ME3392
ENGINEERING MATERIALS AND METALLURGY

UNIT II

HEAT TREATMENT

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AP/MECH

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HEAT TREATMENT PROCESS

- **PROPERTIES** OF METALS AND ALLOYS **CHANGED AS DESIRED** HEAT TREATMENT PROCESS
- **Controlled heating and cooling** of metals for the purpose of **altering their properties**.

Purpose of Heat Treatment:

- To relieve stress created during cold working, welding, casting etc.
- Improve Machinability.
- Change grain size.
- Improve ductility
- Homogenous structure.
- To improve mechanical properties.
- To change the chemical composition.
- To improve magnetic and electrical properties.

HEAT TREATMENT

- Heat treatment may be defined as an **operation or combination of operations involved heating and cooling** of metals/alloys **to obtain desired properties.**

STAGES OF HEAT TREATMENT:

1. **Heating** a metal beyond the critical temperature
2. **Holding** a temperature for a sufficient period (time to allow necessary changes)
3. **Cooling** the metal (Quenching) to change nature , size, distribution of micro constituents

Heat Treatment Processes

1. Annealing
    1. Full annealing
    2. Process annealing
    3. Stress relief annealing
    4. Recrystallisation annealing
    5. Spheroidise annealing
2. Normalizing
3. Hardening

4. Tempering
   - Austempering
   - Martempering
5. Case hardening
   1. Carburising
   2. Nitriding
   3. Cyaniding
   4. Carbonitriding
   5. Flame hardening
   6. Induction hardening
   7. Flame hardening

ANNEALING

Annealing is a process of **heating** the steel slightly **above the critical temperature** of steel (723 degrees Centigrade) and allowing it to **cool down very slowly furnace it self** .

- STAGES OF ANNEALING:
  - HEATING TO THE DESIRED TEMPERATURE
  - HOLDING OR SOAKING AT THE TEMPERATURE
  - COOLING OR QUENCHING USUALLY AT ROOM TEMPERATURE.

ANNEALING

PURPOSE OF ANNEALING

1. To relieve stresses
2. To induce softness
3. To refine grain size
4. To remove gases

APPLICATIONS:

