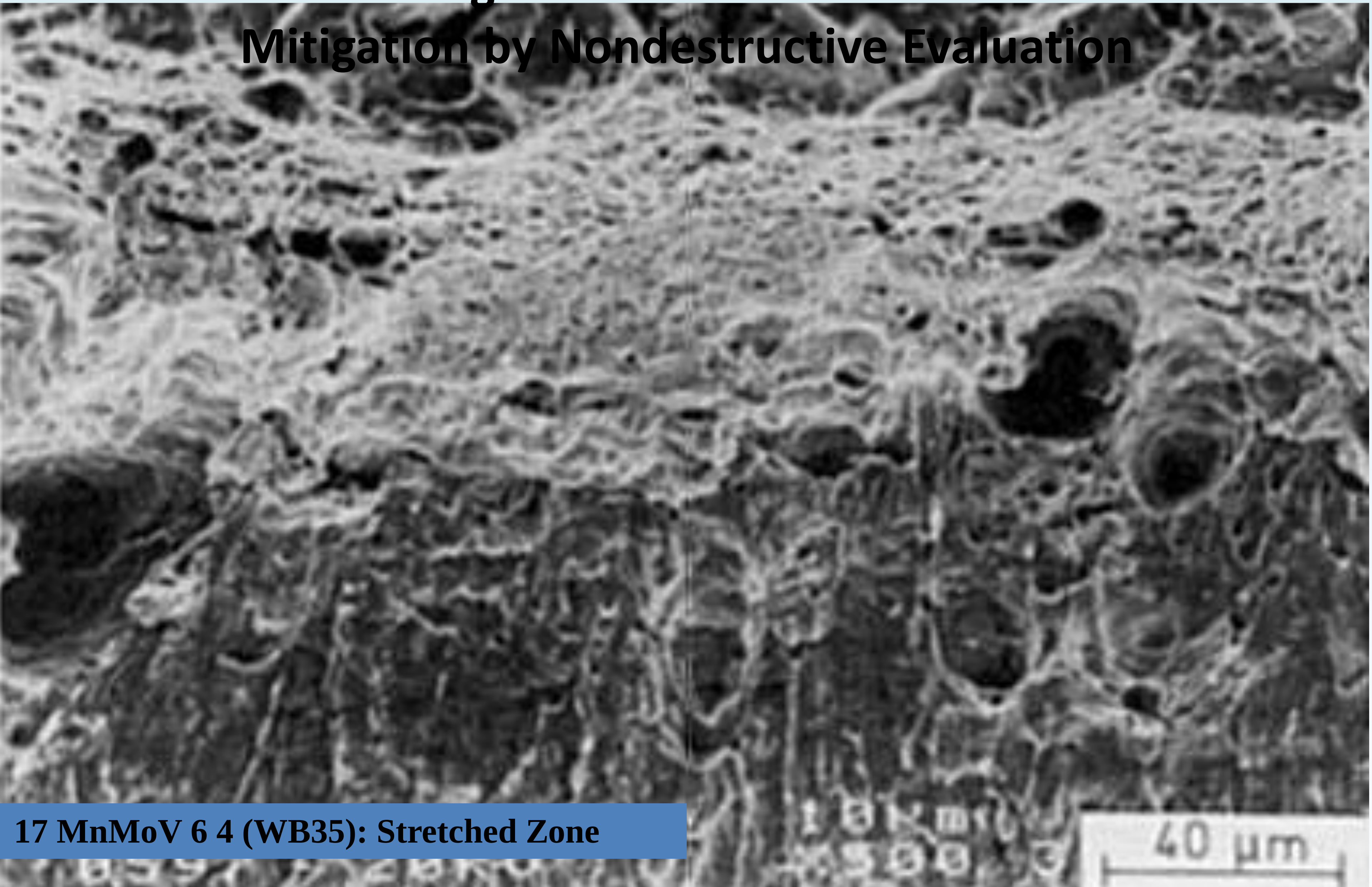
Material Degradation of Nuclear Structures
Mitigation by Nondestructive Evaluation



17 MnMoV 6 4 (WB35): Stretched Zone

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

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

Transformation Diagrams help to understand transformations

There are two main types of transformation diagrams that are helpful in selecting the optimum steel and processing route to achieve a specified set of properties:

- **time-temperature transformation** (TTT) diagram
- **continuous cooling transformation** (CCT) diagram

Time-temperature transformation (TTT) diagrams

(isothermal diagrams: rate of transformation at a constant temperature)

A sample is:

- ***austenitized,***
- ***then cooled rapidly to a specified lower temperature,***
- ***then held at that temperature for a specified time***

Continuous cooling transformation (CCT) diagrams

(extent of transformation during a continiously decreasing temperature)

A sample is:

- ***austenitized,***
- ***then cooled at a predetermined rate***

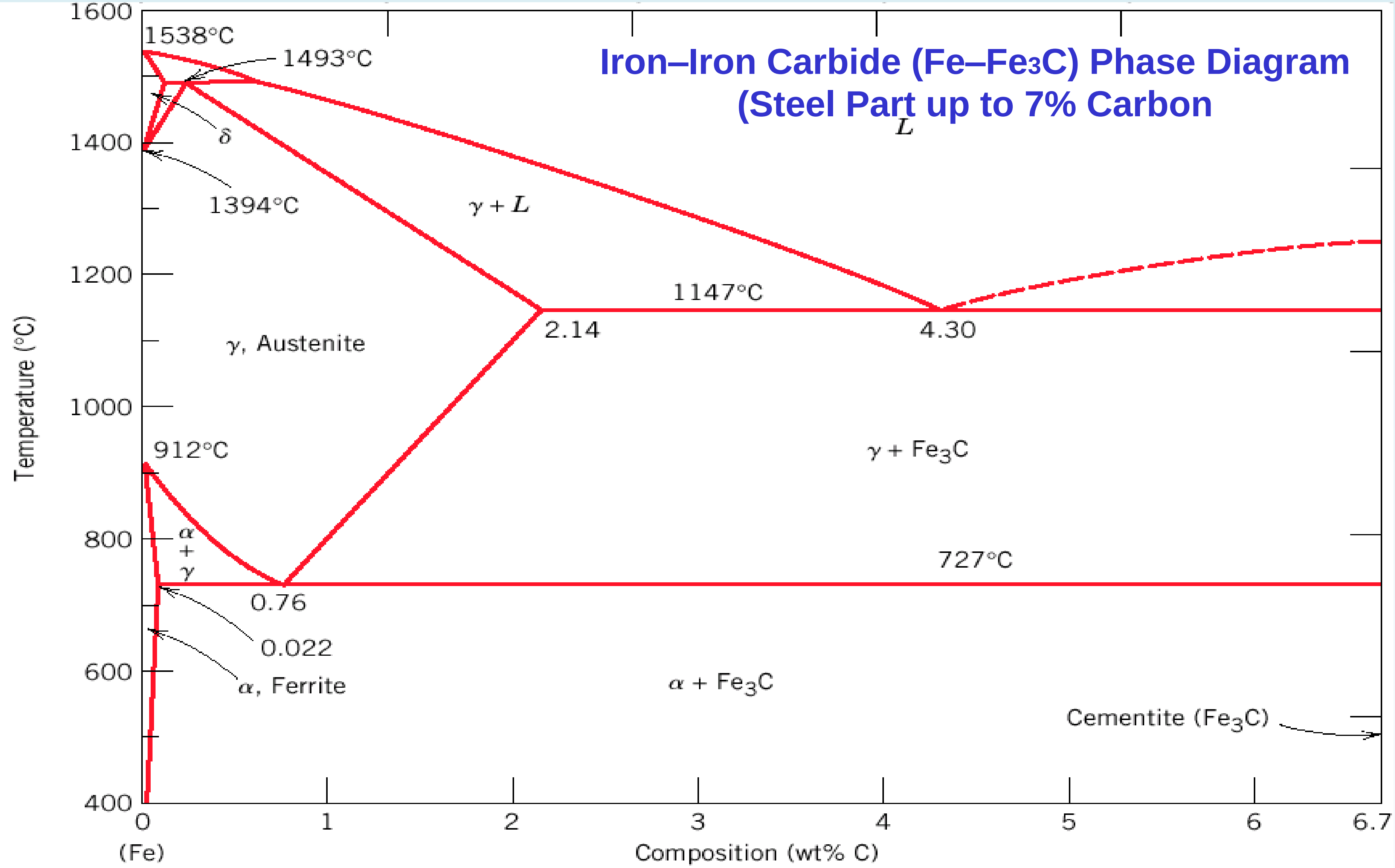
(the rate and degree of transformation is measured by dilatometry, for example)

For understanding:

Let us go to the roots, the

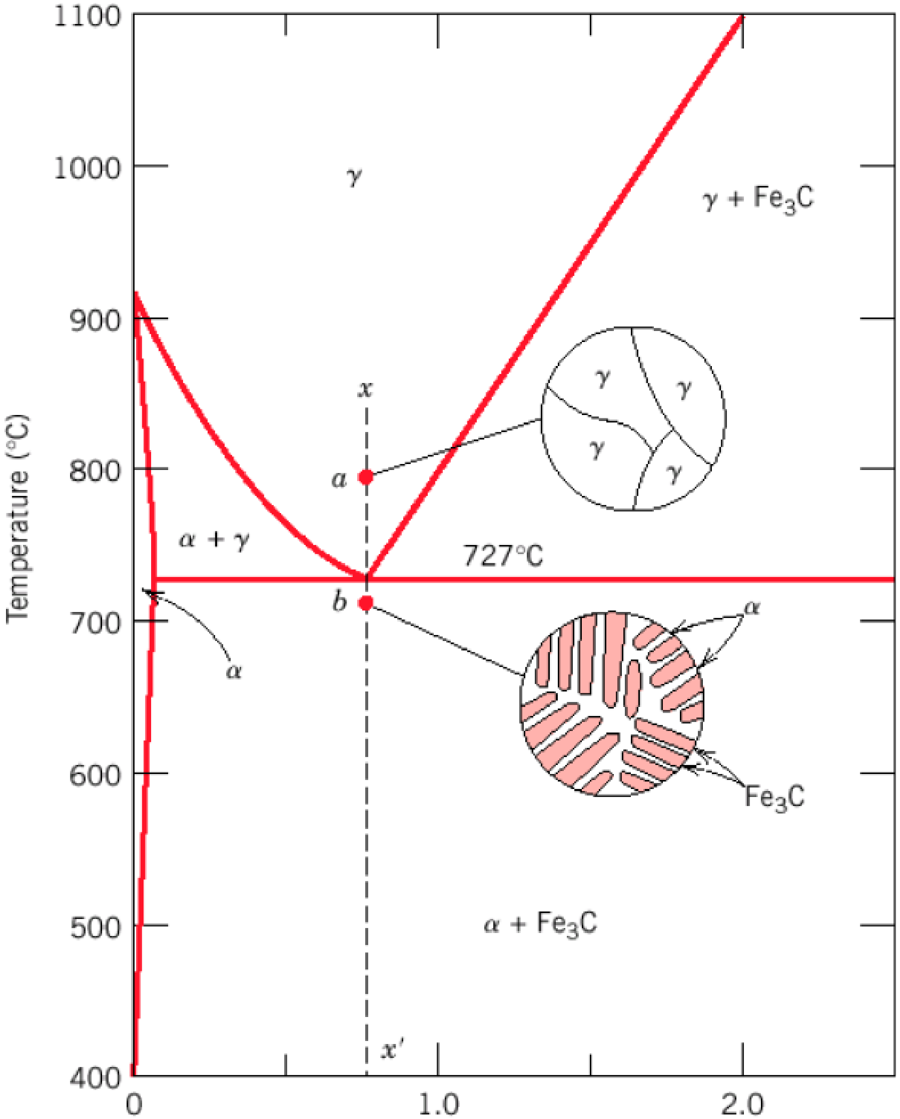
IRON CARBON DIAGRAM

Heat Treatments
A Short Review on the Iron-Carbon Phase Diagram



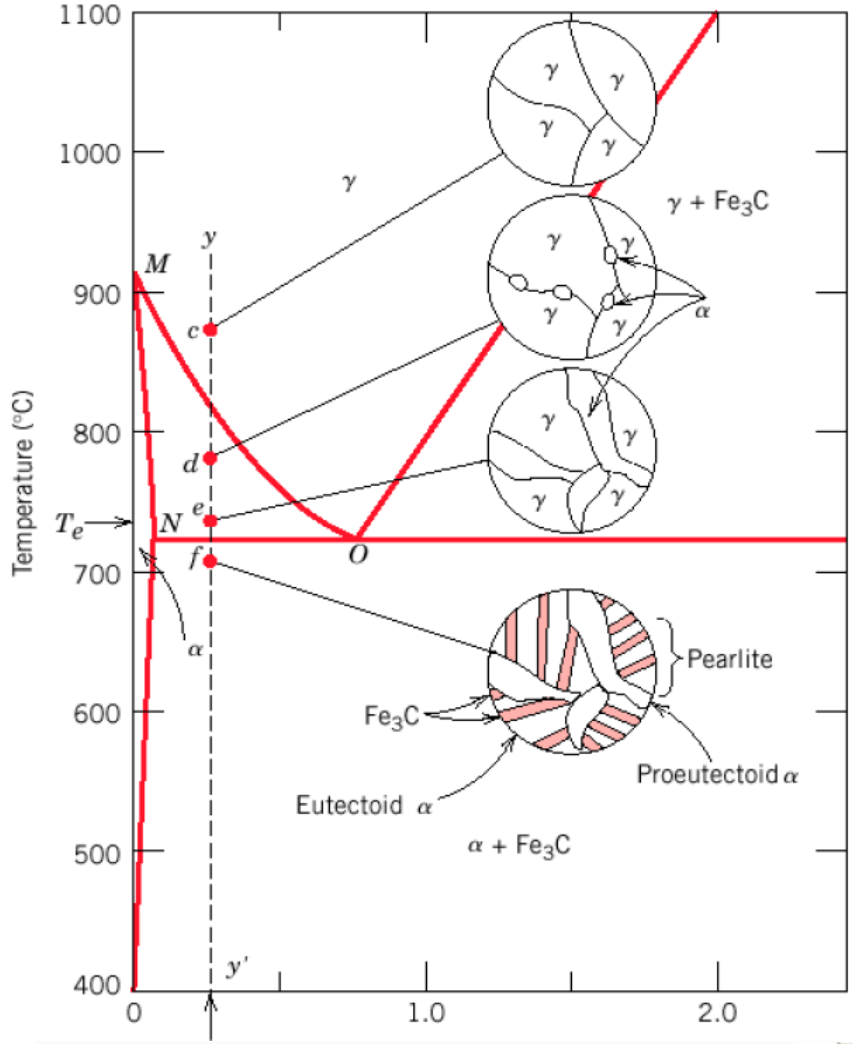
Heat Treatments - Microstructure

Eutectoid Steel

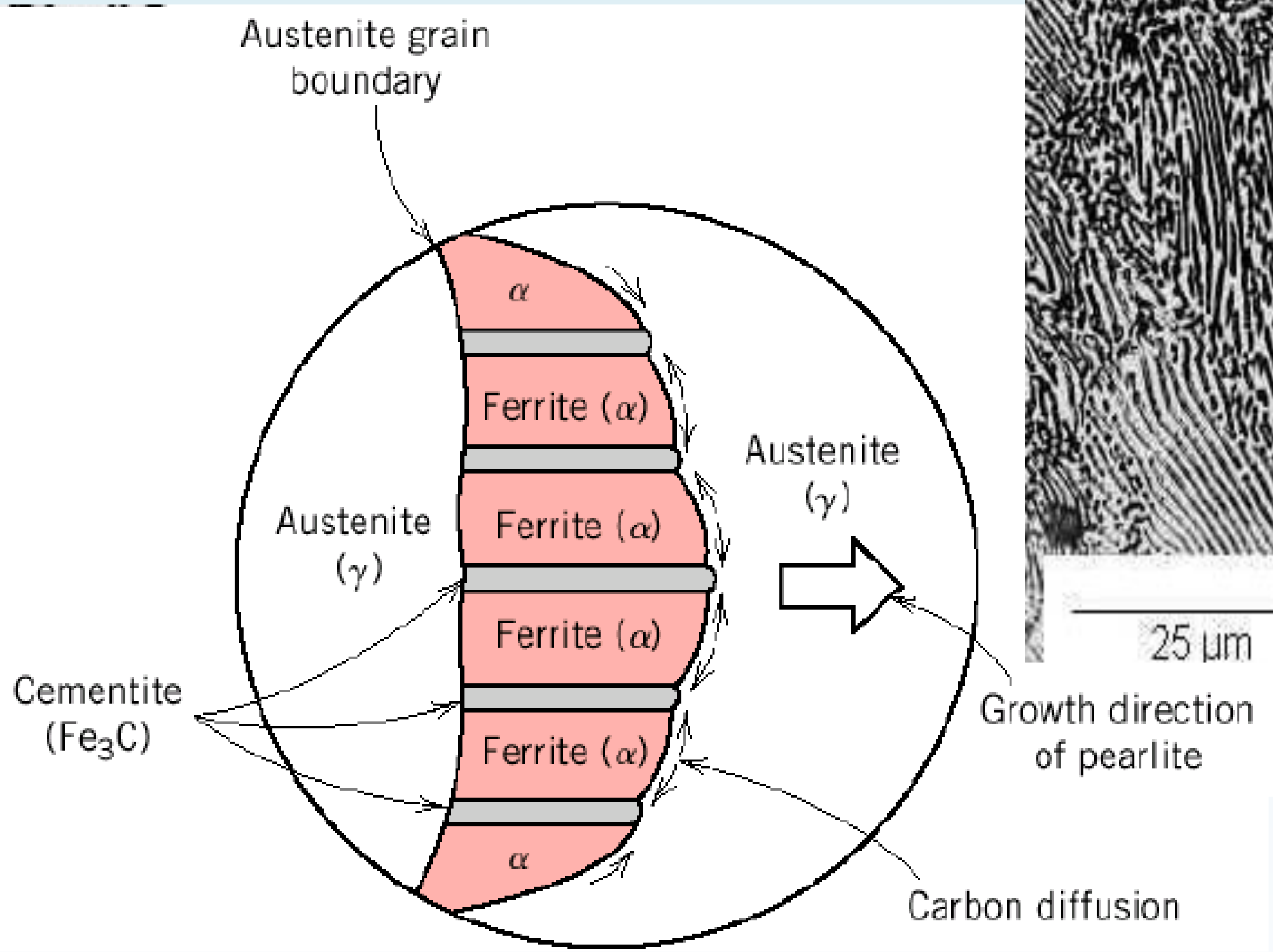


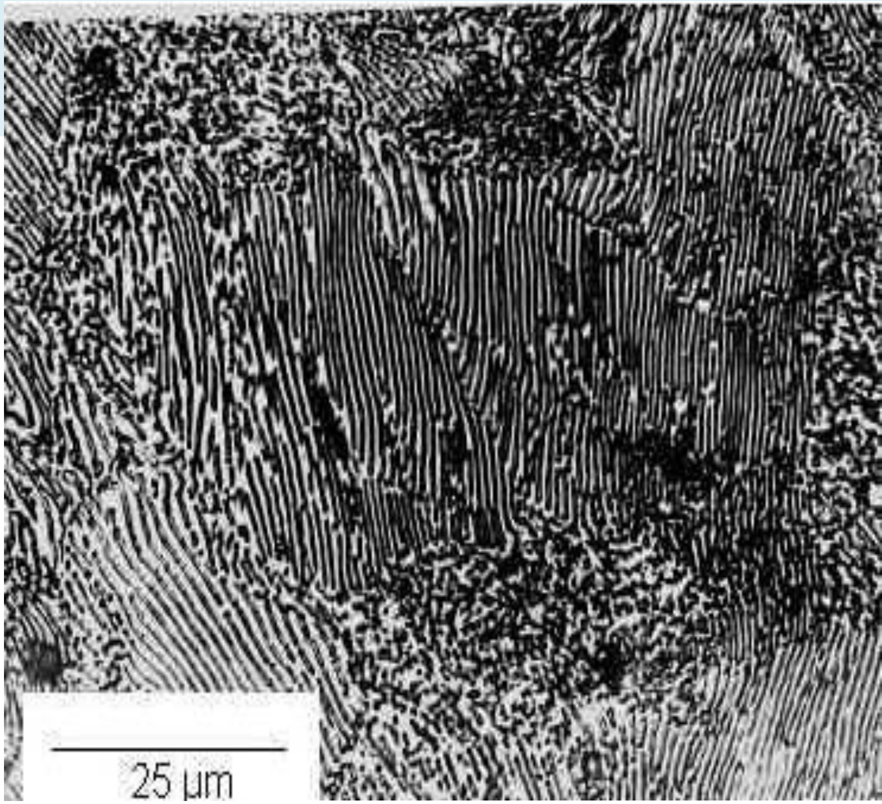
Hypoeutectoid Steel

$\gamma \rightarrow \alpha + \gamma \rightarrow \alpha + Fe_3C$



Heat Treatments
Pearlite





Photomicrograph of Pearlite
(Dark bands: Cementite)

