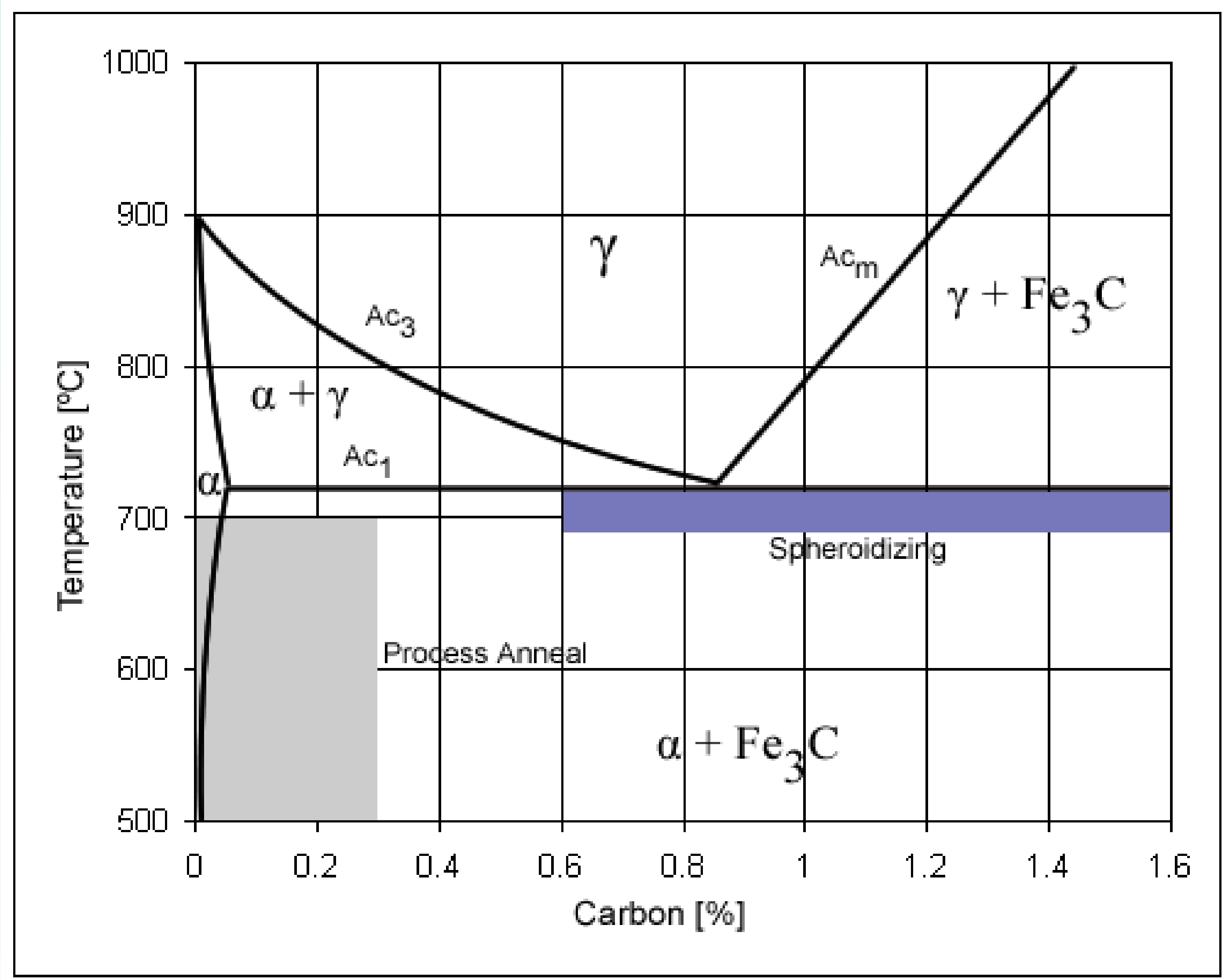
restores some of the ductility to a product during the process of cold working

The temperature ranges from 260 °C (500 °F) to 760 °C (1400 °F), depending on the alloy in question.

Short Cycle Anneal

Short cycle annealing is used for turning normal ferrite into malleable ferrite.

It consists of heating, cooling, and then heating again from 4 to 8 hours.