1. Casting
2. Forging
3. Press work

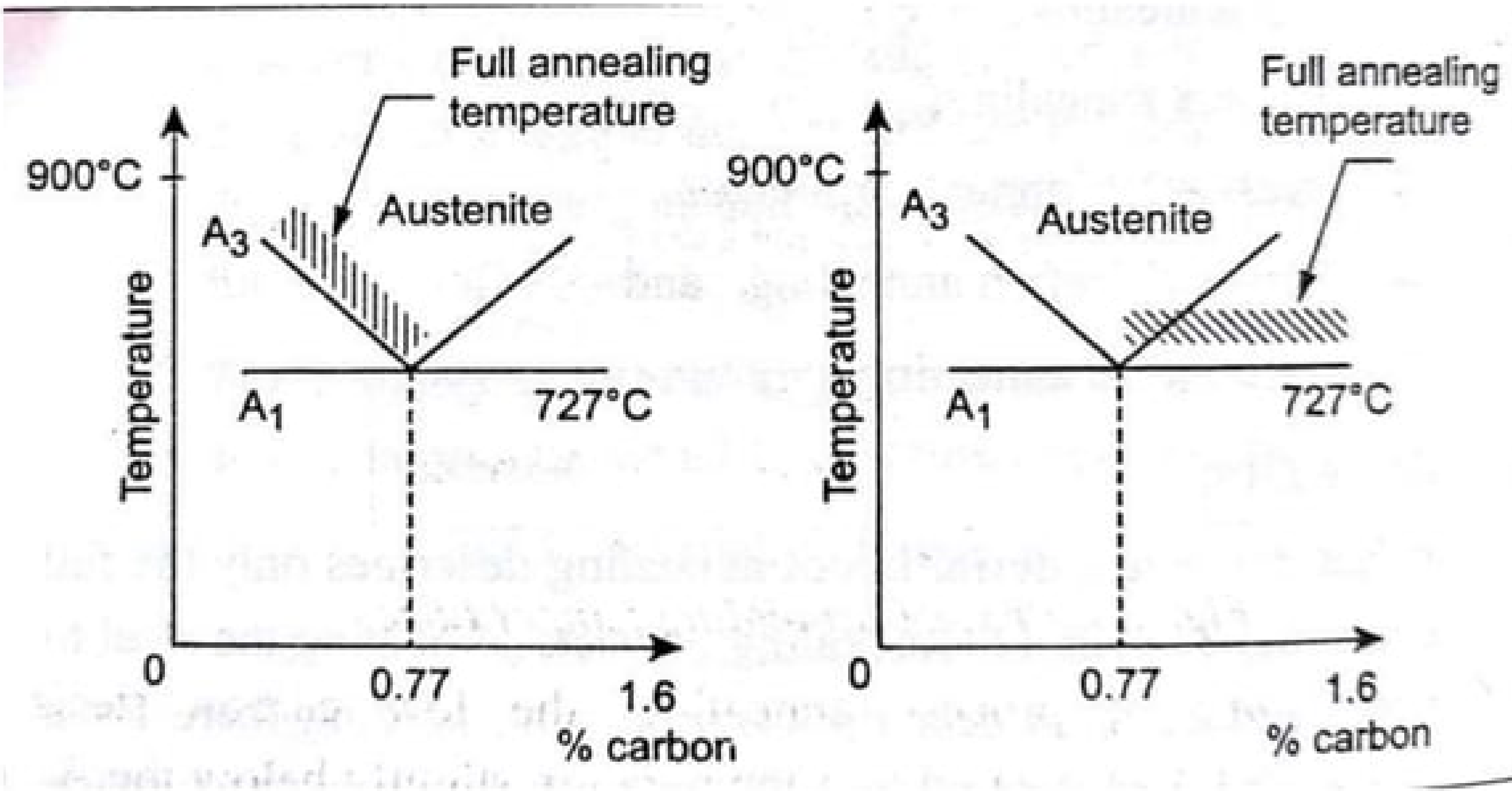
TYPES OF ANNEALING PROCESS

- **Full Annealing**
- **Process Annealing**
- **Stress Relief Annealing**
- **Spherodising Annealing**
- **Recrystallisation Annealing**

FULL ANNEALING

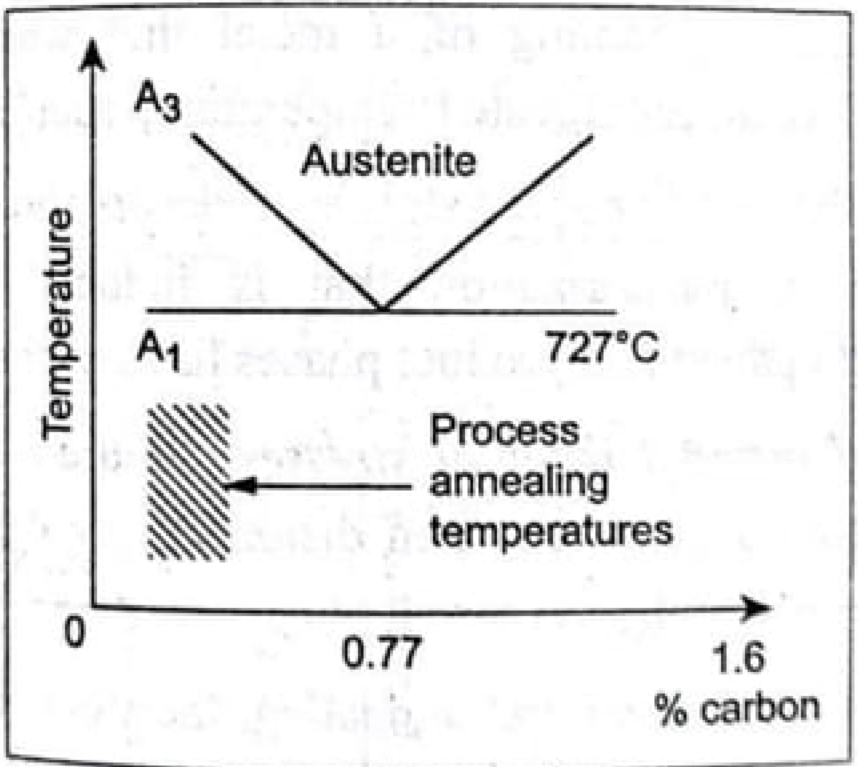
- **Full annealing** is the process of **slowly raising the temperature about 50 ºC (90 ºF) above the *Austenitic temperature*** line A_3 or line A_{CM} in the case of **Hypoeutectoid steels (steels with < 0.77% Carbon)** and 50 ºC (90 ºF) into the Austenite-Cementite region in the case of **Hypereutectoid steels (steels with > 0.77% Carbon)**.
- It is held at this temperature for sufficient time for all the material to transform into Austenite or Austenite-Cementite as the case may be. It is then slowly cooled at the rate of about 20 ºC/hr (36 ºF/hr) in a furnace to about 50 ºC (90 ºF) into the Ferrite-Cementite range. At this point, it can be cooled in room temperature air with natural convection.