Pearlite

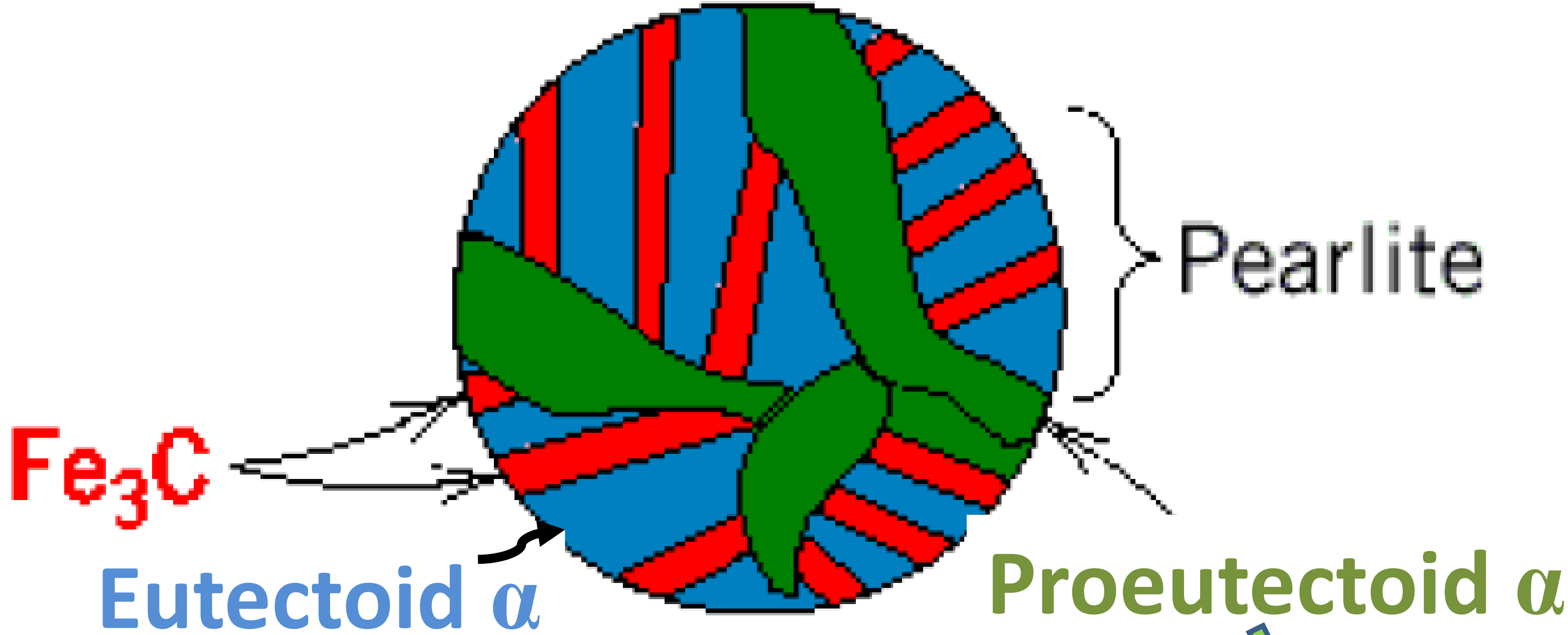
a laminated structure

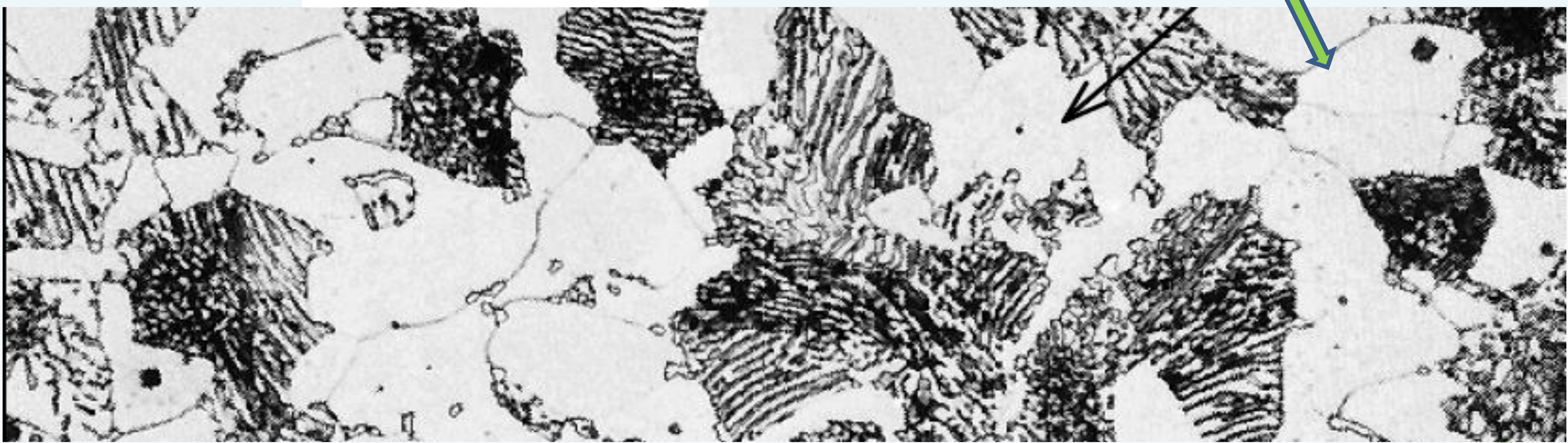
formed of alternate layers of ferrite and cementite.

It combines the hardness and strength of cementite with the ductility of ferrite.
It is the key to the wide range of steel properties.

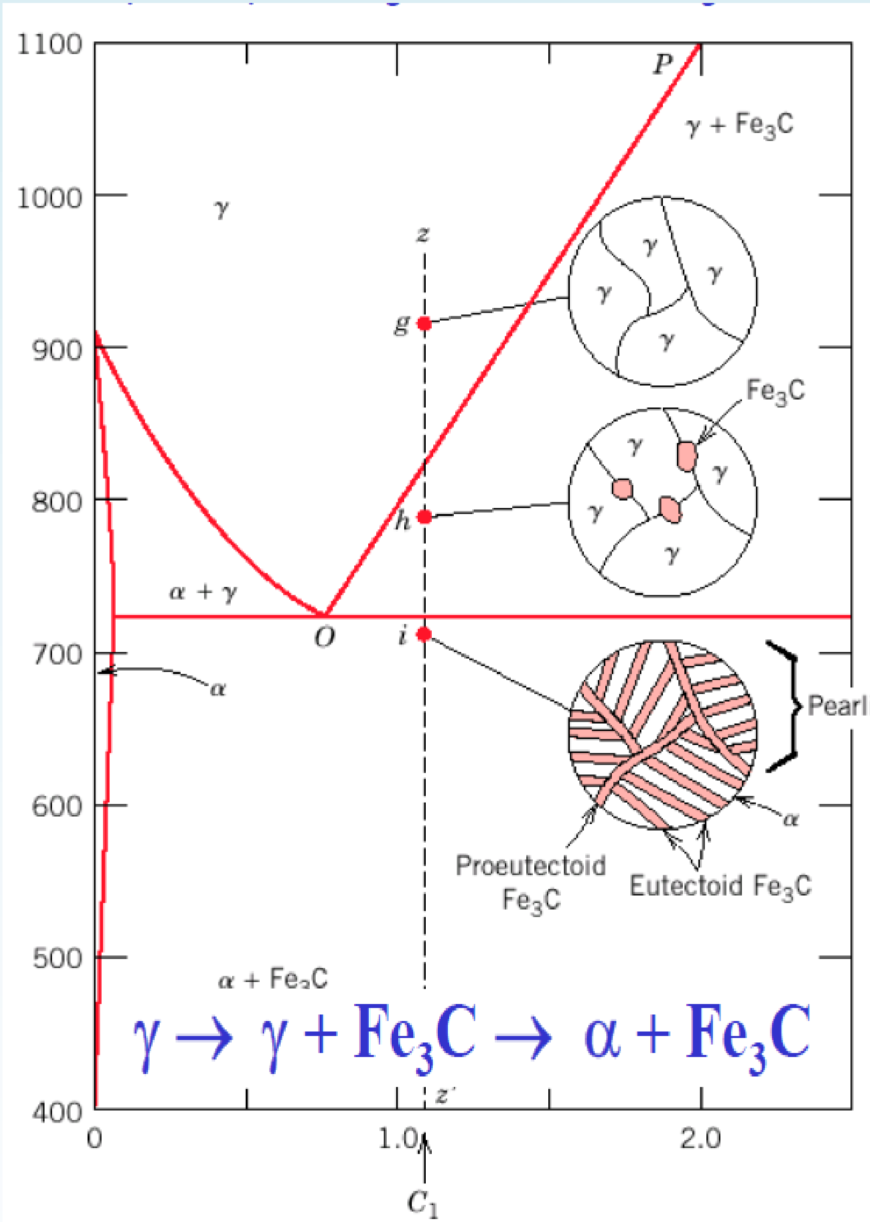
The laminar structure acts as a barrier to crack movement as in composites.
This gives it toughness.

Heat Treatments – Hypoeutectic Alloys

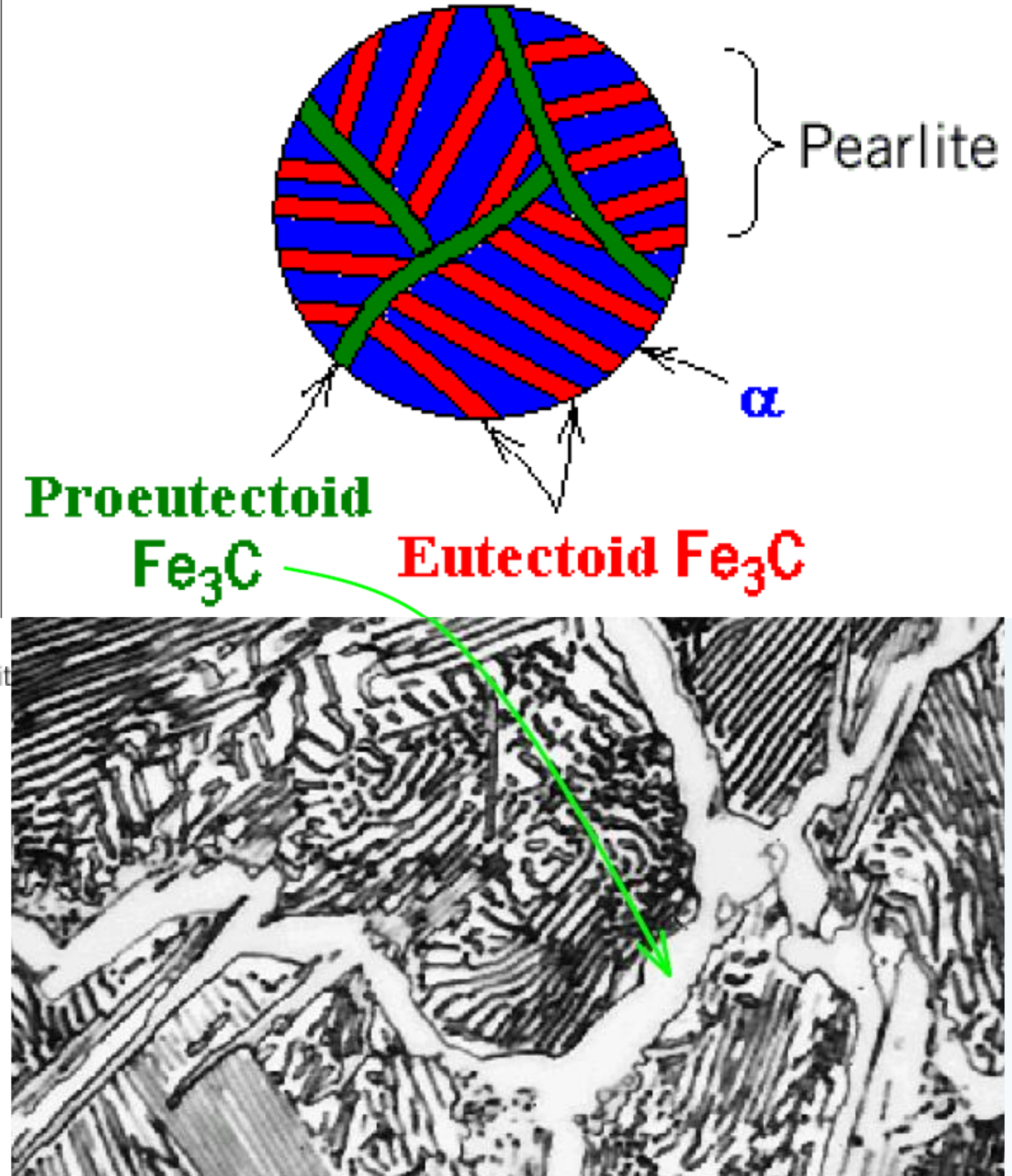




Heat Treatments – Microstructure of Hypereutectic Steels



$$\gamma \rightarrow \gamma + Fe_3C \rightarrow \alpha + Fe_3C$$



TTT Diagrams

TTT diagram stands for
"time-temperature-transformation " diagram

TTT diagrams give the
kinetics of isothermal transformations

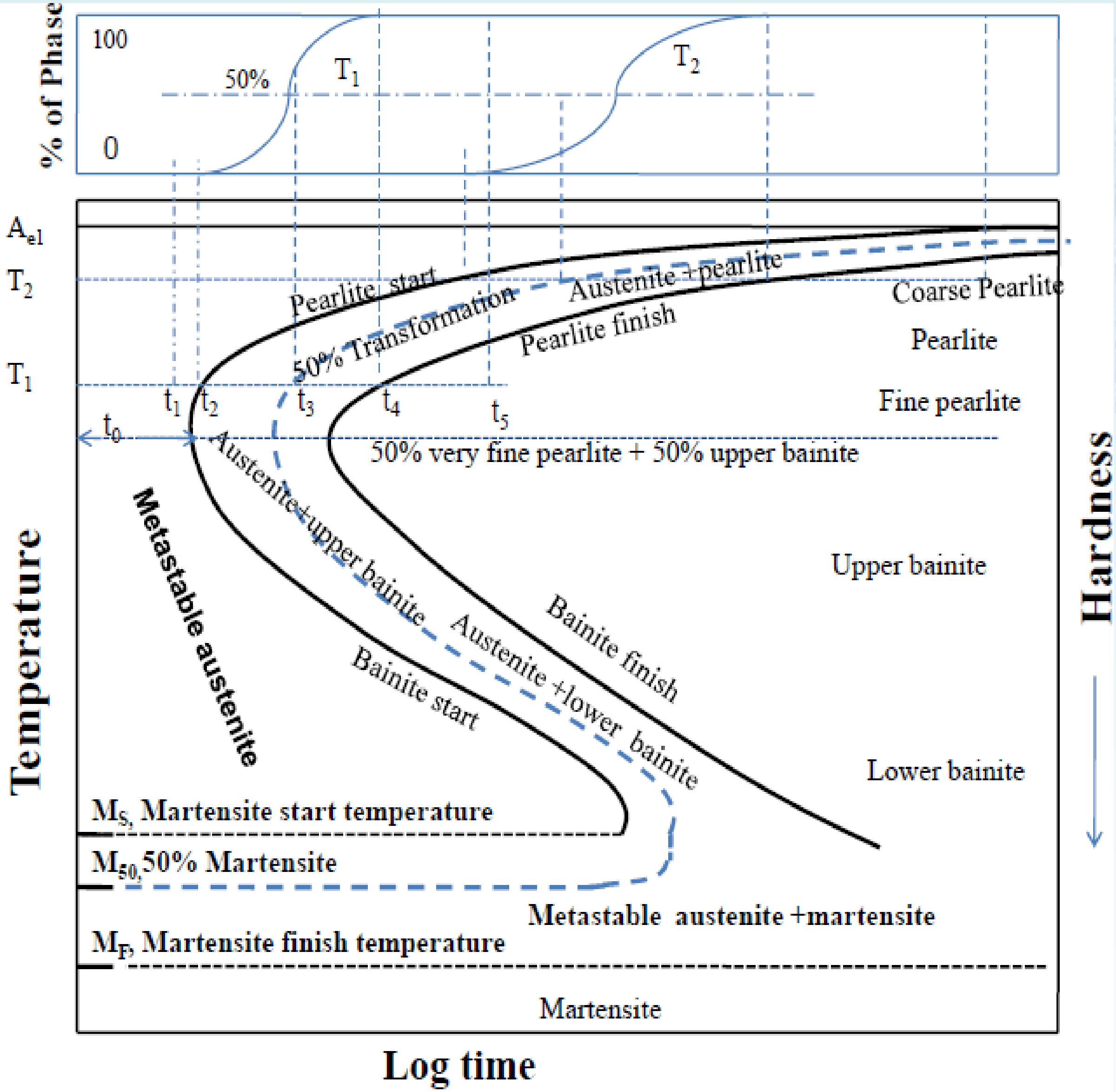
TTT diagrams

measure the rate of transformation at a constant temperature:

A sample is austenitized and then cooled rapidly to a lower temperature and held at that temperature whilst the rate of transformation is measured*.

* for example by dilatometry.