Common temperature ranges for heat treating plain-carbon steels

Heat Treatments Spheroidizing

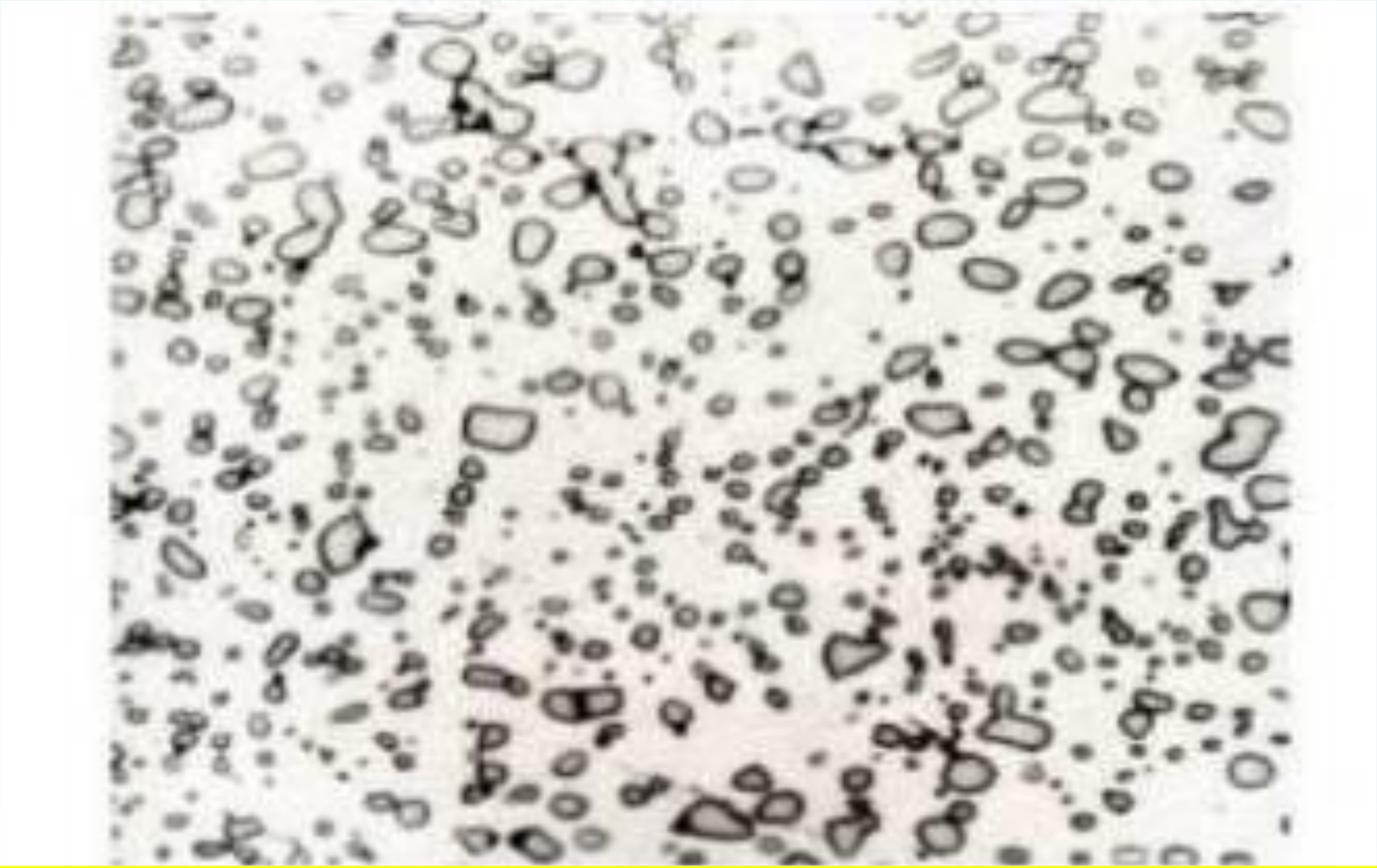
Spheroidizing

Heating steels just below Ae_1
until the shape of cementite particles becomes relatively spherical.
(McGraw-Hill Dictionary of Scientific & Technical Terms, 6E, Copyright © 2003)

Annealing of pearlitic or bainitic microstructures
at elevated temperatures just below eutectoid (e.g. 24 h at 700 C)
leads to the formation of new microstructure –
spheroidite-spheres of cementite in a ferrite matrix.

- *Composition or relative amounts of ferrite and cementite are not changing in this transformation,* ***only the shape of the cementite inclusions is changing***
- *Transformation proceeds by C diffusion – needs high temperature*
- *Driving force for the transformation is the reduction in total ferrite - cementite boundary area*

Heat Treatments Spheroidizing



The spheroidal distribution of cementite gives improved ductility and machinability

Focus on Steel – Steel Qualities

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Heat Treatments
Transformation Diagrams

Questions:
a) What temperature is steel heated to when it is annealed?
b) What temperature is hot working carried out at?
c) Which of the following are alternate layers of ferrite and cementite known as:
(i) austenite
(ii) martensite
(iii) pearlite

Our experts view is: a) Work hardened metal is annealed by heating it to a temperature that is approximately half of its melting point.
b) Hot working is carried out on a metal heated to about 0.6 of its melting point.
c) Alternate layers of ferrite and cementite are known as pearlite

STEEL CLASSIFICATION

BY PURPOSE:

DIN EN 10027-1

Code Nr.	Scope
D	Steels for cold working
E	Engineering steels
H	High-strength flat products
L	Steels for pipe lines
P	Steels for pressure vessels
R	Rail steels
S	Steels for steel construction

M	thermo mechanically rolled
N	normalized
Q	tempered
G	other features with 1 or more digits

S235JR+C

S: steel for steel construction

235: SMYS 235 N/mm^2

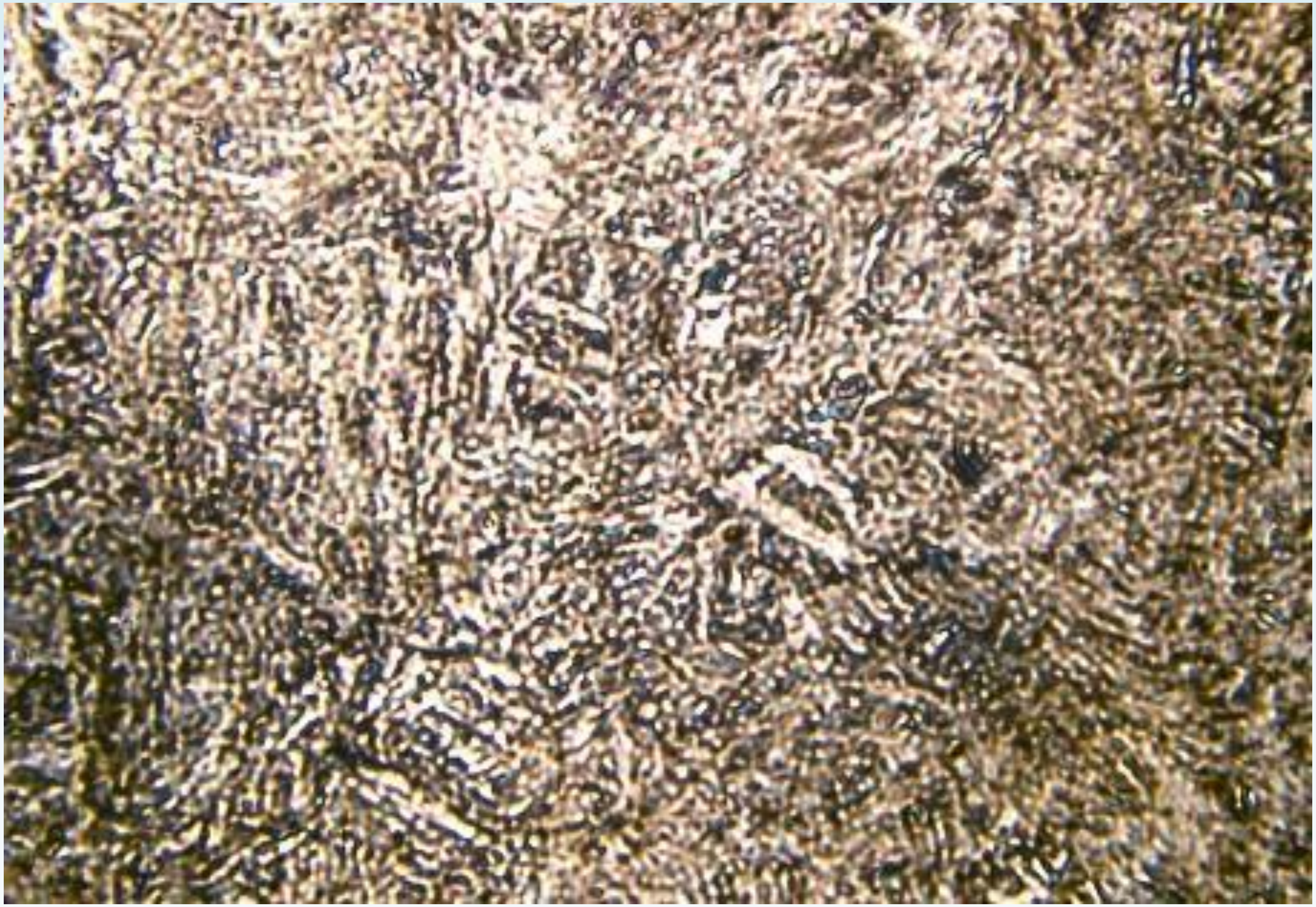
JR = 27J notch impact strength 20 °

C = cold rolled

+20	0	-20	-30	-40	-50	-60	
JR	J0	J2	J3	J4	J5	J6	27 J
KR	K0	K2	K3	K4	K5	K6	40 J
LR	L0	L2	L3	L4	L5	L6	60 J

C	**cold working**
L	**for low temperatures**
H	**for semi profiles**
W	**weatherproof**

Focus on Steel – Bainit Formation



Bainite Microstructure