FULL ANNEALING



Process Annealing

- PURPOSE:
  - It is used to soften and increase the ductility
- Material :
  - Steel wires and sheet products
- OPERATION:
  - Low carbon steels less than 0.25% c heated slightly below the critical temperature
  - It achieve softening and cooled at any desired rate
  - The heating is not like that full annealing
- APPLICATION:
  - Preparing steel sheets and wires of drawing.



A3
Austenite
Temperature
A1
727°C
Process
annealing
temperatures
0
0.77
1.6
% carbon

STRESS RELIEF ANNEALING

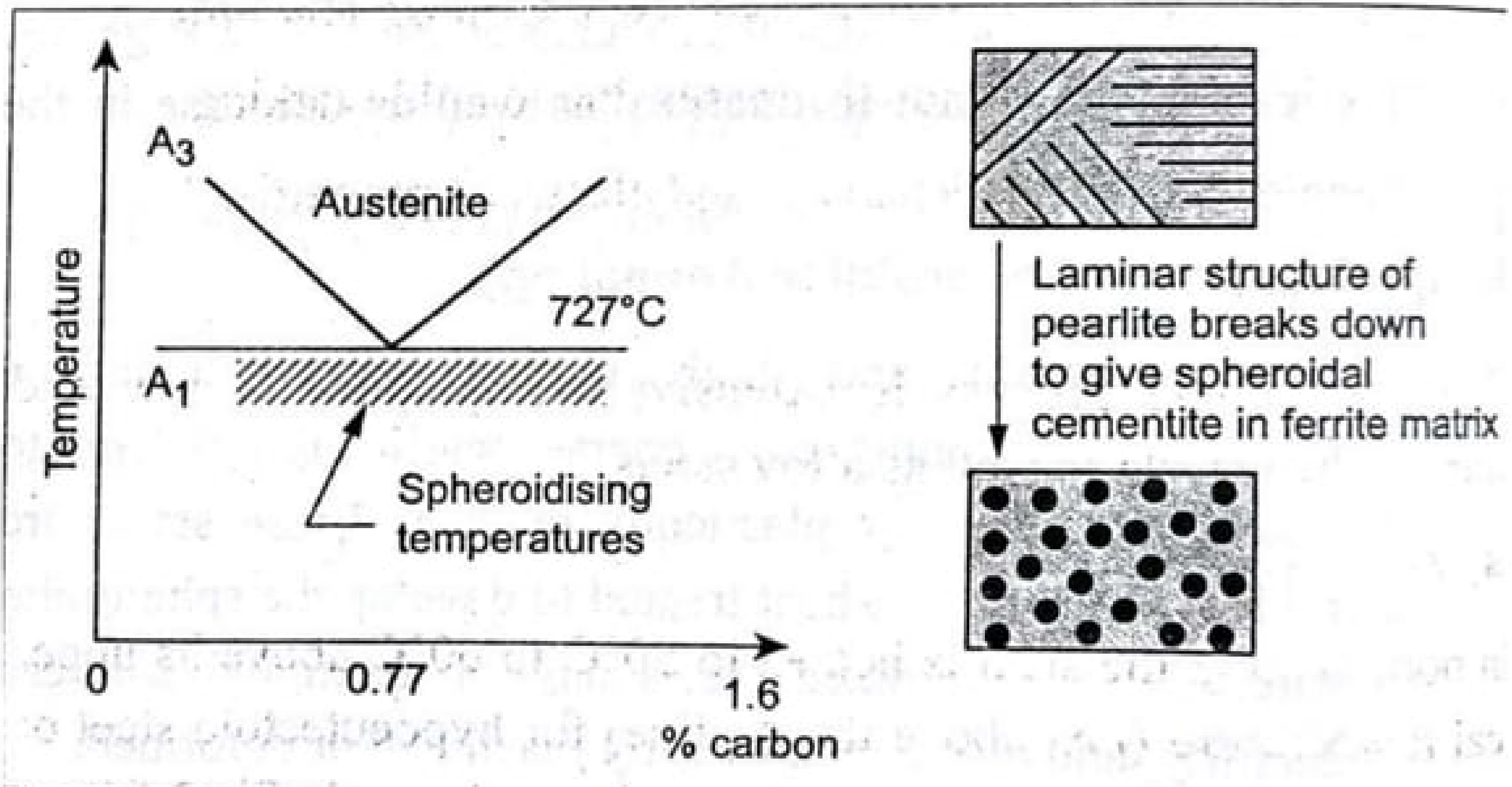
- **PUROPSE:**
  - It is heat treatment process
  - Eliminate residual stress induced by casting, quenching, etc
- **CAUSES OF INTERNAL RESIDUAL STRESSES:**
  - Plastic deformation
  - Non uniform cooling of metal
- **EFFECTS OF INTERNAL RESIDUAL STRESSES:**
  - Due to stresses Warpage takes place
- **OPERATION:**
  - Heated range 550-650 degree celcius, held for a period of time and cooled slowly.