Heat Treatments-Isothermal Transformation (TTT-) Diagram



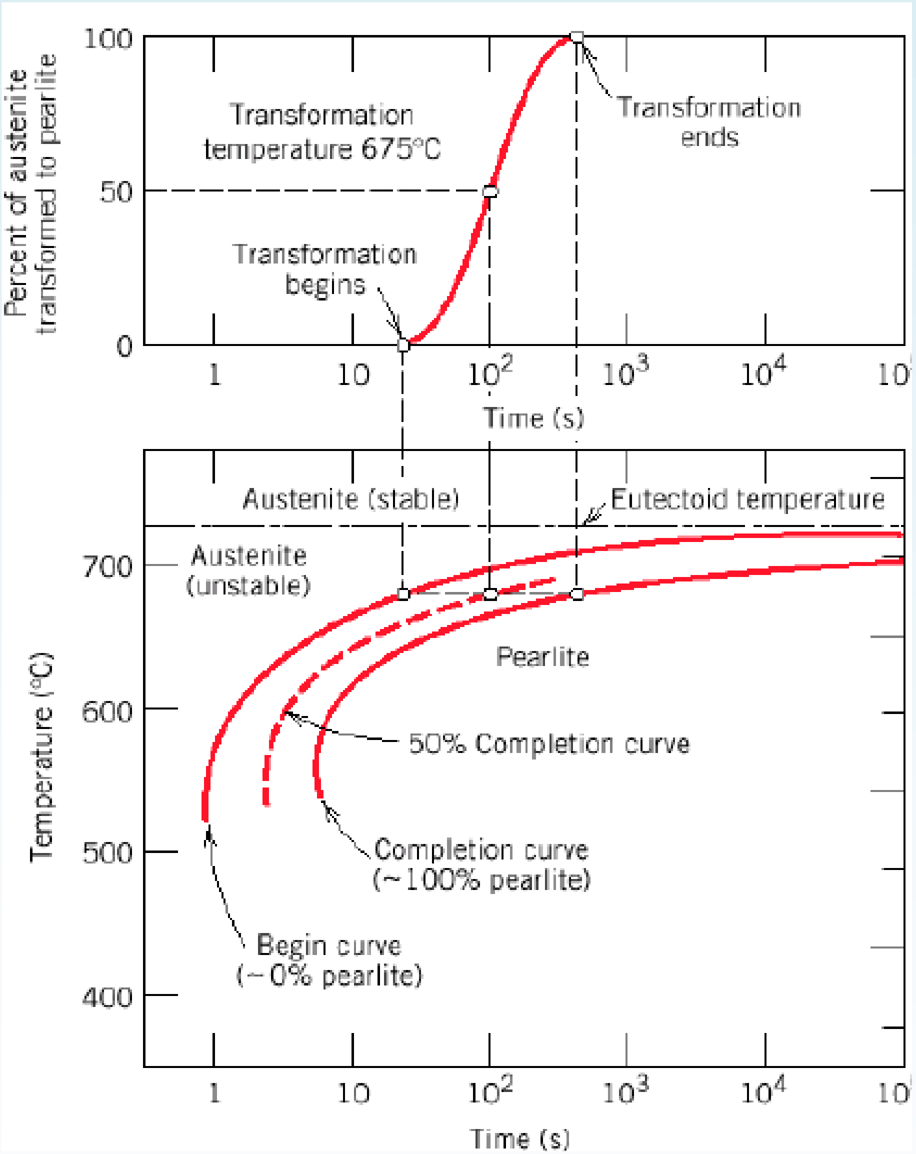
At T_1:
t_2 = incubation period
t_4 = finish time

At t_1 ("nose"):
minimum incubation period

R. Manna:
Time Temperature Transformation (TTT) Diagrams,
University of Cambridge
rm659@cam.ac.uk
Institute of Technology,
Banaras Hindu University,
Varanasi, India
rmanna.met@itbhu.ac.in

Time temperature transformation (schematic) diagram for plain carbon eutectoid steel

Heat Treatments-Isothermal Transformation (TTT-) Diagram (Temperature, Time, and % Transformation)C

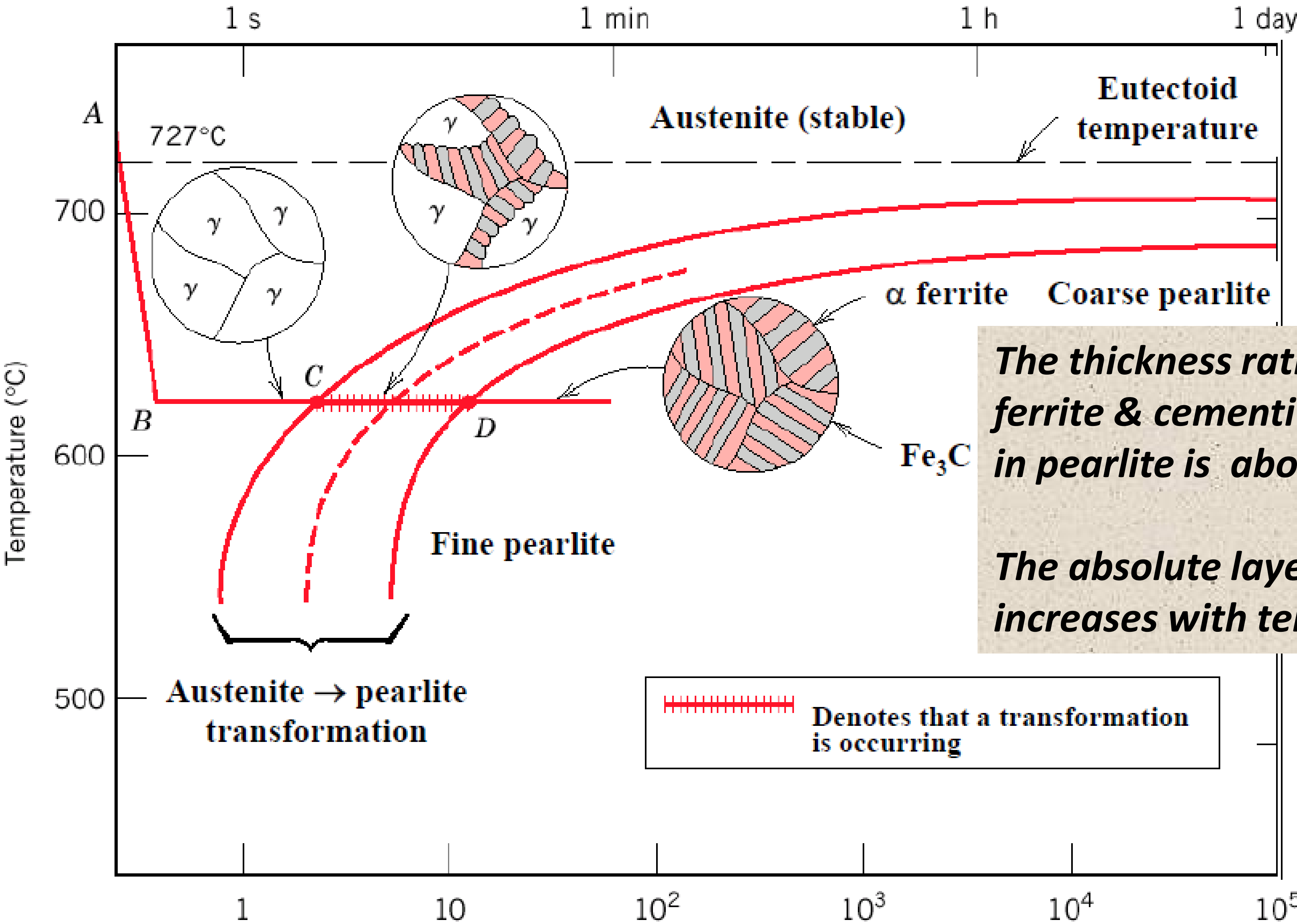


EXAMPLE: EUTECTOID STEEL

The S-shaped curves are shifted to longer times at higher T showing that the transformation is dominated by nucleation and not by diffusion.

Diffusion occurs faster at higher temperatures, nucleation rate increases with super-cooling.

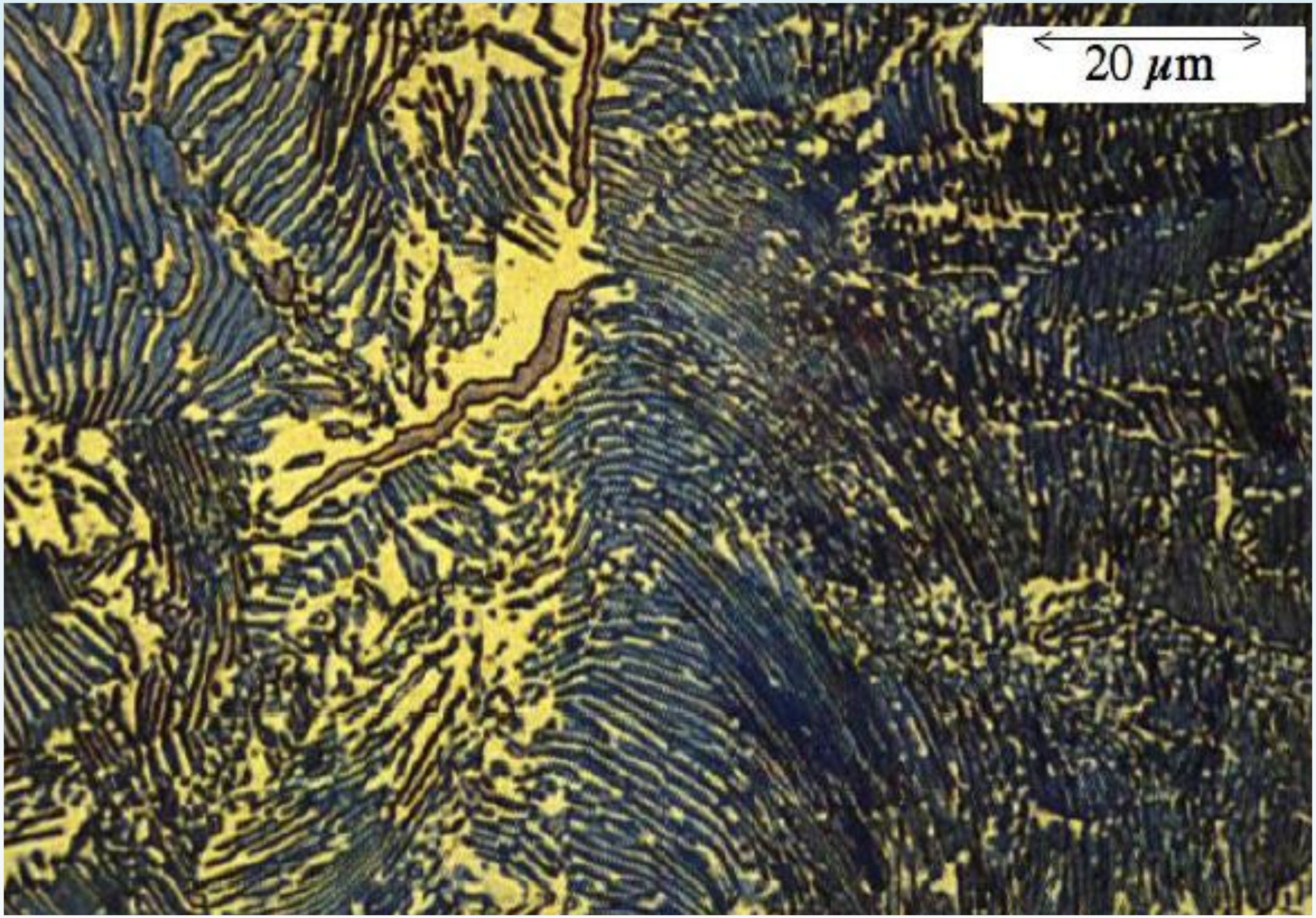
Heat Treatments-Isothermal Transformation (TTT-) Diagram



The thickness ratio of the ferrite & cementite layers in pearlite is about 8:1.

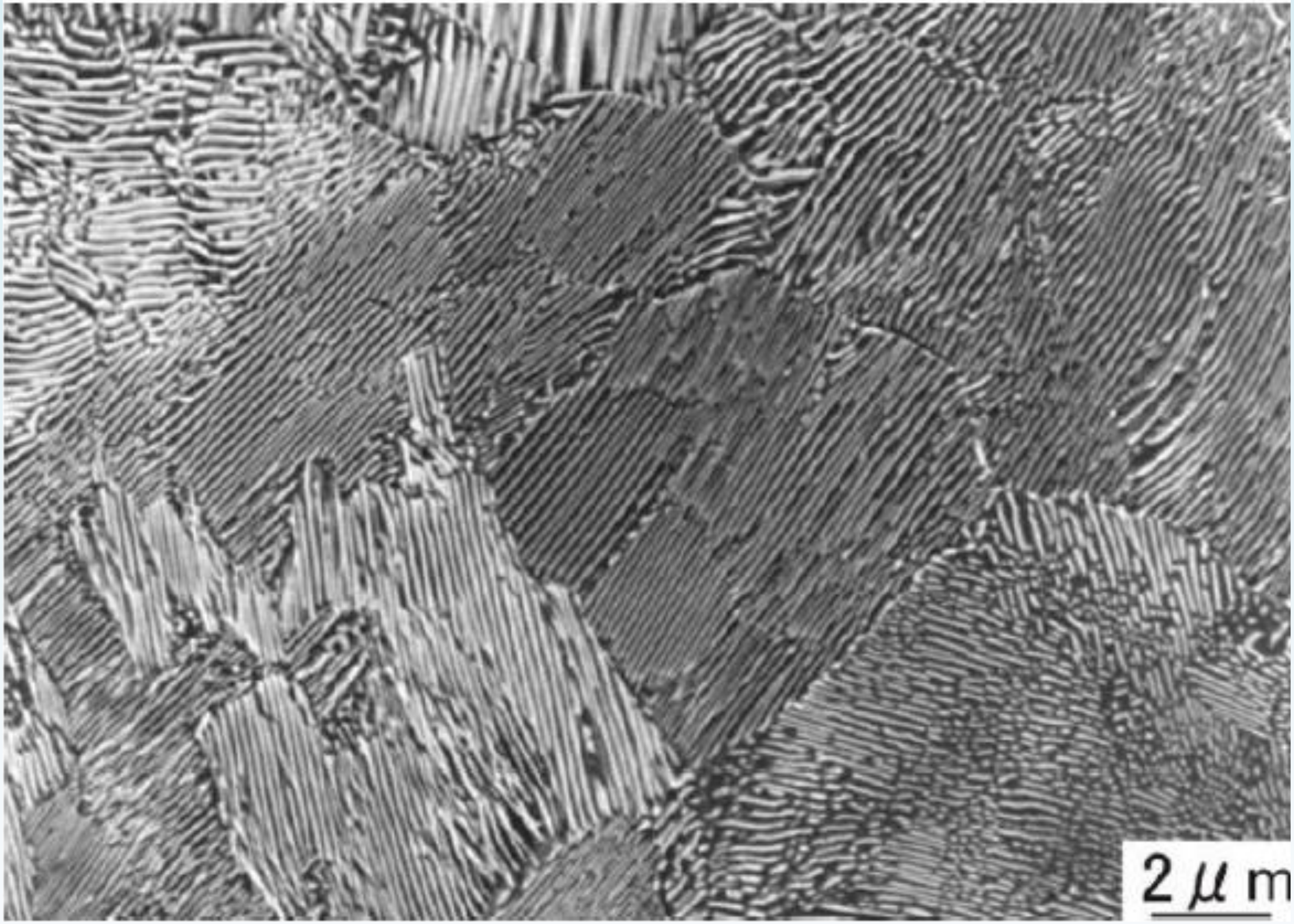
The absolute layer thickness increases with temperature

Heat Treatments-Isothermal Transformation (TTT-) Diagram



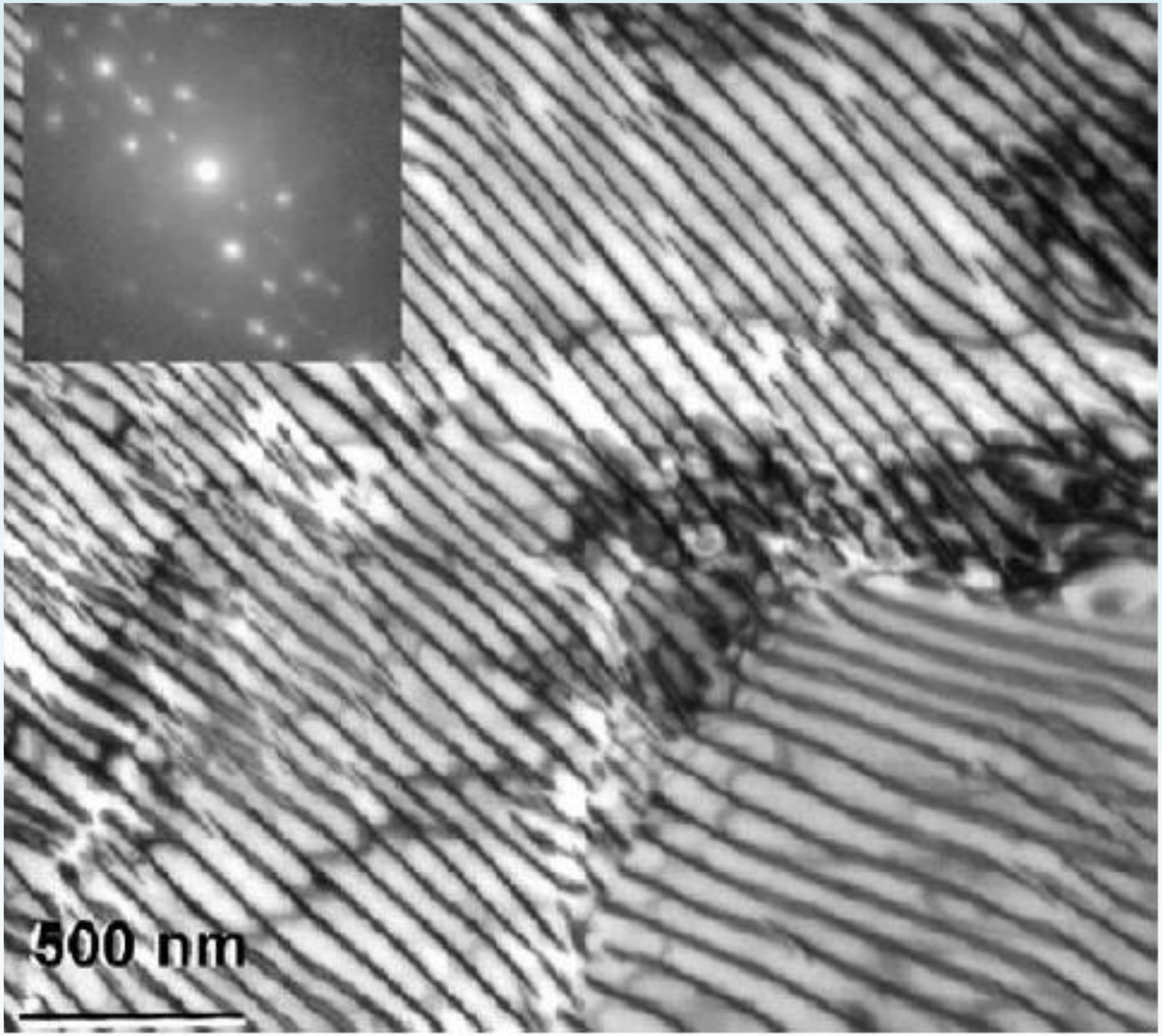
(Coarse) Pearlitic Microstructure under Optical Microscope

Heat Treatments-Isothermal Transformation (TTT-) Diagram

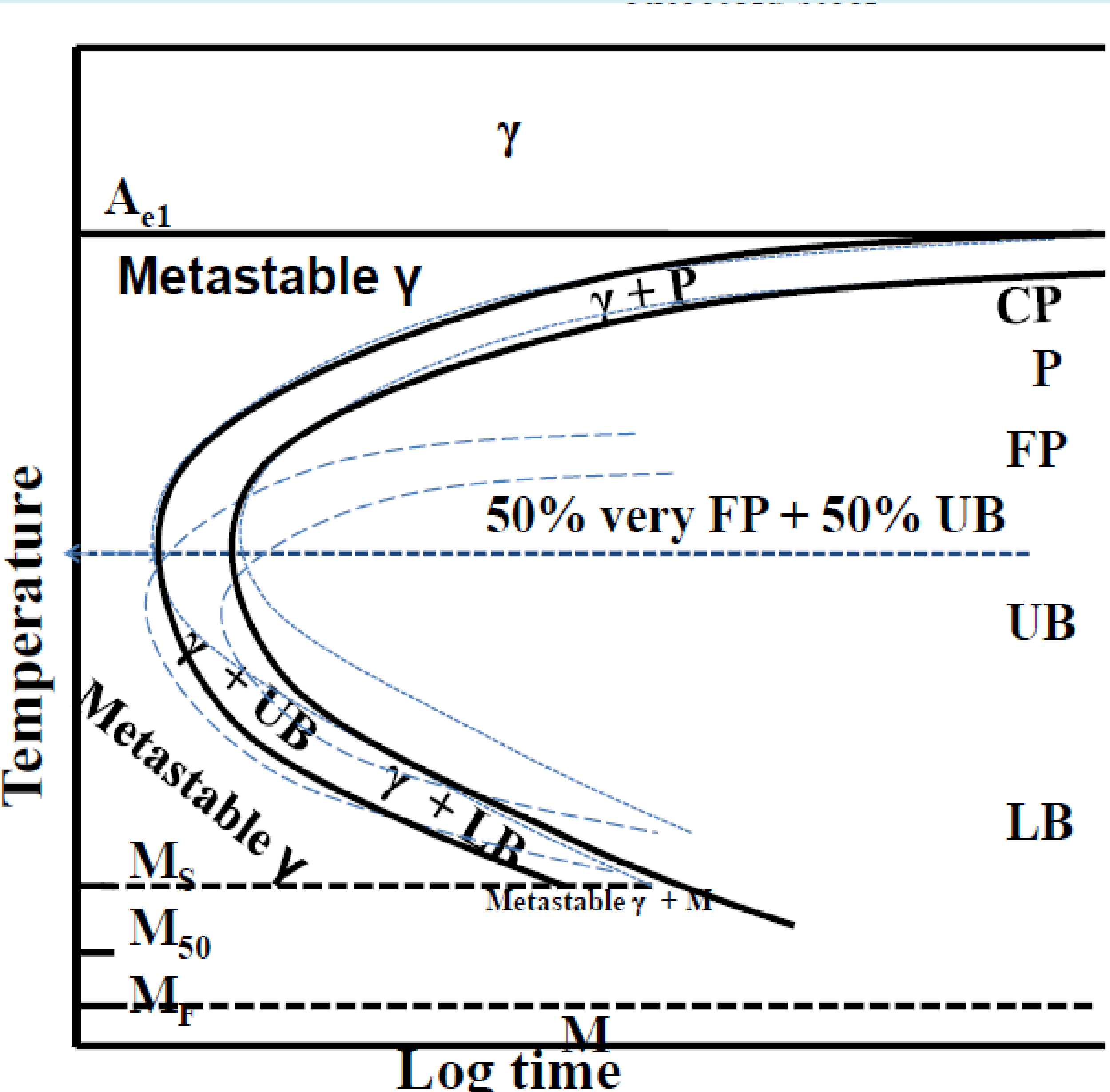


Colonies of Pearlite under Optical Microscope (Courtesy of S.S. Babu www)

Heat Treatments-Isothermal Transformation (TTT-) Diagram



Transmission Electron Micrograph of extremely fine Pearlite



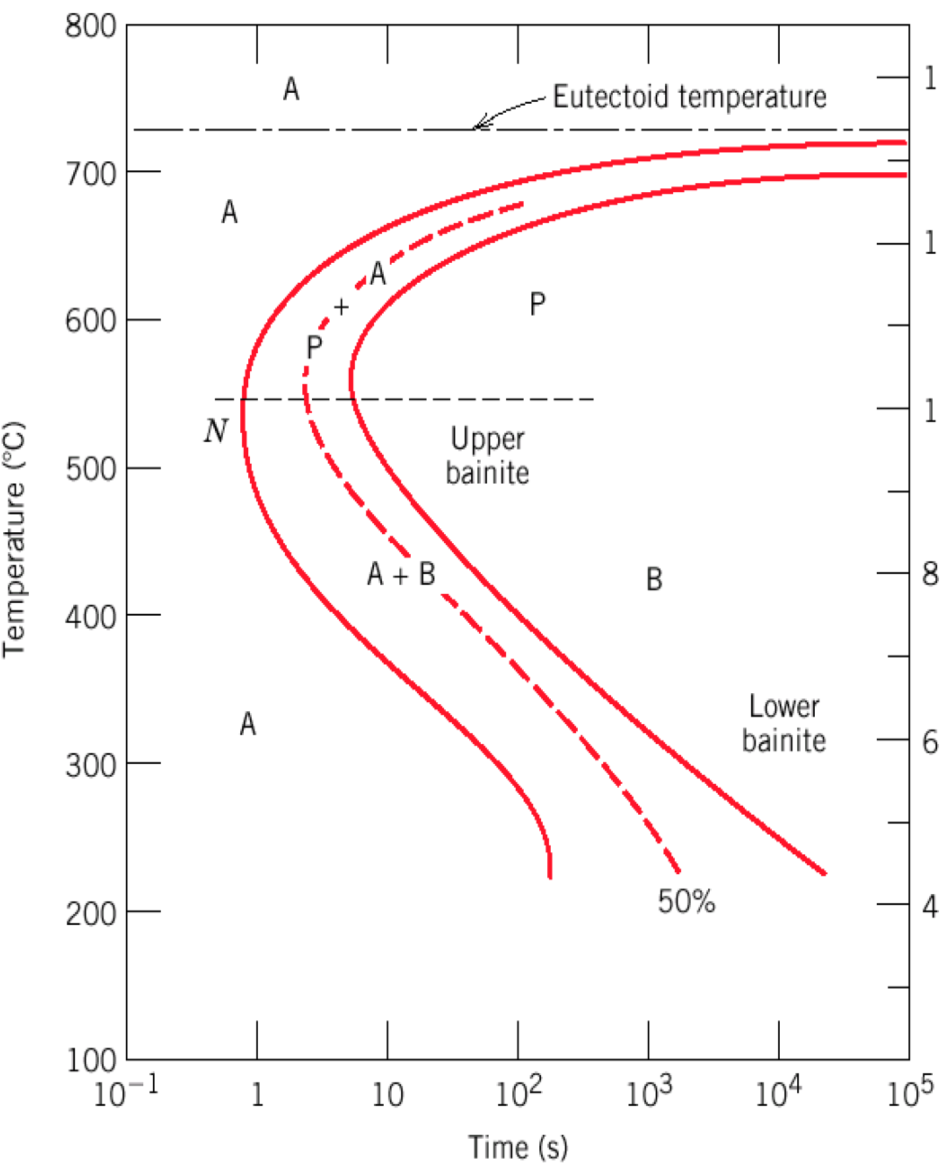
At the nose temperature,
fine pearlite and
upper bainite
form simultaneously
though the mechanisms
of their formation
are entirely different.

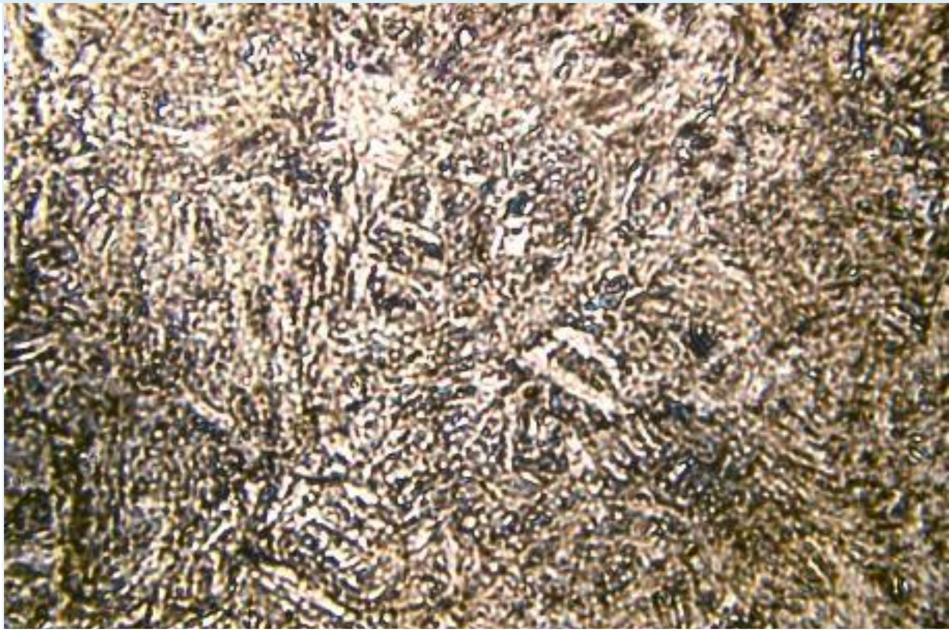
The nose is the result of
superimposition of two
transformation noses:
one for pearlitic reaction
other for bainitic reaction

SUMMARY

- ***S-shaped curves at different T build up the TTT diagram***
- ***The TTT diagram are for the isothermal transformations***
- ***At low temperatures, nucleation rate is higher, and the transformation occurs sooner; furthermore, diffusion is slower and grain growth is reduced***
- ***Slow diffusion leads to fine-grained microstructure with thin layered pearlite (fine pearlite)***
- ***At higher temperatures, high diffusion rates allow for larger grain growth and the formation of thick layered pearlite (coarse pearlite)***
- ***At compositions other than eutectoid, a proeutectoid phase (ferrite or cementite) coexists with pearlite***
- ***Additional curves for proeutectoid transformation must be included on TTT diagrams***

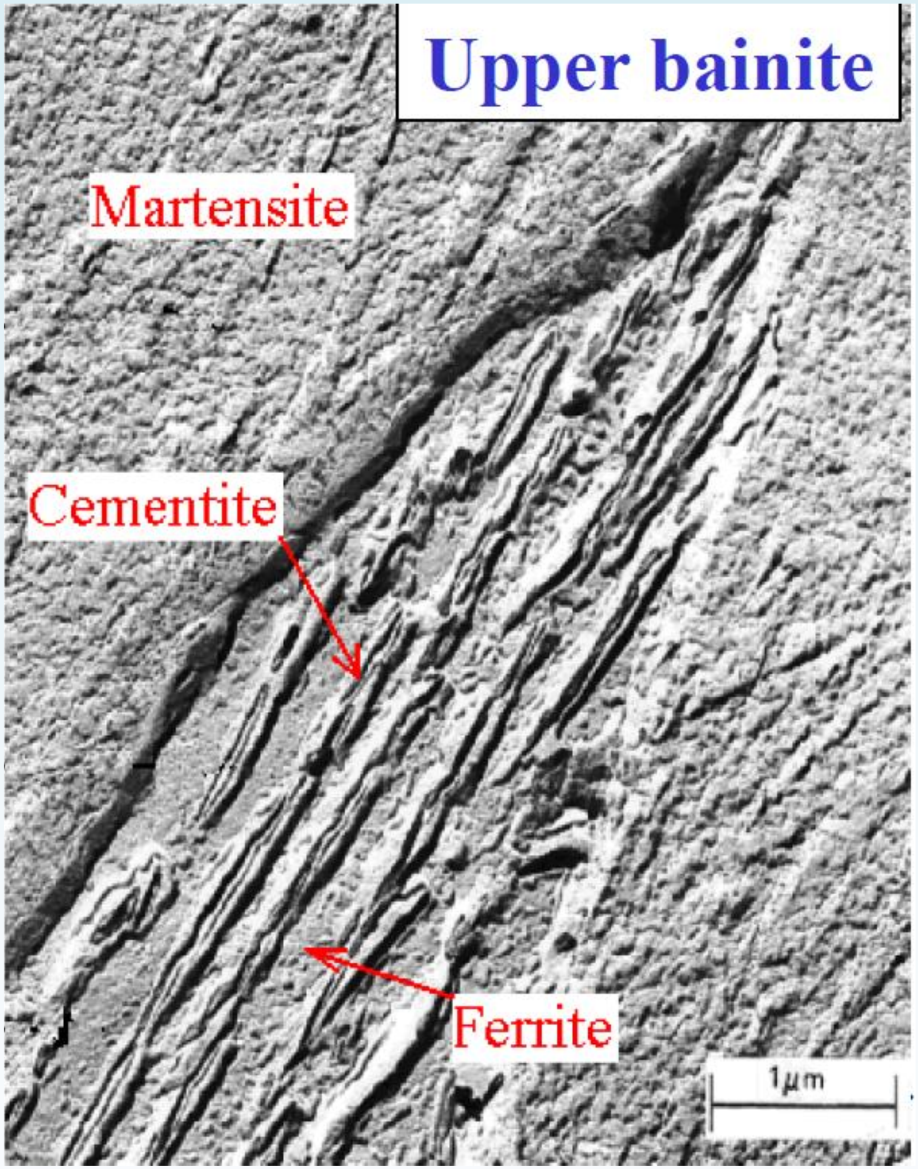
Heat Treatments – Formation of Bainite Microstructure

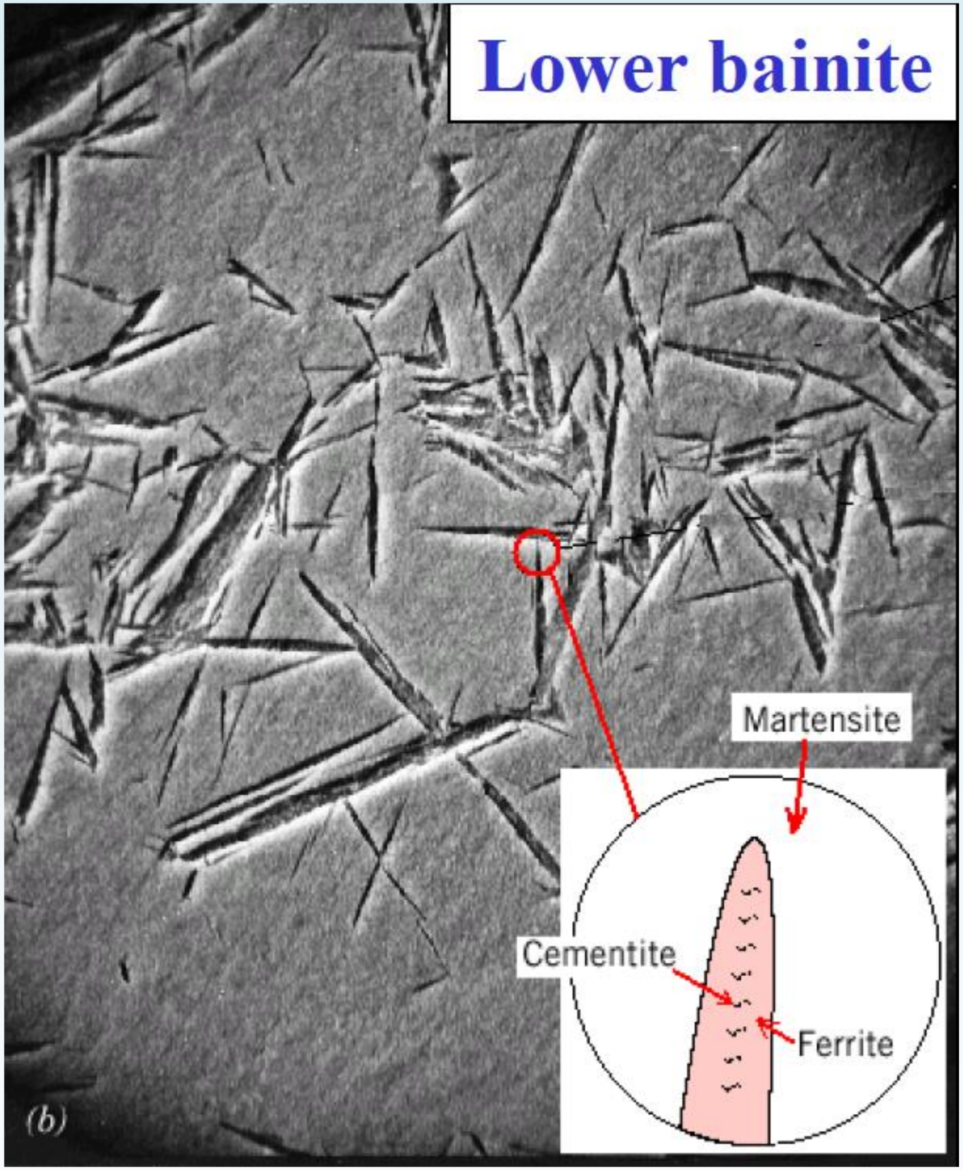




- For T ~ 300-540°C, **upper bainite** consists of needles of ferrite separated by long cementite particles
- For T ~ 200-300°C, **lower bainite** consists of thin plates of ferrite containing very fine rods or blades of cementite
- In the bainite region, transformation rate is controlled by microstructure growth (diffusion) rather than nucleation. Since diffusion is slow at low temperatures, this phase has a very fine (microscopic) microstructure.
- Pearlite and bainite transformations are competitive; transformation between pearlite and bainite not possible without first reheating to form austenite

Heat Treatments – Formation of Bainite Microstructure





Factors affecting TTT diagram ?

- **Composition of steel**

  (a) carbon wt%,
  (b) alloying element wt%

- **Grain size of austenite**
- **Heterogeneity of austenite**
- **Strain**

Transformation Diagrams – Effect of Carbon Content

Carbon wt%- (C%) < 0.77 wt%

C% ↑ → A_3 and A_{r3} ↓

during cooling (A_{r3})
during heating (A_{c3})
Equilibrium (A_{c3}

The incubation period for the austenite to pearlite increases: i.e. the C-curve of the diagram moves to right.

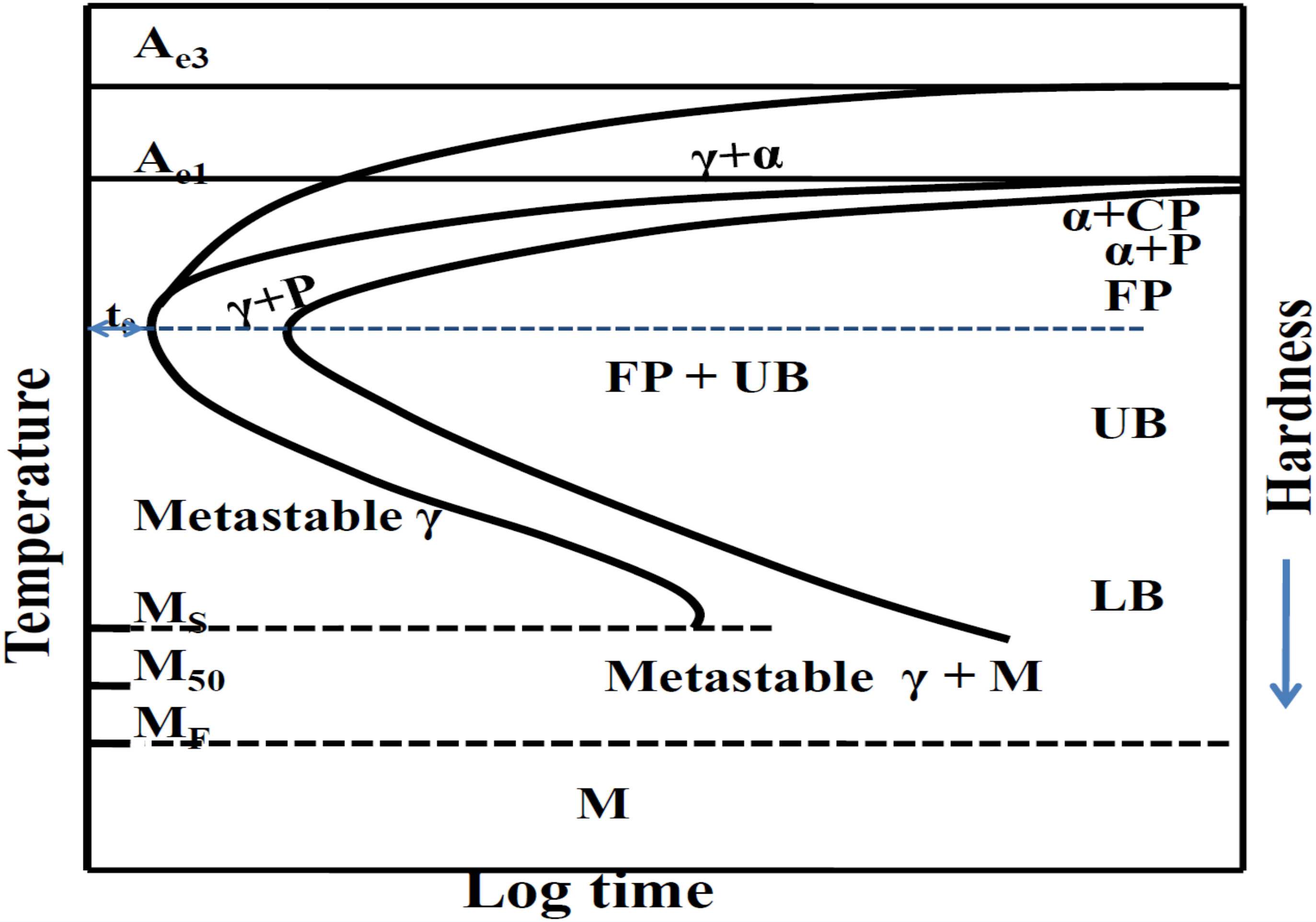
Carbon wt% > 0.77 wt%

C% ↑ → A_{cm} ↑

Austenite becomes less stable with respect to cementite precipitation, transformation to pearlite becomes faster. Therefore C curve moves towards left.

The critical cooling rate required to prevent diffusional transformation is minimum for eutectoid steel.