RECRYSTALLISATION ANNEALING

- RECRYSTILLATION:
  - Stress **grains are replaced by new, strain free grains** during heating above a **specific minimum temperature**
- RECRYSTALLISATION TEMP:
  - When the recrystallisation takes place(new grains formed) that temp is called recrystallisation temp.
- OPERATION:
  - Cold worked steels are heated to a recrystallisation temp and held for some time, and then cooled
- RESULT:
  - Stress free grains, increase ductility.

SPHEROIDIING ANNEALING

- PURPOSE:
  - Medium and **high carbon steels** are having **coarse pearlite** it is too hard for machining.
  - So heat treatment to **develop sheroidite structure**.
  - This structure gives **maximum softness and ductility**
- OPERATION:
  - Prolonged heating **below the critical temperature** then slow cooling
  - Prolonged heating **above and below the critical temp**
  - Holding for several hours followed by slow cooling.



Temperature
A3
Austenite
727°C
A1
Spheroidising
temperatures
0
0.77
1.6
% carbon
Laminar structure of
pearlite breaks down
to give spheroidal
cementite in ferrite matrix

NORMALISING

Normalizing

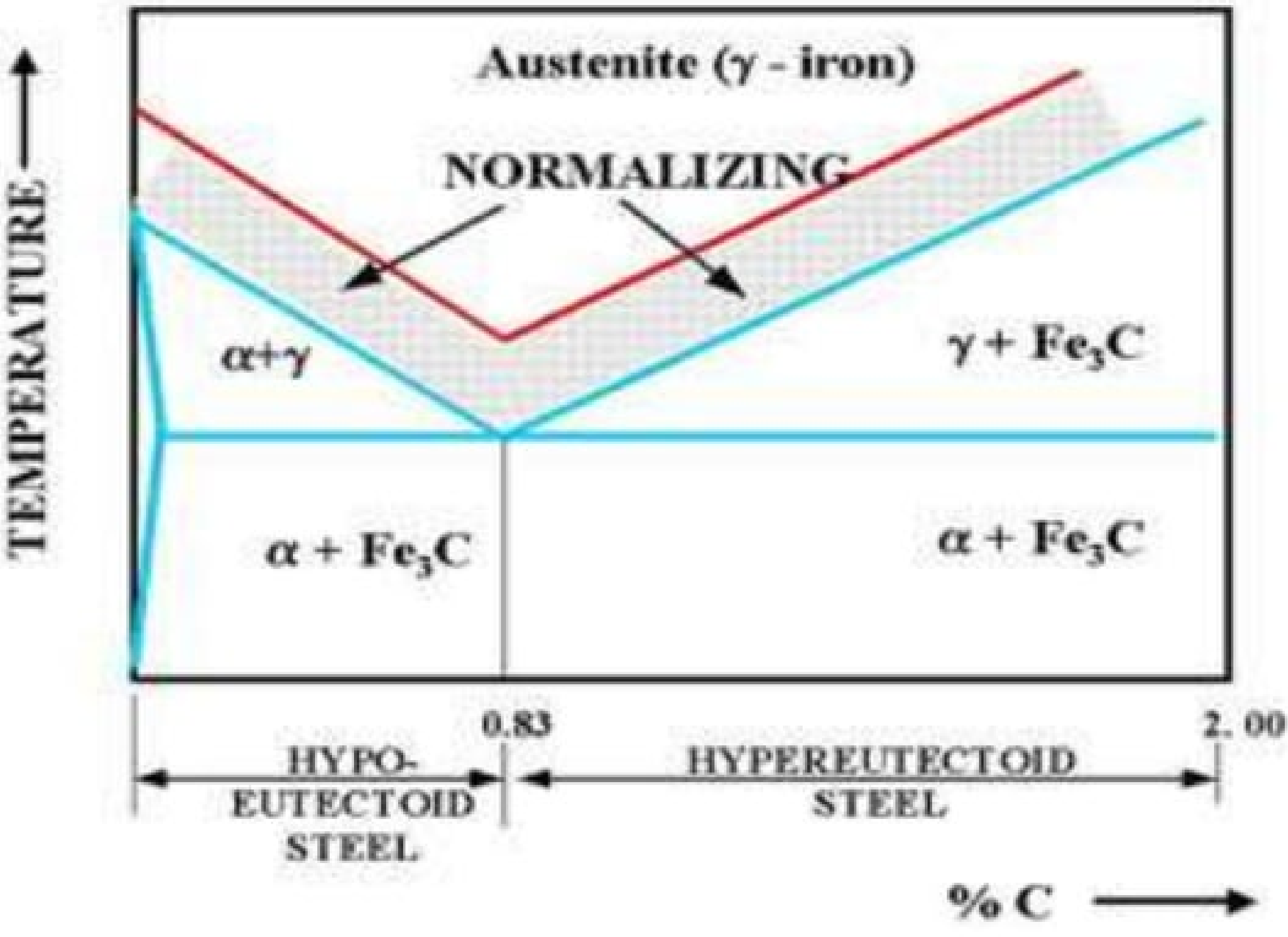
- It is similar to full annealing.
- Cooling in air rather than furnace.
- FULL ANNEALING is expensive and time consuming
- Instead of full annealing, normalising takes place.

OBJECTIVES:

- Refine grainsize
- Increase strength of steel
- Uniform structure
- Relieve of internal stresses

NORMALISING

- **OPERATION:**
  - Heated up to 50-60 degree celcius above critical temperature
  - Normalizing contains ferrite and pearlite for hypo eutectoid steels.
  - Pearlite and cementite for hyper eutectoid steels.



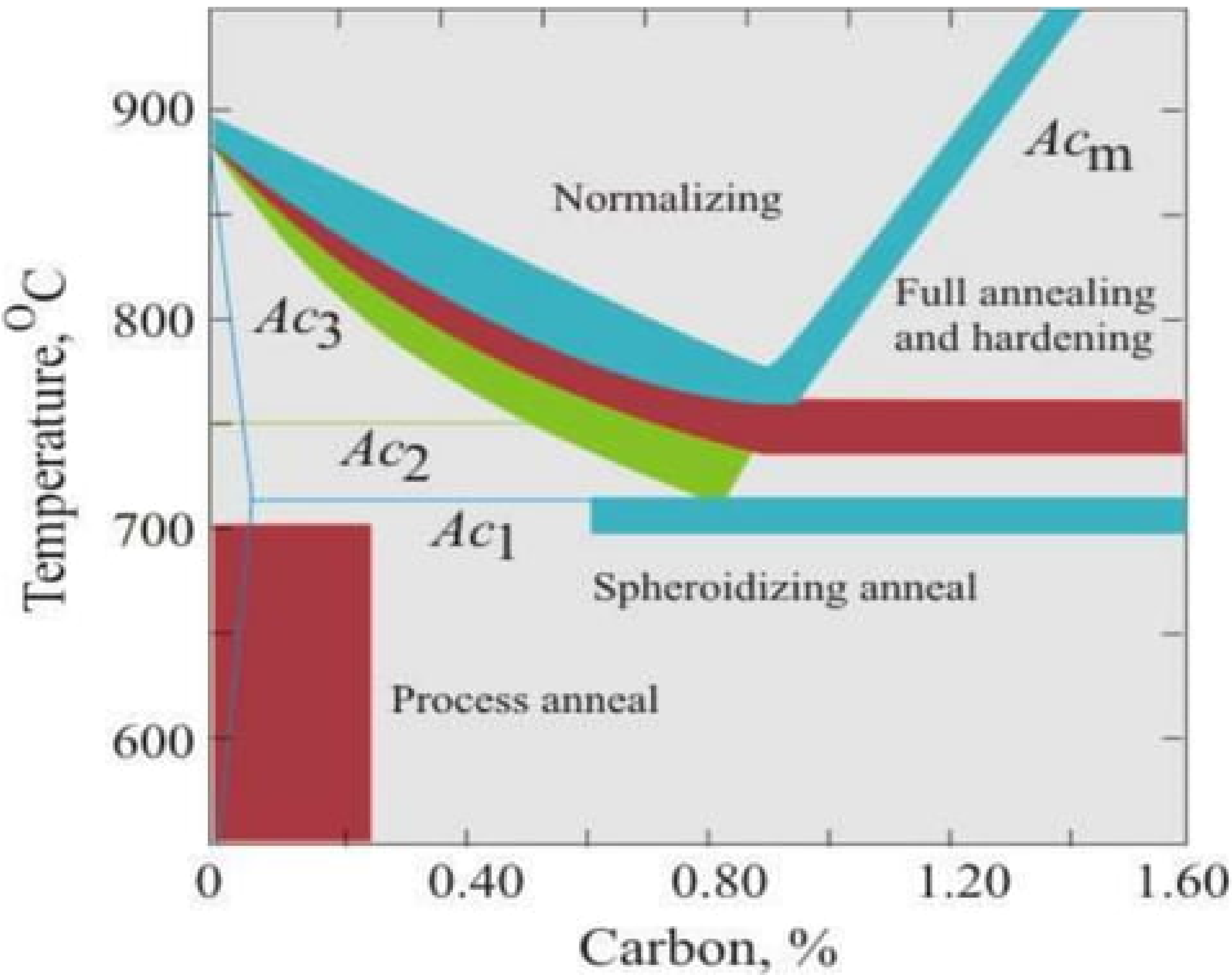
Austenite (γ - iron)
NORMALIZING
α+γ
γ + Fe3C
α + Fe3C
α + Fe3C
TEMPERATURE
0.83
2. 00
HYPO-
EUTECTOID
STEEL
HYPEREUTECTOID
STEEL
% C