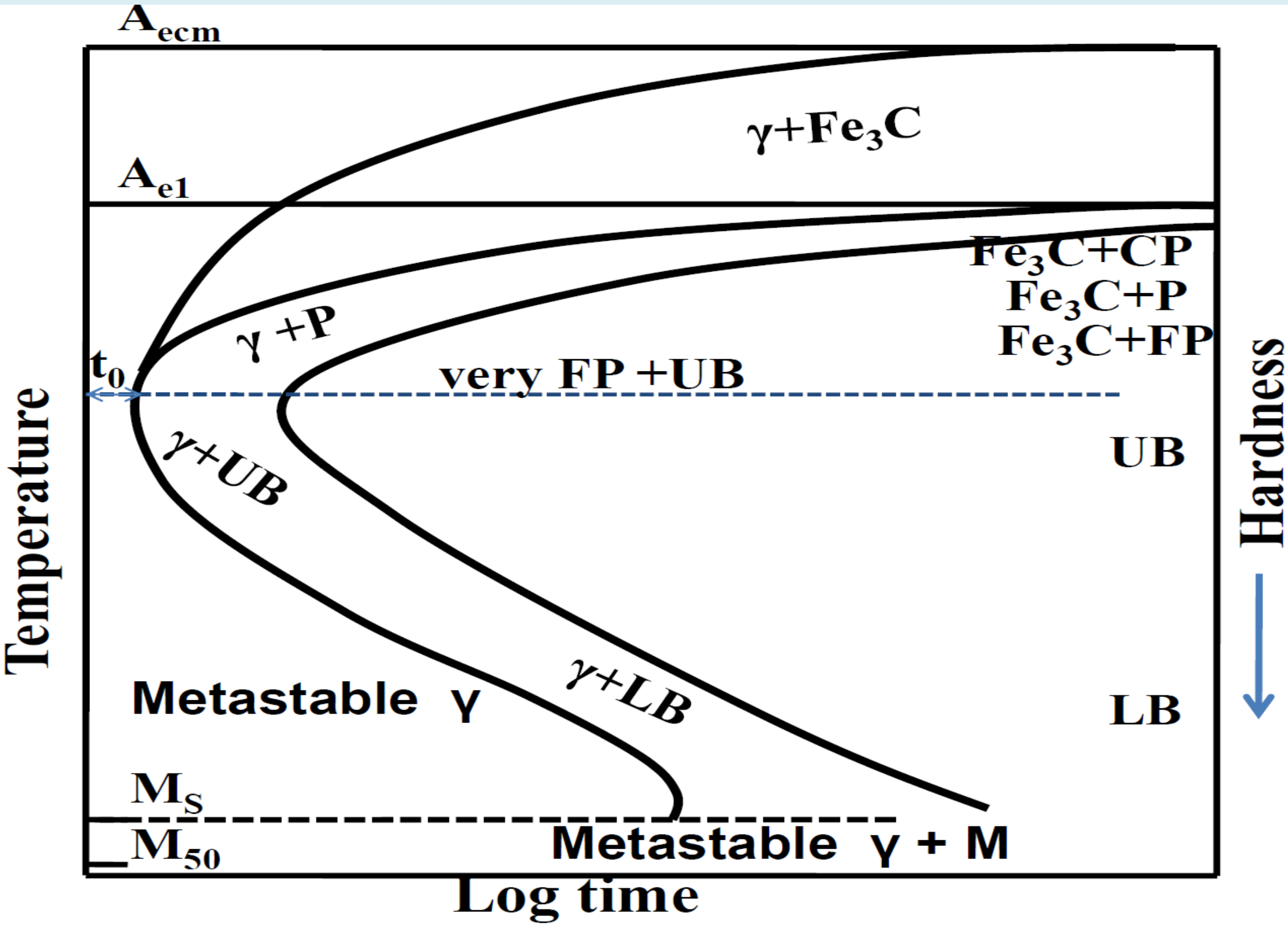
Transformation Diagrams – Effect of Carbon Content



γ=austenite
α=ferrite
CP=coarse pearlite
P=pearlite
FP=fine pearlite
UB=upper Bainite
LB=lower Bainite
M=martensite
M_S=Martensite start temperature
M_{50}=temperature for 50% martensite formation
M_F= martensite finish temperature

Schematic TTT diagram for plain carbon hypoeutectoid steel

Transformation Diagrams – Effect of Carbon Content



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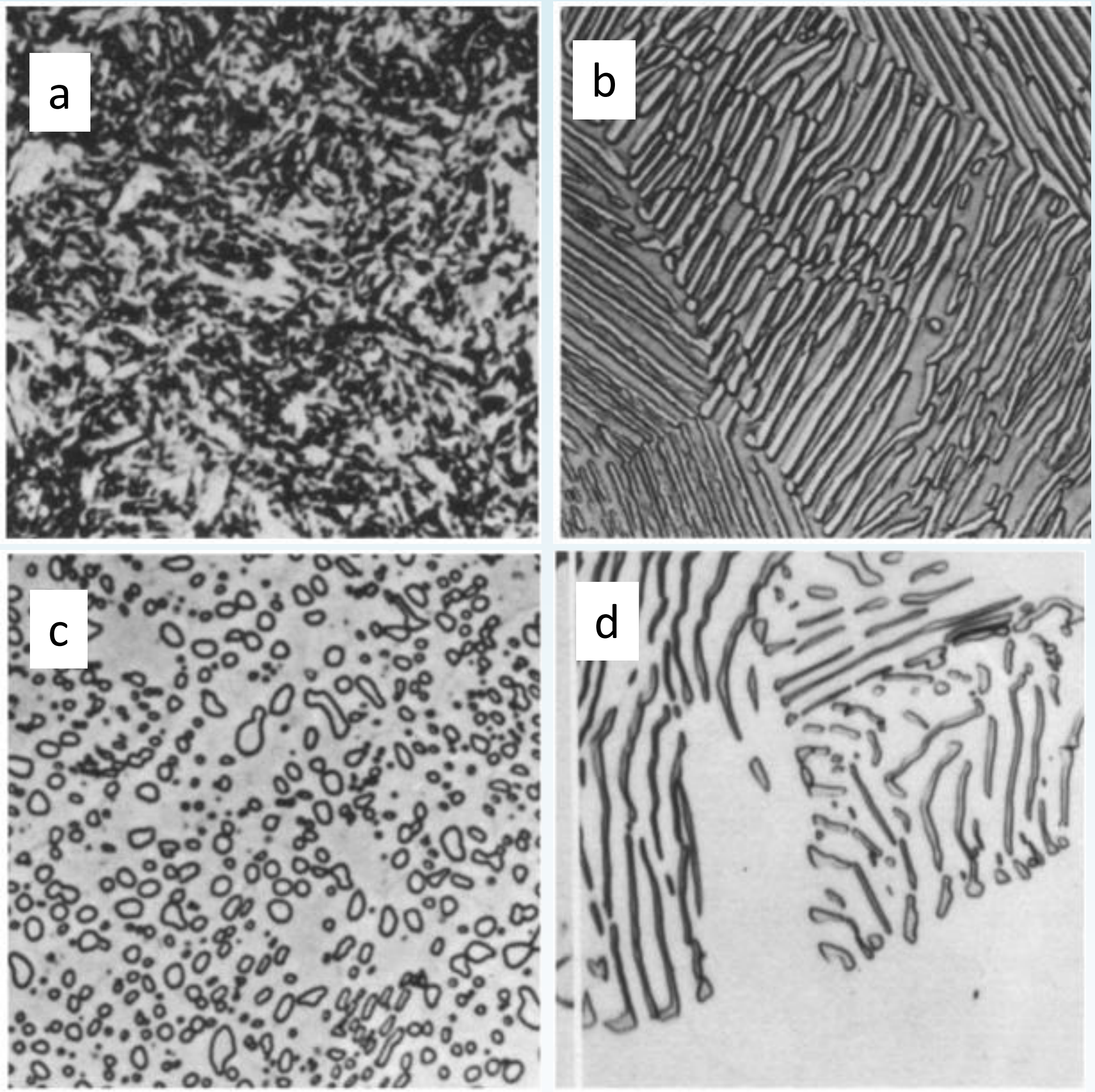
Schematic TTT diagram for plain carbon hypereutectoid steel

Focus on Steel – Steel Qualities



Effects of carbon content on the microstructures of plain-carbon steels:

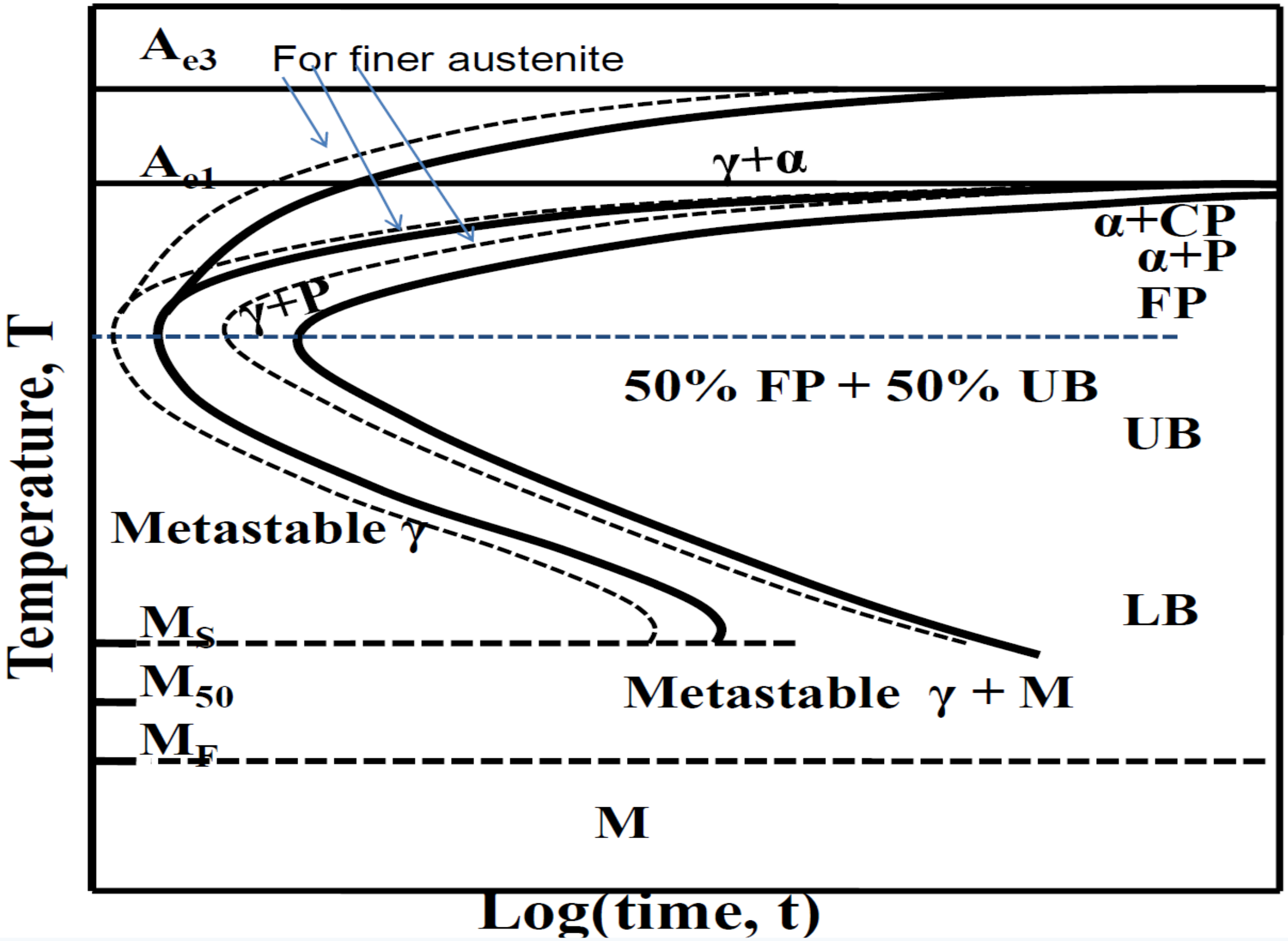
a) Hypoeutectoid steel (0.4% C) ferrite grains (white) and pearlite (gray streaks) in a white matrix . 1000.

(b) Eutectoid steel (0.77% C) (all pearlite grains). 2000.

(c) Eutectoid steel (0.77% C) with all cementite in the spheroidal form.1000.

(d) Hypereutectoid steel (1.0% C) pearlite with excess cementite bounding the grains. 1000.

Transformation Diagrams – Effect of Austenite Grain Size



Hardness

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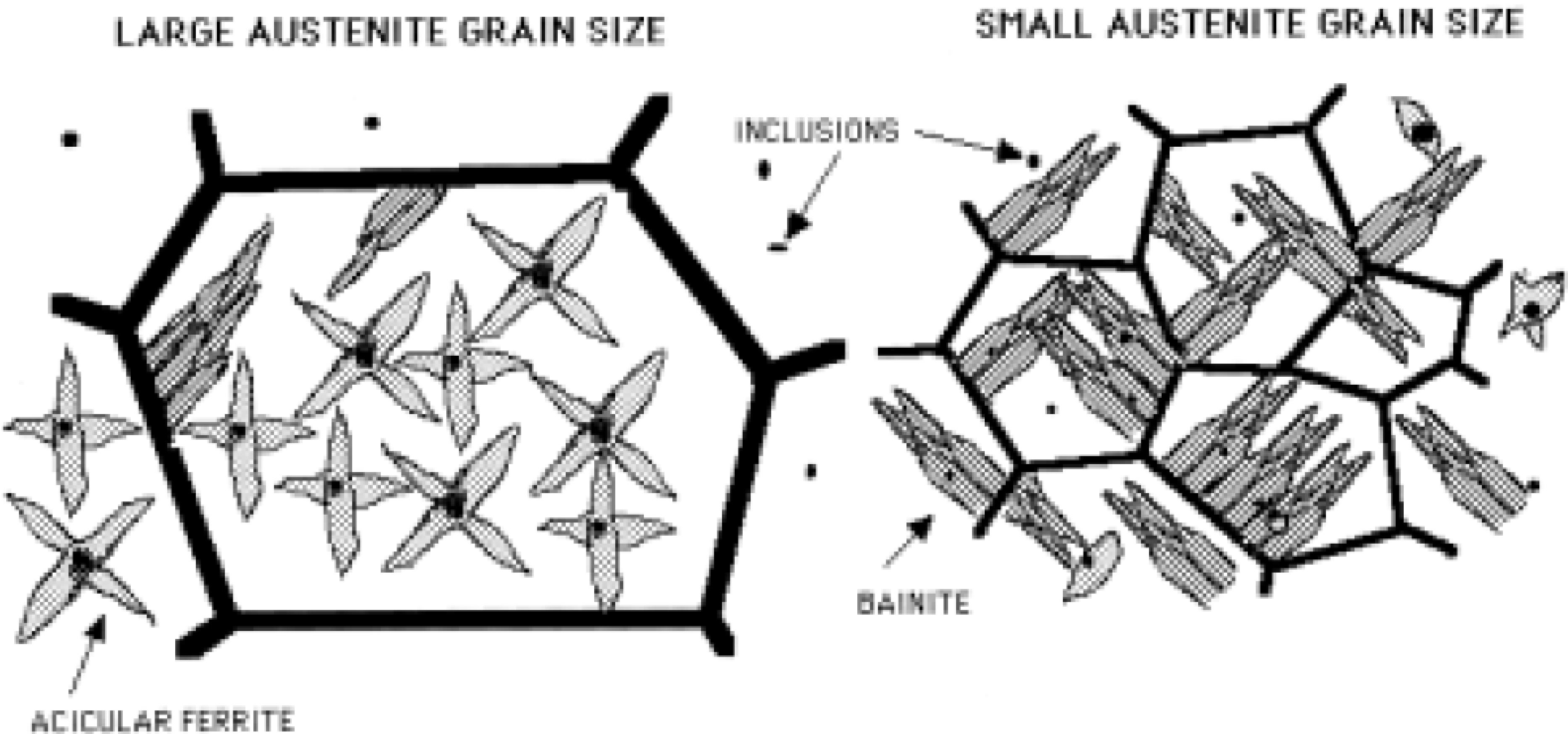
Effect of Austenite Grain Size on TTT Diagram of Plain Carbon Hypoeutectoid Steel

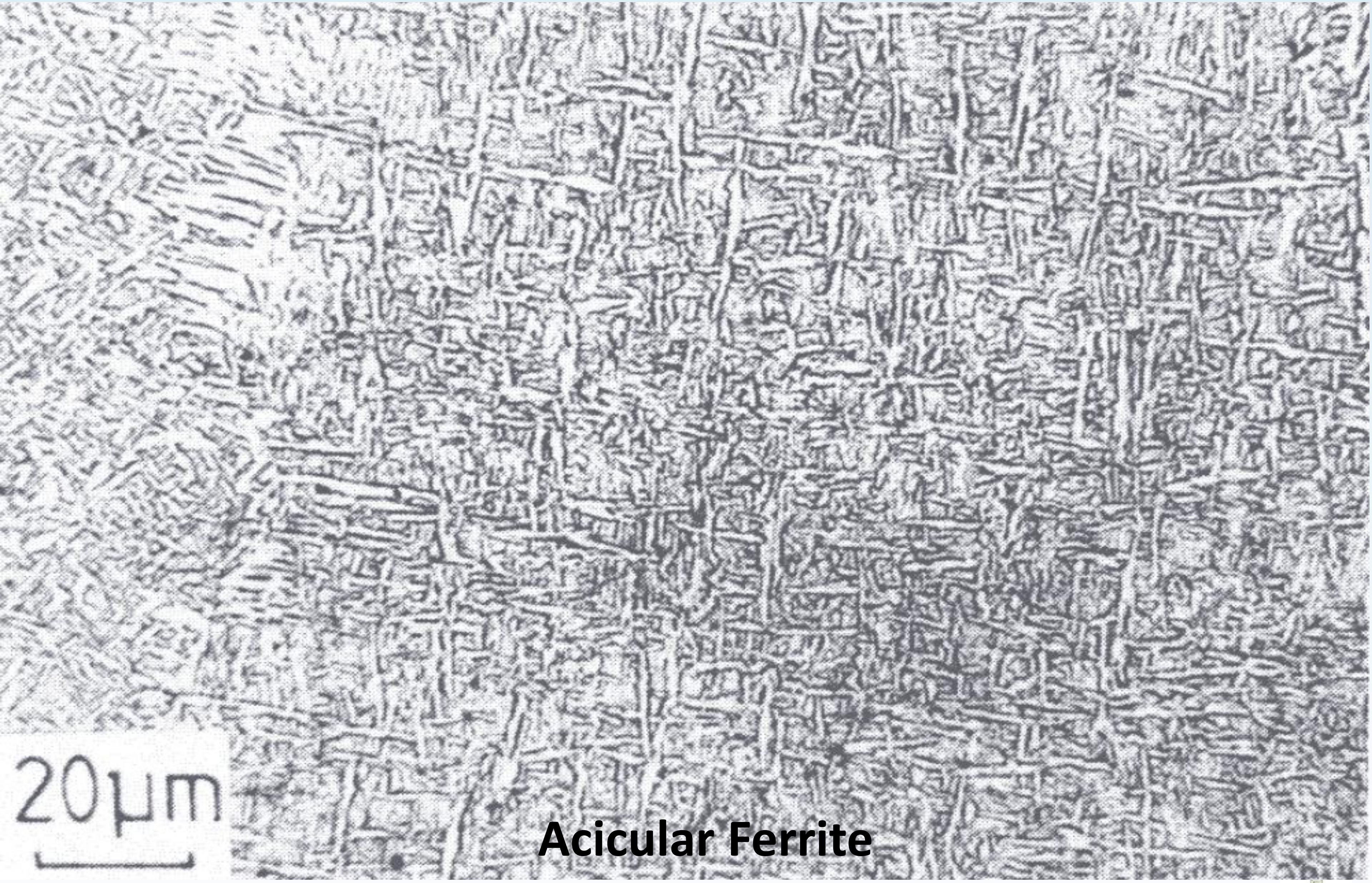
Transformation Diagrams – Effect of Austenite Grain Size



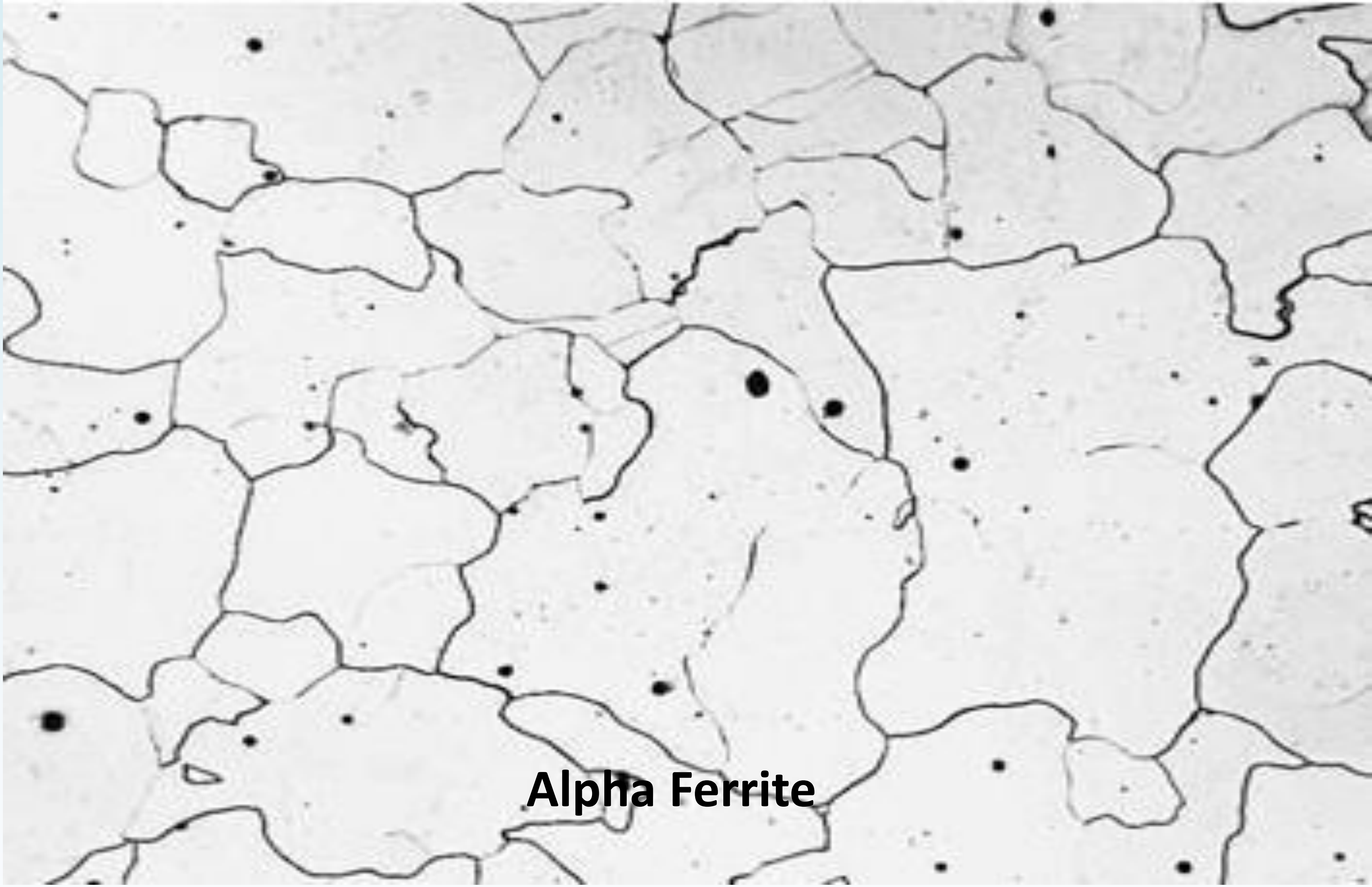
Morphology and Nucleation Site of Acicular Ferrite

Within the bainitic transformation temperature range, large grain size promotes acicular ferrite formation under isothermal condition

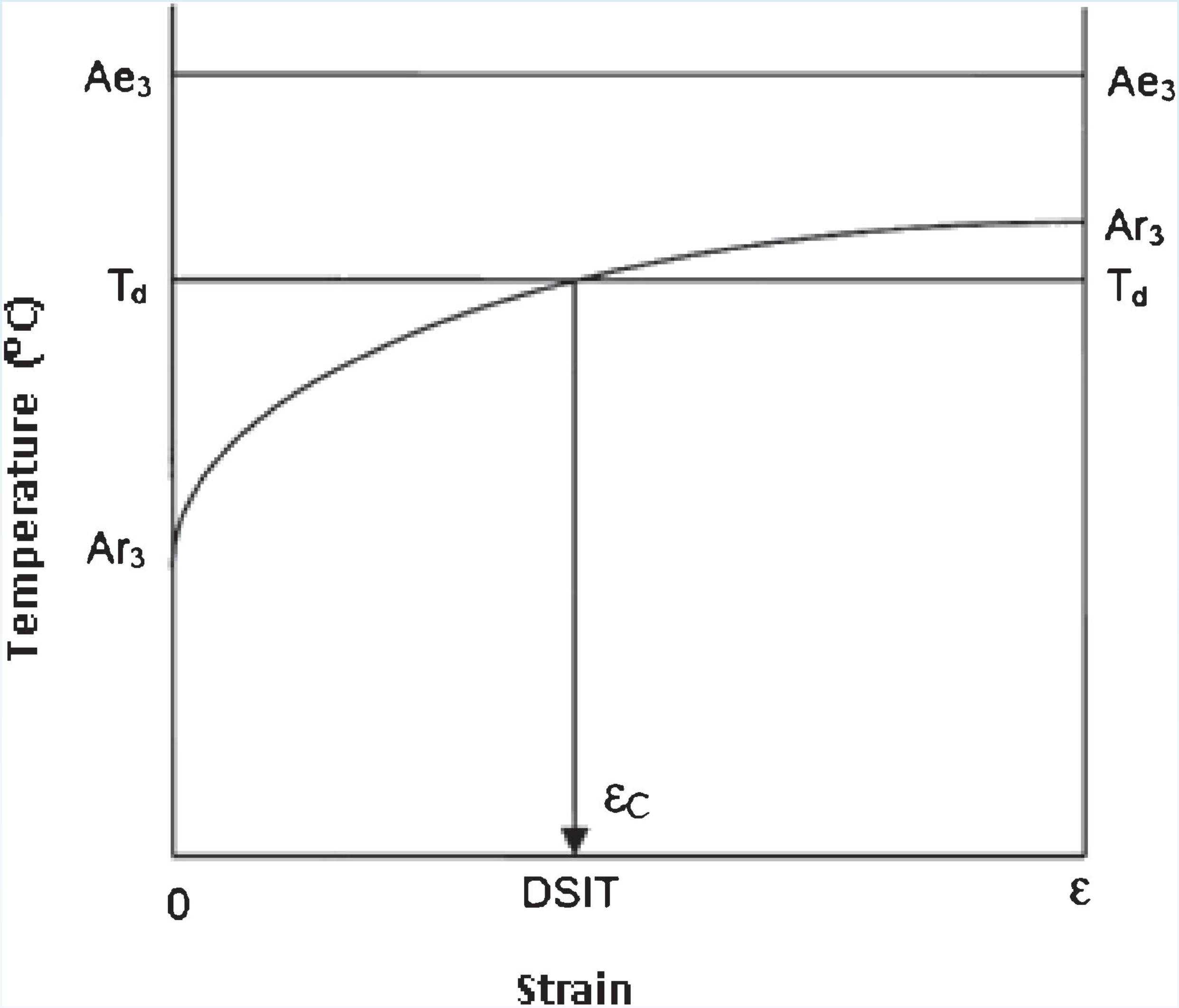
Transformation Diagrams – Effect of Austenite Grain Size



Transformation Diagrams – Massive Alpha Ferrite (for comparison)

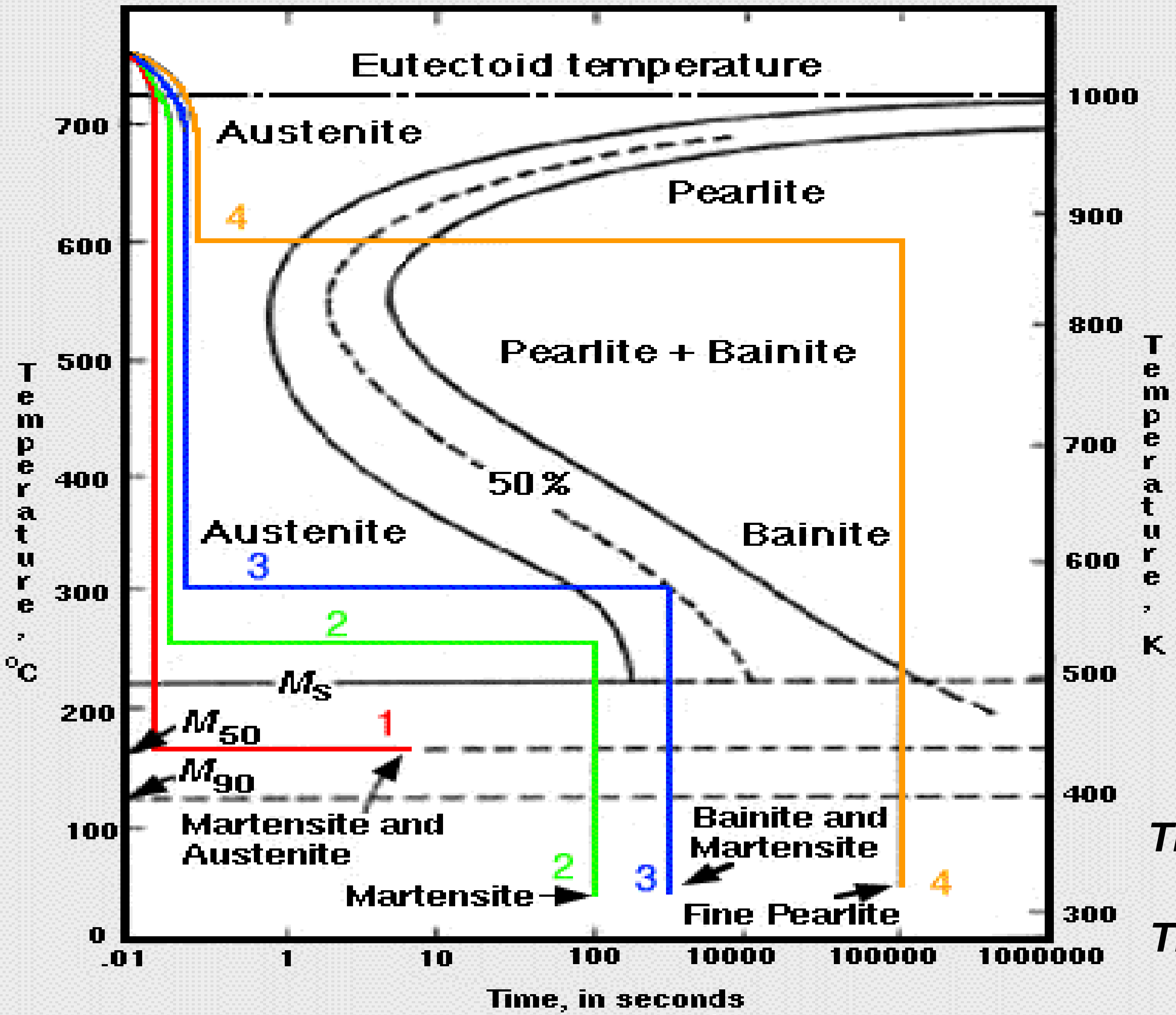


Heat Treatments TTT Diagram –Modification by Strain



Principles of dynamic strain induced transformation (DSIT) during deformation at constant temperature

Heat treatments –TTT diagram



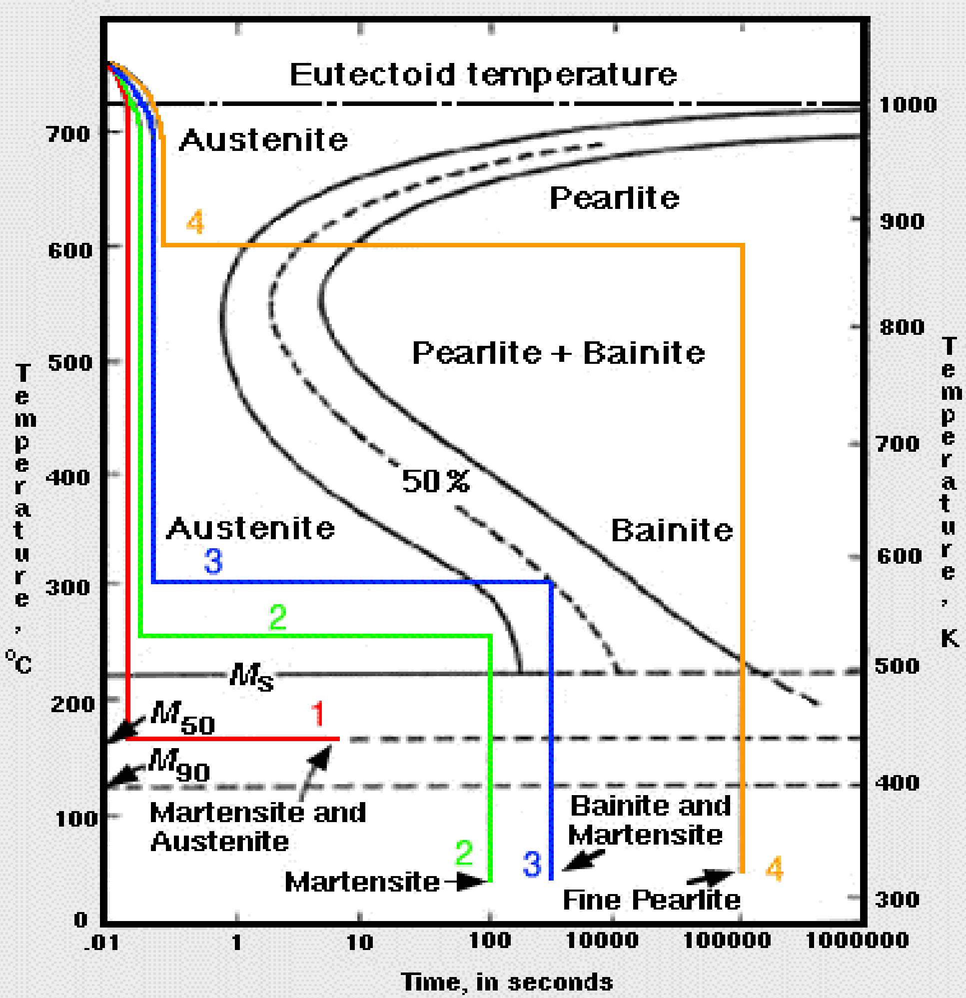
M_S : Martensitic Start Temperature

M_{50} : 50% Martensite

M_{90} : 90% Martensite

Time-Temperature Paths on Isothermal Transformation Diagram

Heat Treatments
Time Temperature Transformation (TTT) Diagram



Time-Temperature Paths on Isothermal Transformation Diagram

Austenite converts completely to fine pearlite after eight seconds at 873 K. This phase is stable and will not be changed on holding for 100,000 seconds at 873 K.

The final structure, when cooled, is fine pearlite.

Focus on Steel – Quenching and Tempering

ASTM A508 / A508M - 14

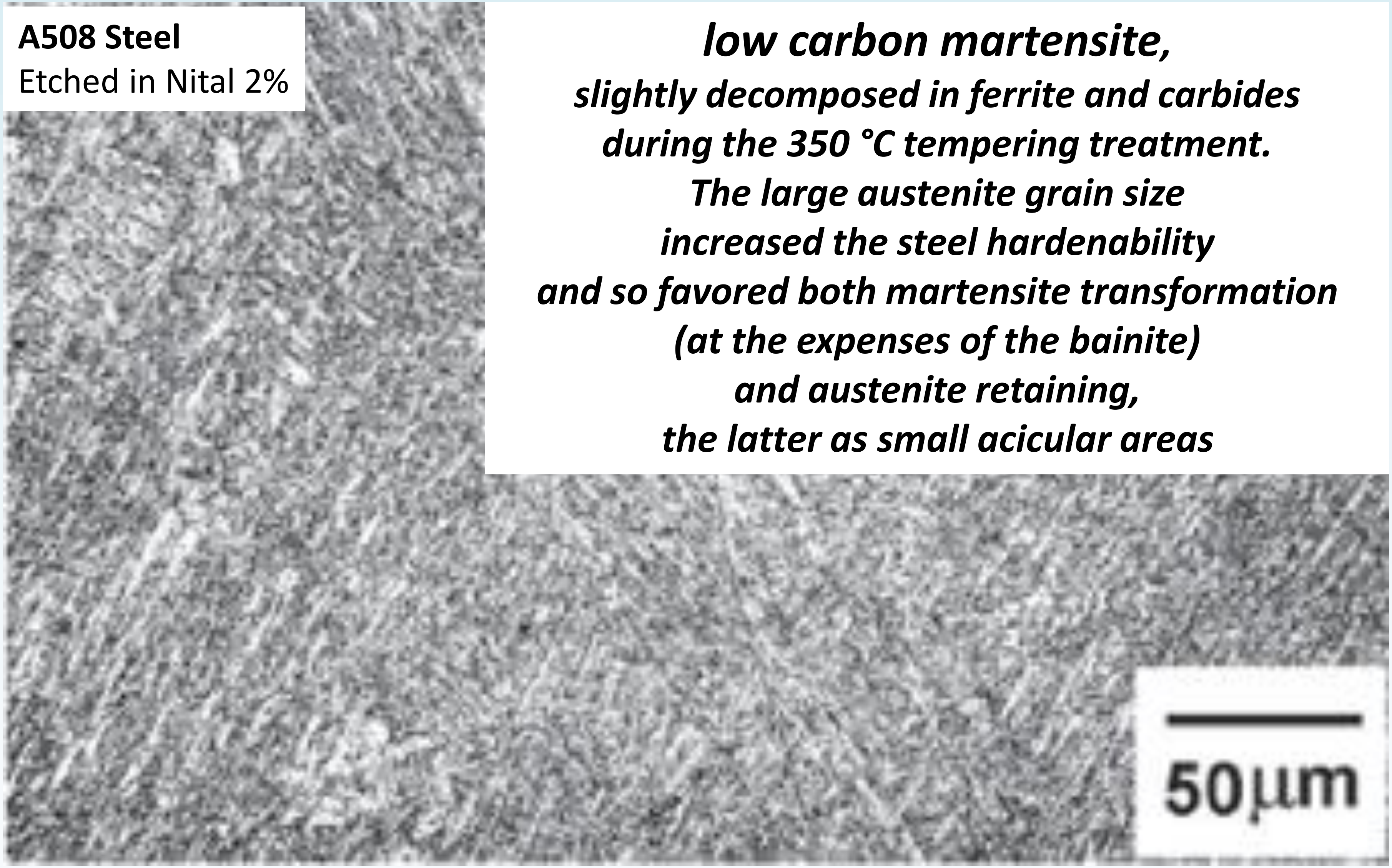
Standard Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels

Basic chemical composition of the steel, wt. (%)

C	Mn	Si	P	S	Cu	Ni	Cr	Mo
0.09	0.27	0.08	0.011	0.008	0.09	3.75	1.68	0.48

V	Ti	As	Sn	Sb	Al	Nb	N	O
0.008	0.006	0.005	0.004	0.003	[illegible]0.010	0.003	0.0029	0.0052