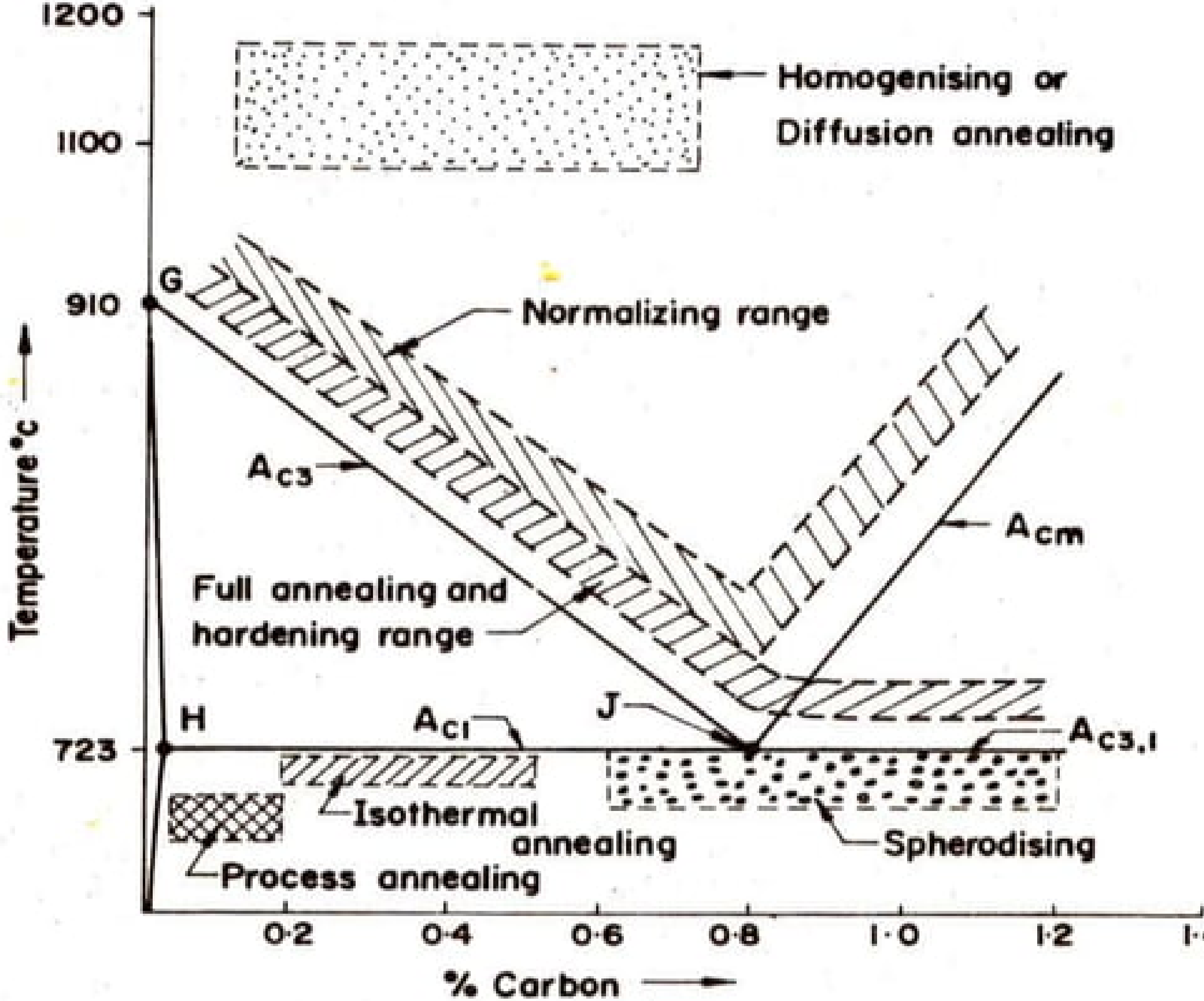
DIFFERENCE BETWEEN NORMAILISING AND FULL ANNEALING

- **Distinguish between annealing &Normalising.**
  (At least 4 points 1 Mark for each point – 4 Marks)

ANNEALING	NORMALISING
Main purpose of annealing is to relieve internal stresses	Main purpose of normalizing is to improve mechanical properties of steel.
Less hardness, more T.S. & toughness	Slightly more hardness, less T.S. and toughness
Pearlite is coarse and usually gets	Pearlite is fine and usually appears unresolved with optical microscope
Grain size distribution is more	Grain size distribution is

SUMMARY OF HEAT TREATMENTS

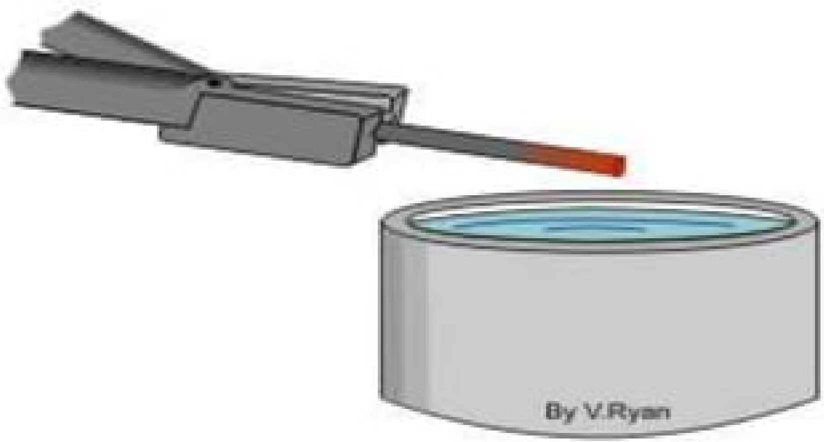




Annealing, Hardening & Normalising

QUENCHING

- It's the operation of **rapid cooling** by dipping the hot metal piece **into a quenching bath**.
- The heated steel become much harder and **stronger by a rapid cooling**.