Focus on Steel – Quenching and Tempering

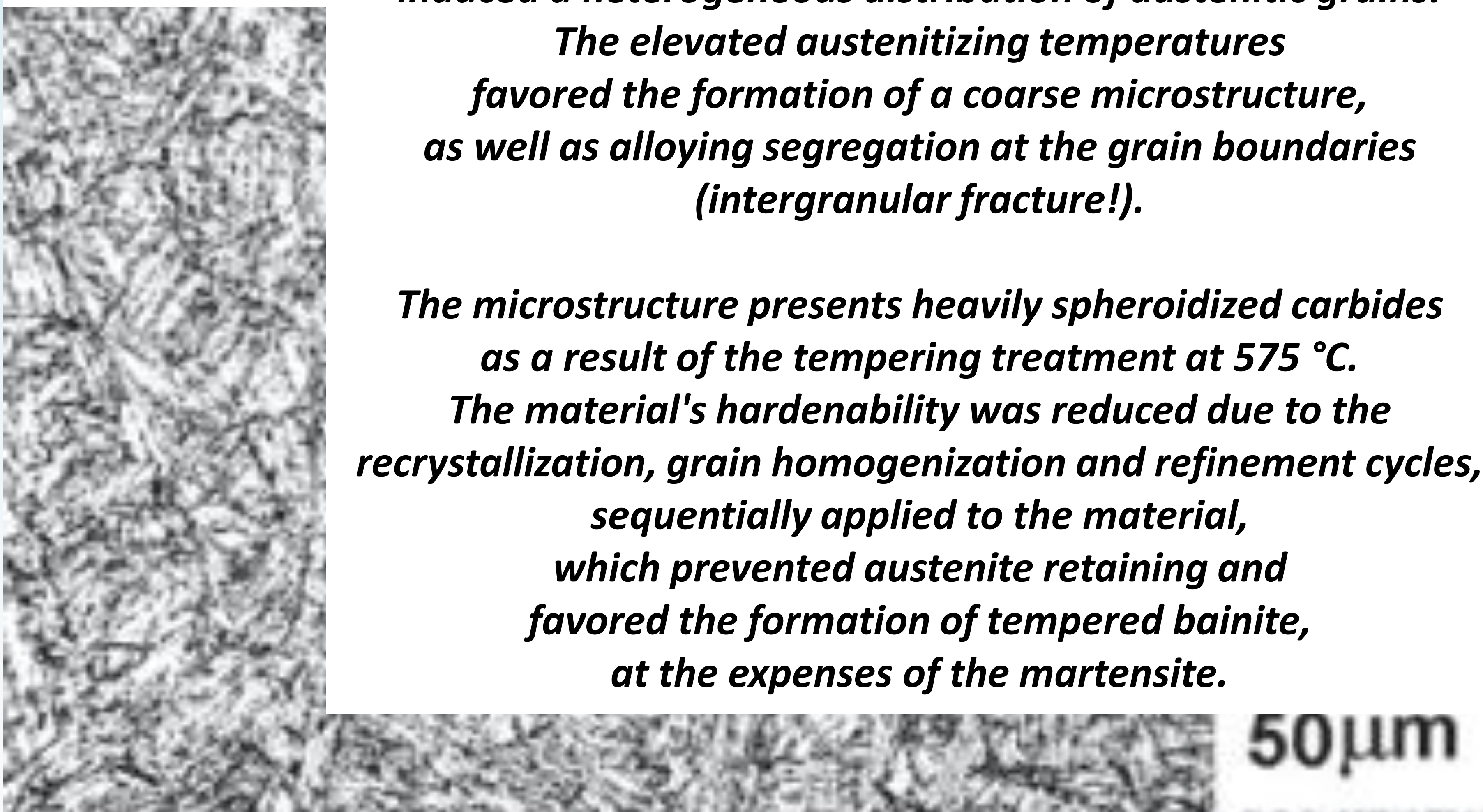


A508 Steel
Etched in Nital 2%

low carbon martensite,
slightly decomposed in ferrite and carbides
during the 350 °C tempering treatment.
The large austenite grain size
increased the steel hardenability
and so favored both martensite transformation
(at the expenses of the bainite)
and austenite retaining,
the latter as small acicular areas

Focus on Steel – Quenching and Tempering

A508 Steel
Etched in Nital 2%

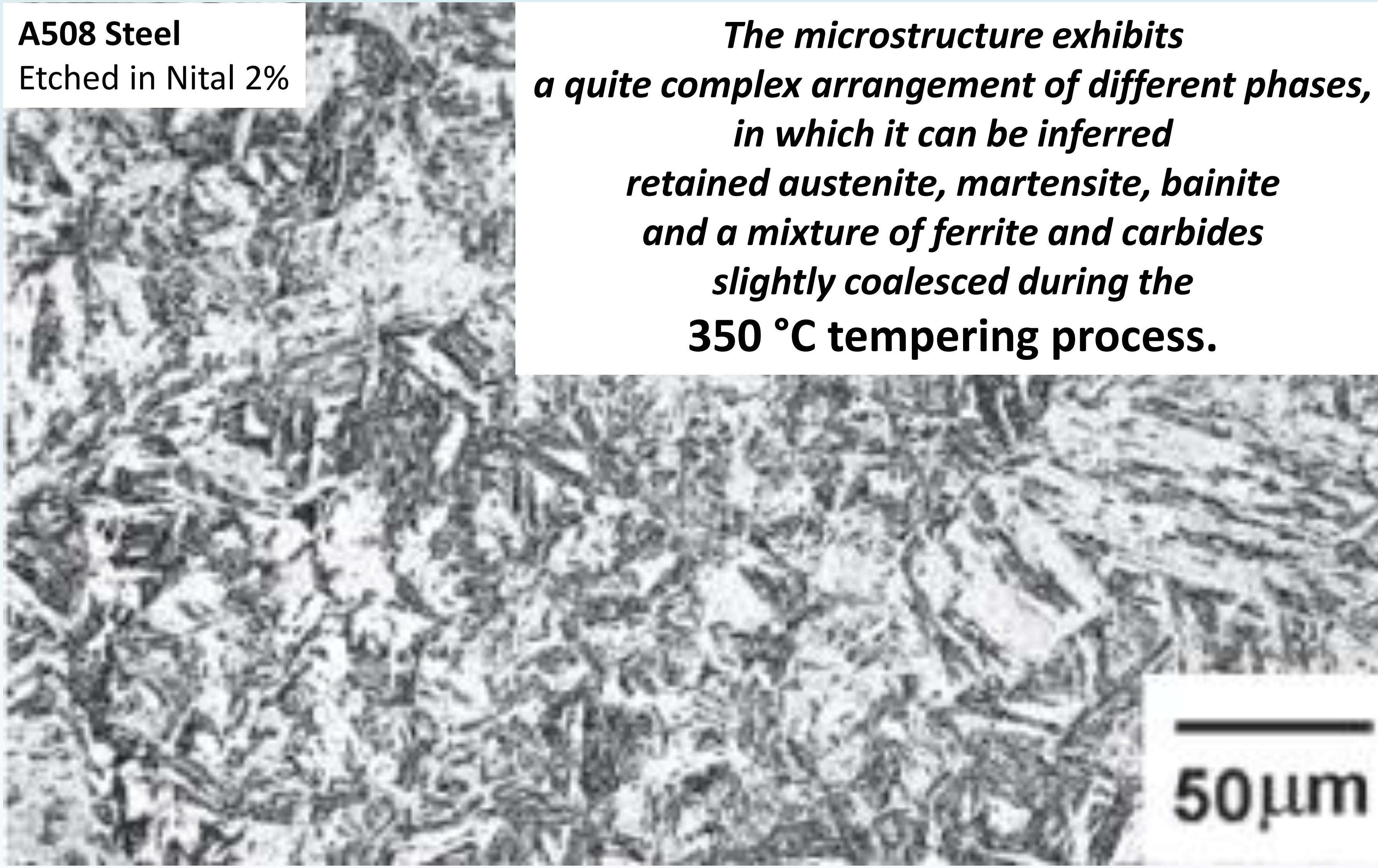


Partial recrystallization during discontinuous cooling,
induced a heterogeneous distribution of austenitic grains.
The elevated austenitizing temperatures
favored the formation of a coarse microstructure,
as well as alloying segregation at the grain boundaries
(intergranular fracture!).

The microstructure presents heavily spheroidized carbides
as a result of the tempering treatment at 575 °C.
The material's hardenability was reduced due to the
recrystallization, grain homogenization and refinement cycles,
sequentially applied to the material,
which prevented austenite retaining and
favored the formation of tempered bainite,
at the expenses of the martensite.

Focus on Steel – Quenching and Tempering

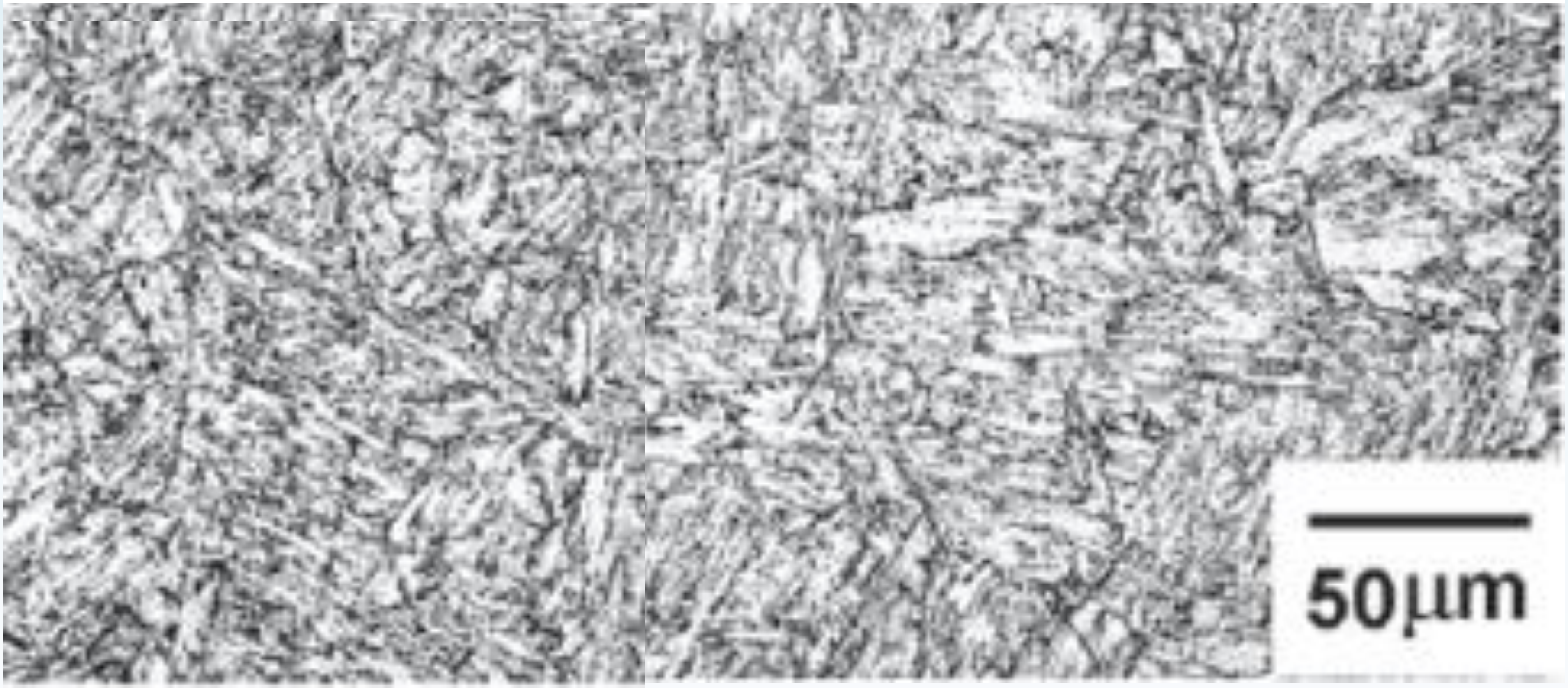
A508 Steel
Etched in Nital 2%



The microstructure exhibits
a quite complex arrangement of different phases,
in which it can be inferred
retained austenite, martensite, bainite
and a mixture of ferrite and carbides
slightly coalesced during the
350 °C tempering process.

Focus on Steel – Quenching and Tempering

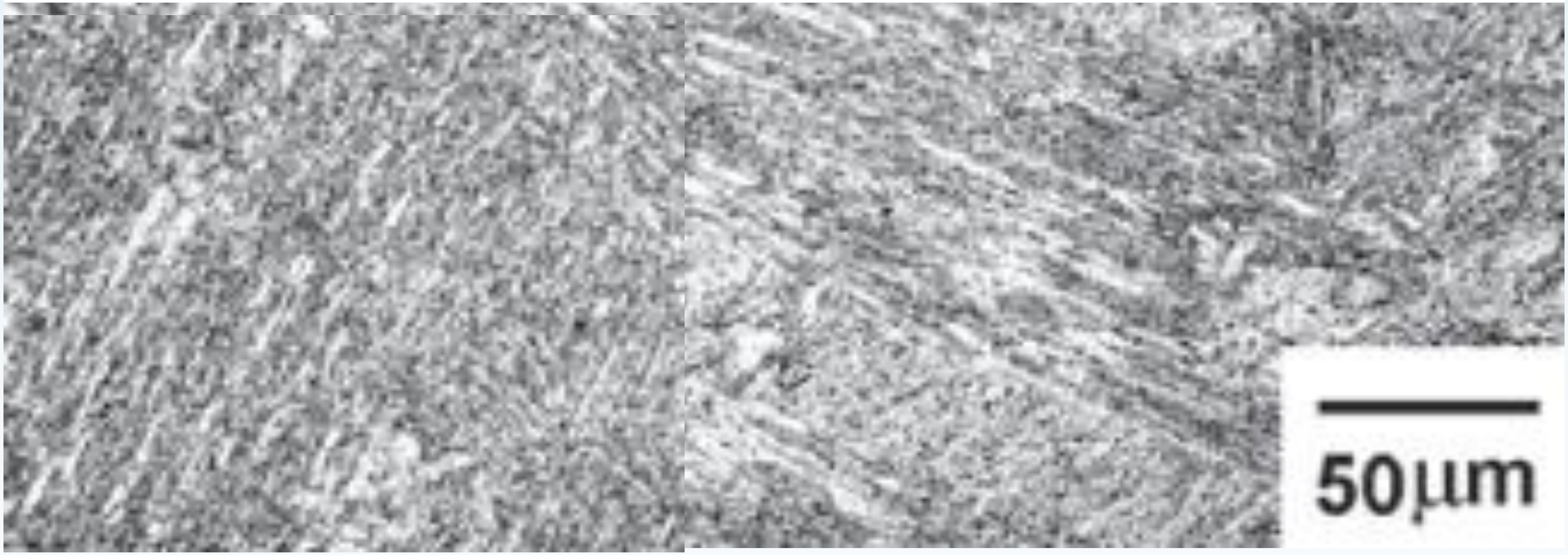
The microstructure maintain great morphologic similarity to
the microstructure generated by partial recrystallization
due to the likeness between their quenching and final tempering conditions.
As a consequence of higher austenitizing soaking time and temperature applied,
it rendered a coarser microstructure. This leads to a lower toughness value.



Focus on Steel – Quenching and Tempering

Very high austenitizing soaking times and temperatures

result in grain coarseness.
This condition also induces segregation at grain boundaries
with the risk of intergranular crack propagation.
It resembles the microstructure of “low carbon martensite”
related to the very high hardenability caused by large austenitic grain size
that gave rise to low carbon martensite, instead of bainite.



Heat treatments – continuous cooling transformation diagram

A continuous cooling transformation (CCT) phase diagram is used to represent which types of phase changes will occur in a material as it is cooled at different rates.
These diagrams are often more useful than TTT diagrams because it is more convenient to cool materials at a certain rate than to cool quickly and hold at a certain temperature.

Types of Continuous Cooling Diagrams

There are two types of continuous cooling diagrams drawn for practical purposes. The diagrams plot transformation start, a specific transformation fraction, and transformation finish temperature for all products against:

- **Type 1: transformation time on each cooling curve**
- **Type 2: cooling rate or bar diameter of the specimen for each type of cooling medium.**

Heat treatments – continuous cooling transformation diagram

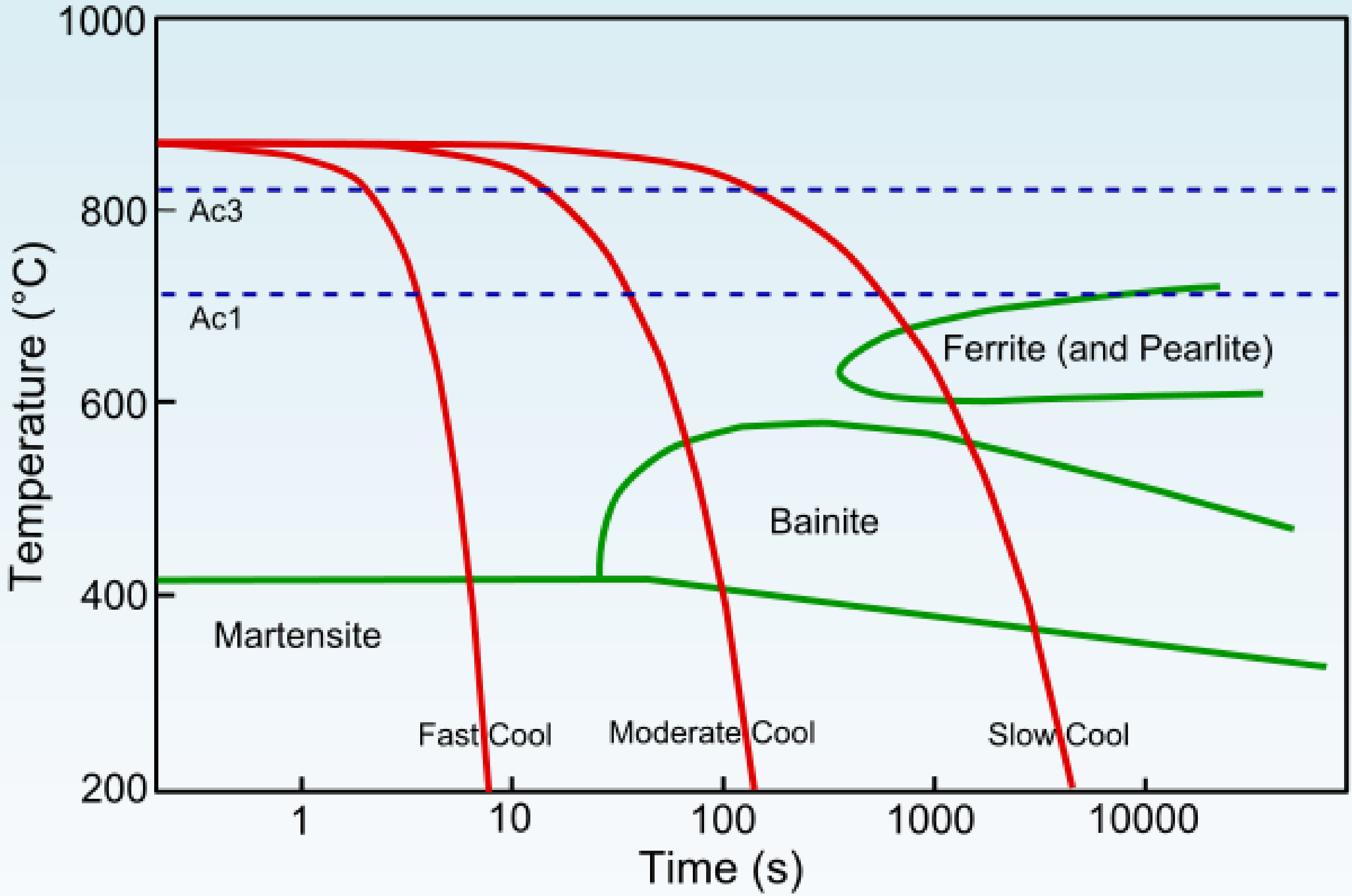
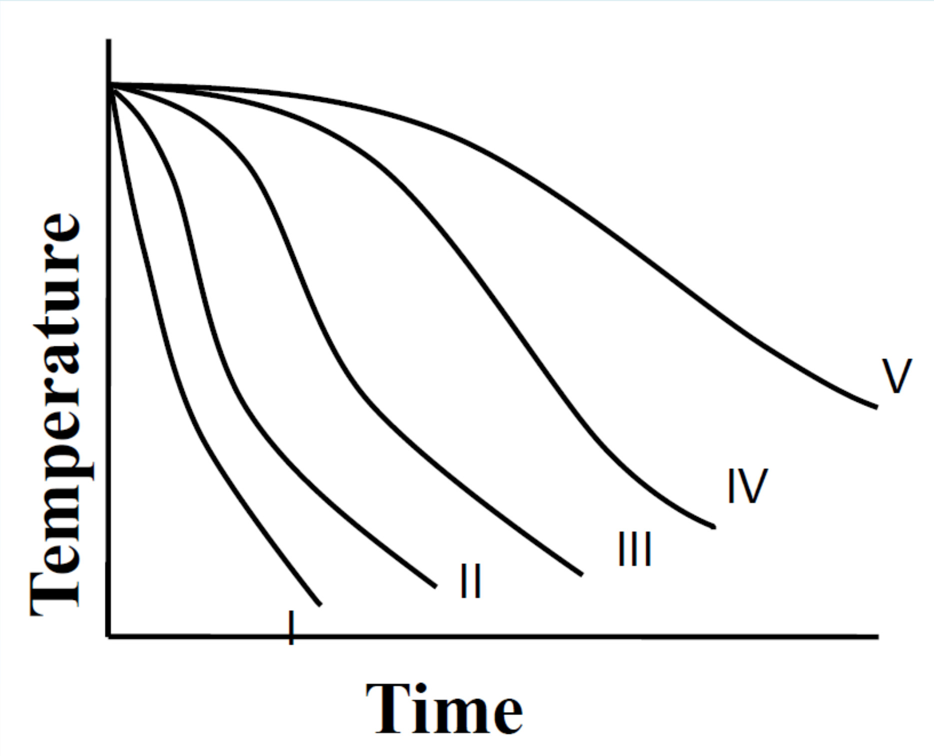
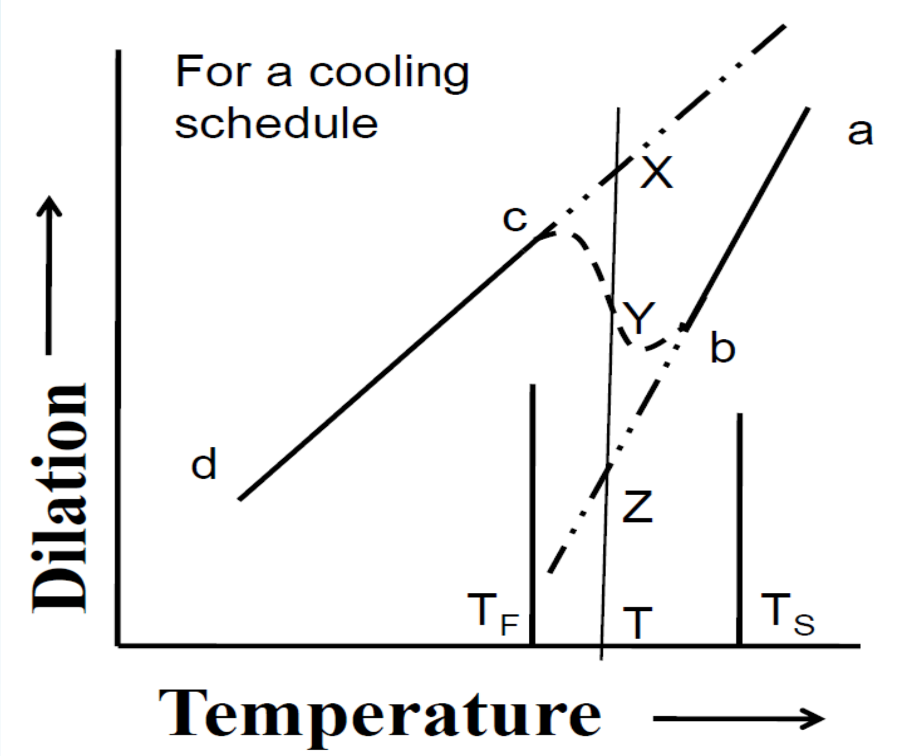


Illustration of a continuous cooling transformation (cct) diagram for steel

Heat treatments – continuous cooling transformation diagram



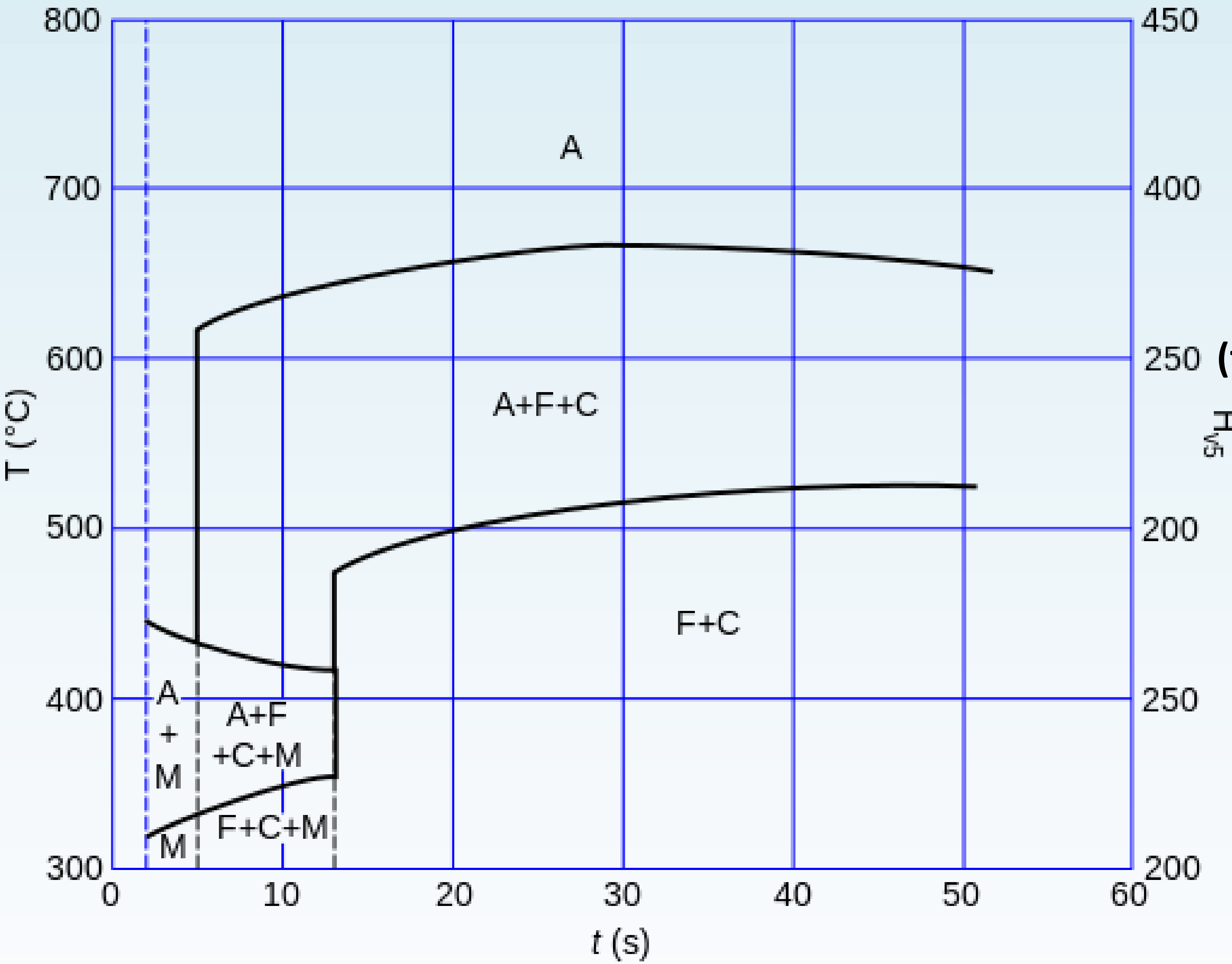
Schematic Cooling Curves



Dilation-Temperature Plot for a Cooling Curve

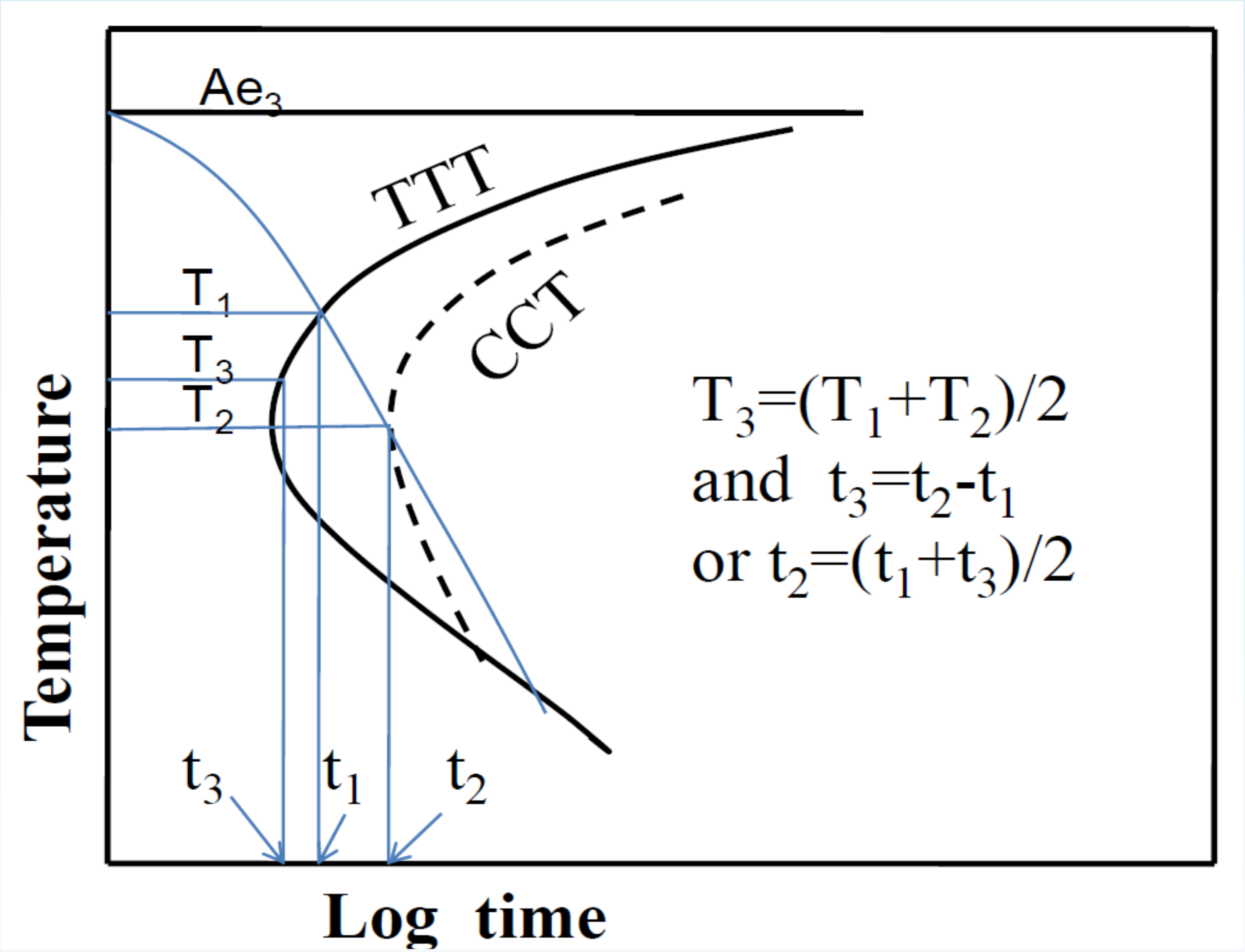
Any slope change indicates phase transformation. Fraction of transformation roughly can be estimated

Heat Treatments
Continuous Cooling Transformation (CCT) Diagram



Steel EN S355
(ASTM A-572 Grade 50)
warranted yield stress:
355 MPa for welding
(fast cooling, linear scale)

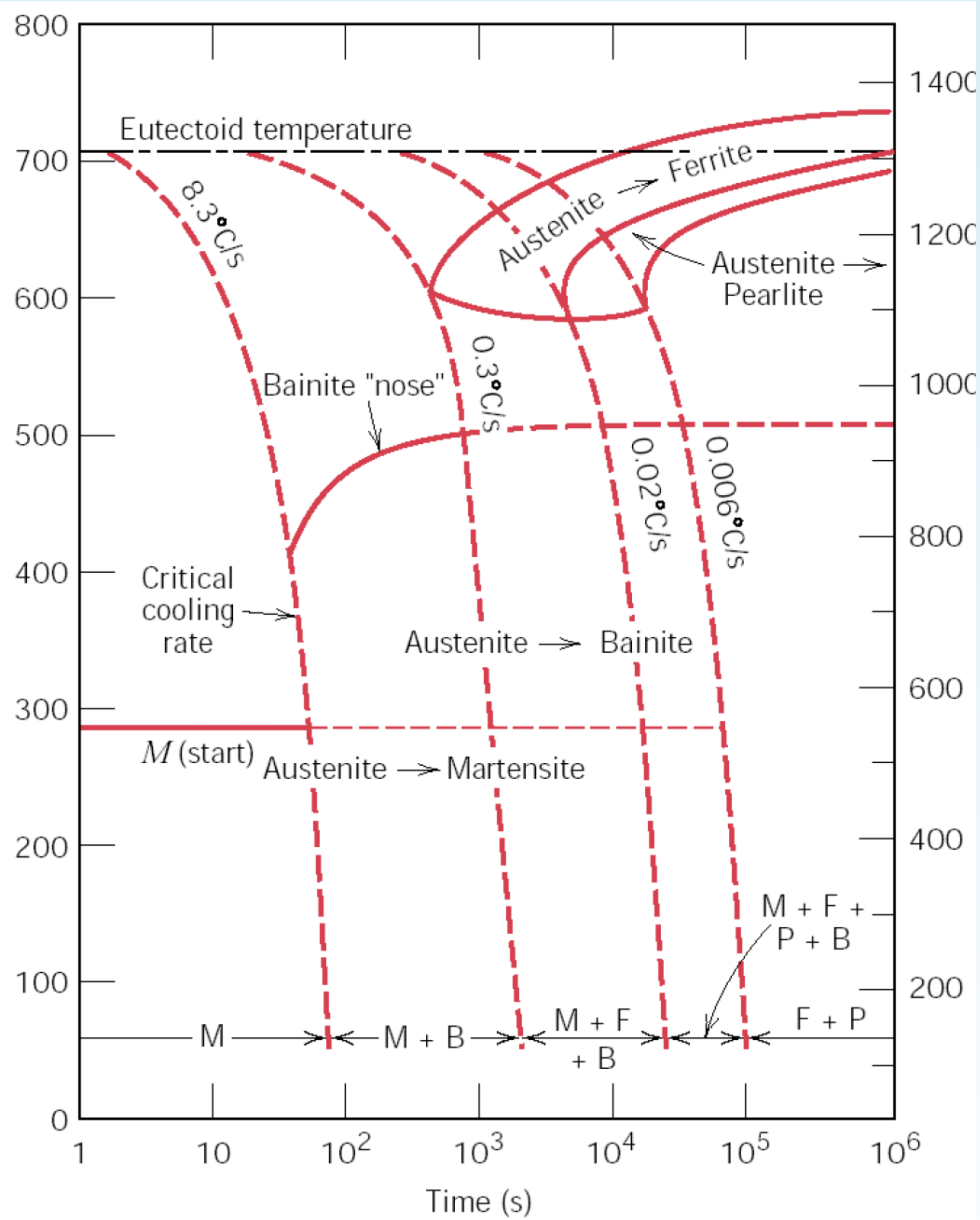
Heat Treatments
Continuous Cooling Transformation (CCT) Diagram



An Example of Converting TTT to CCT: Graphic Method (Grange & Kiefer 1941)

Continuous Cooling Transformation (CCT) Diagram & Microstructure

4340 Steel Alloy



Typical Industrial Heat Treatment Service

Spec	Grade	Remarks
ASME	Sec VIII DIV1 UCS-56	Post Weld Heat Treatment for Pressure Vessels Constructed of Low Alloy Steels
	Sec VIII DIV1 UNF-56	Post Weld Heat Treatment of Nonferrous Materials
	Sec VIII DIV1 UHA-32	Post Weld Heat Treatment for Pressure Vessels Constructed of High Alloy Steels
ASTM	A671 Table 2	Heat Treatment of EFW Steel Pipe for Atmospheric and Low Temperatures
	A672 Table 2	Heat Treatment of EFW Steel Pipe for High-pressure Service at Moderate Temperatures
	A691 Table 2	Heat Treatment of Carbon & Alloy Steel Pipe, EFW for High-Pressure Service at High Temperatures
Others		Normalized or Normalized and Tempered of Steel Structure

Focus on Steel – Carbon Steels

IT IS A MATTER OF CONTINUING RESEARCH & DEVELOPMENT:

For example,
the group „mechanical properties of interfaces“ investigates
homophase (grain boundaries, stacking faults)
as well as
heterophase (coatings, precipitates, lamellar alloys) interfaces,
with a focus on metals and alloys.

Focus on Steel – Steel Qualities

Literature

1. *web.utk.edu/~prack/MSE%20300/FeC.pdf*
2. R. Manna, *Time Temperature Transformation (TTT) Diagrams,*
   Centre of Advanced Study, Department of Metallurgical Engineering,
   Institute of Technology, Banaras Hindu University, Varanasi-221 005, India;
   rmanna.met@itbhu.ac.in
3. Heat Treatment of Steel Terminology
   TPU Lectures 14 15\Heat Treatment Of Steel Terminology.docx
4. http://www.virginia.edu/bohr/mse209/chapter11.htm
5. M. Shaban, S. Gozalzadeh and B. Eghbali, *Dynamic Strain Induced Transformation of Austenite to Ferrite during High Temperature Extrusion of Low Carbon Steel,* Materials Transactions, Vol. 52, No. 1 (2011) pp. 8 to 11

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

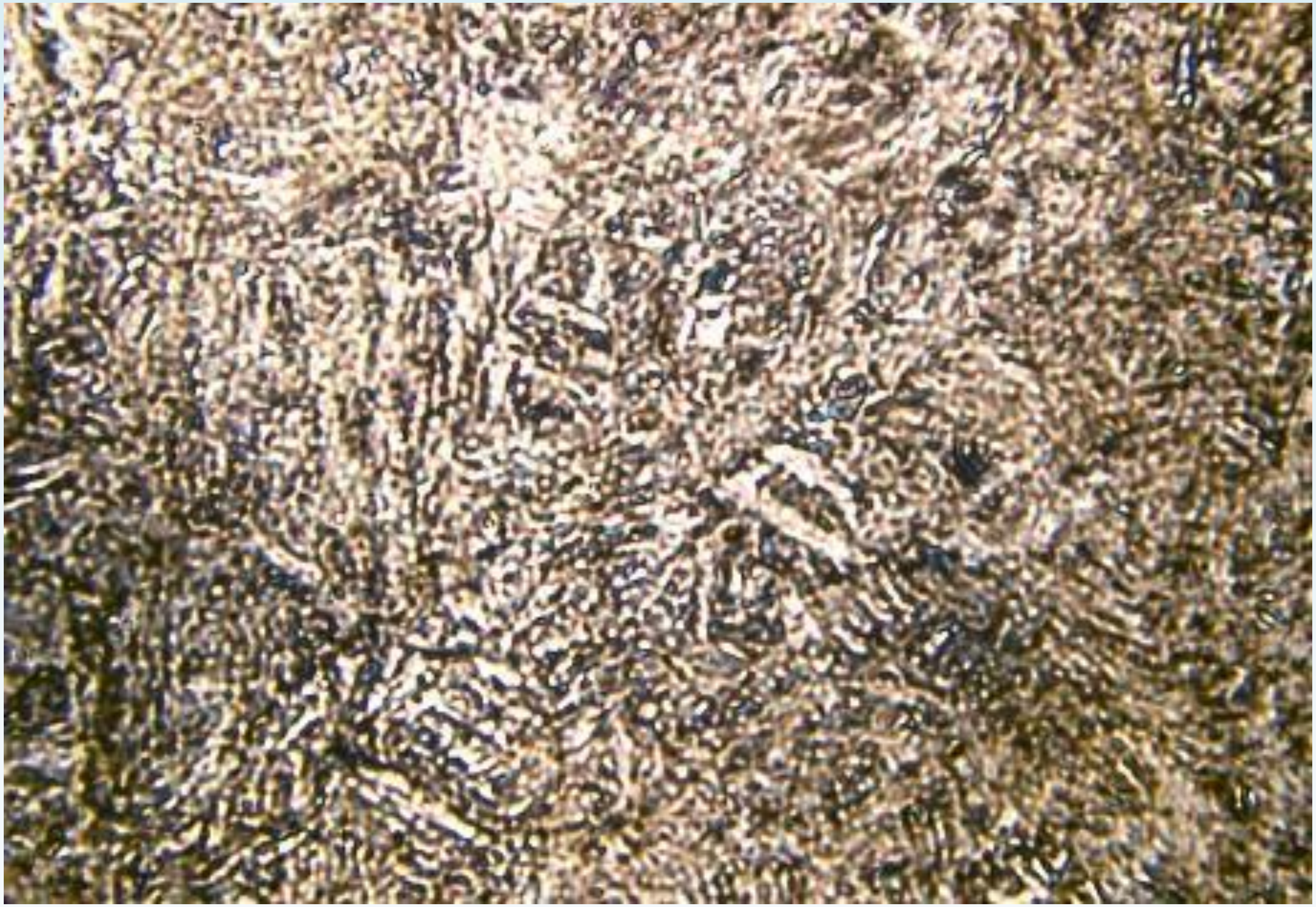
C	**cold working**
L	**for low temperatures**
H	**for semi profiles**
W	**weatherproof**

Over 0.8% Carbon

As carbon content increases beyond 0.8%, no more *pearlite* can be formed.

The excess carbon forms *cementite* which is deposited in between the *pearlite* grains. This increases the hardness, but slightly reduces the strength. The ductility of all plain carbon steels over 0.8% carbon is very low.

Focus on Steel – Bainit Formation



Bainite Microstructure