Quenching Medium

- Cold water
- 5-10% of CAUSTIC SODA
- Liquid salt
- Oil
- Air
- 5-20% of NaCl

- **The rate of cooling determines the level of hardness and microstructure of steel**

STAGES OF QUENCHING

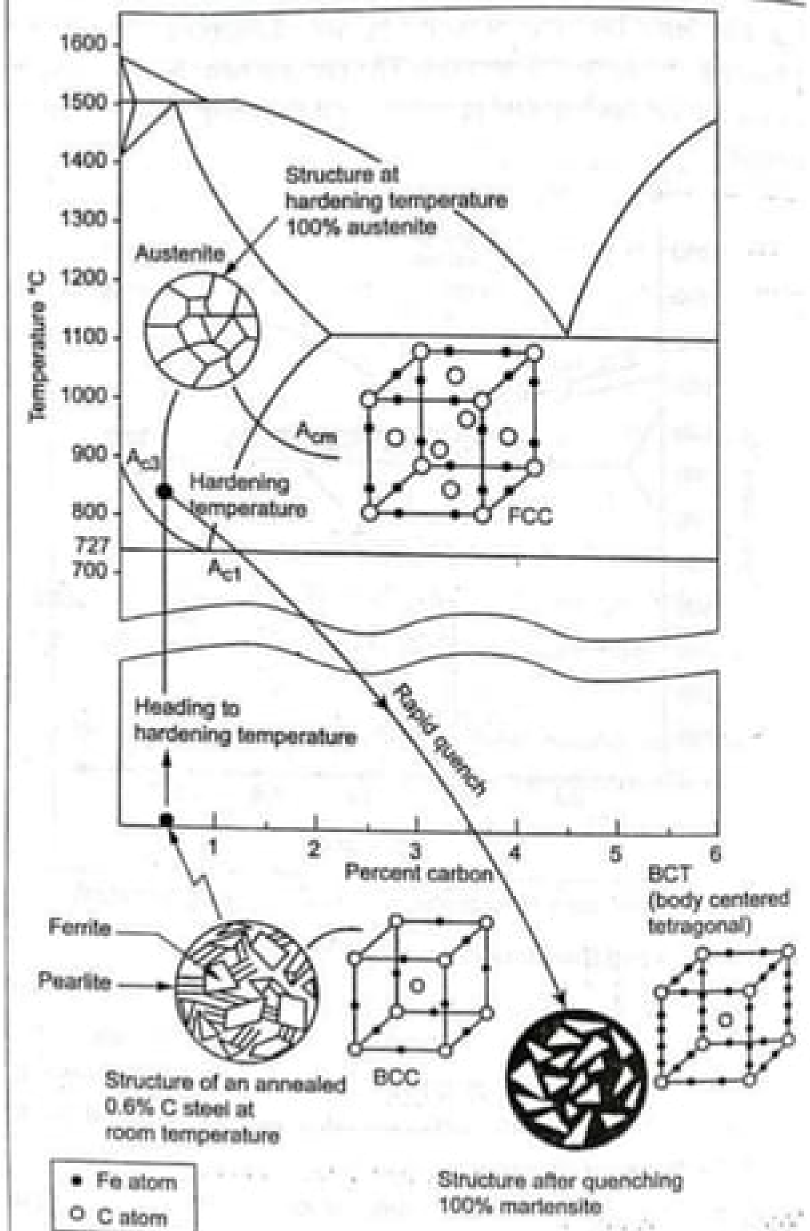
1. **VAPOUR JACKET STAGE**
   – Time of quenching forms a gaseous layer
2. **VAPOUR TRANSPORT COOLING STAGE**
   1. Gaseous layer is not stable
   2. Bubbles nucleate
3. **LIQUID COOLING STAGE**
   1. Metals cools below the boiling point
   2. Conduction (solid liquid) takes place.

Hardening(BY QUENCHING)

- Its a process of **heating the steel above or below the critical temperature** for a particular period and then **allow to cool by oil or water rapidly**

PURPOSE OF HARDENING

- Hardness of the metal can be **improved to resist wear**
- Cutting ability of the material can **be improved to cut other material**
- **OPERATION:**
  - **HEATING**
  - **SOAKING**
  - **COOLING**



1600
1500
1400
1300
1200
1100
1000
900
800
727
700
Temperature °C
Structure at
hardening temperature
100% austenite
Austenite
A_{cm}
A_{c3}
Hardening
temperature
FCC
A_{c1}
Heading to
hardening temperature
Rapid quench
1
2
3
4
5
6
Percent carbon
BCT
(body centered
tetragonal)
Ferrite
Pearlite
Structure of an annealed
0.6% C steel at
room temperature
BCC
Structure after quenching
100% martensite
• Fe atom
○ C atom

Factors for getting good hardness

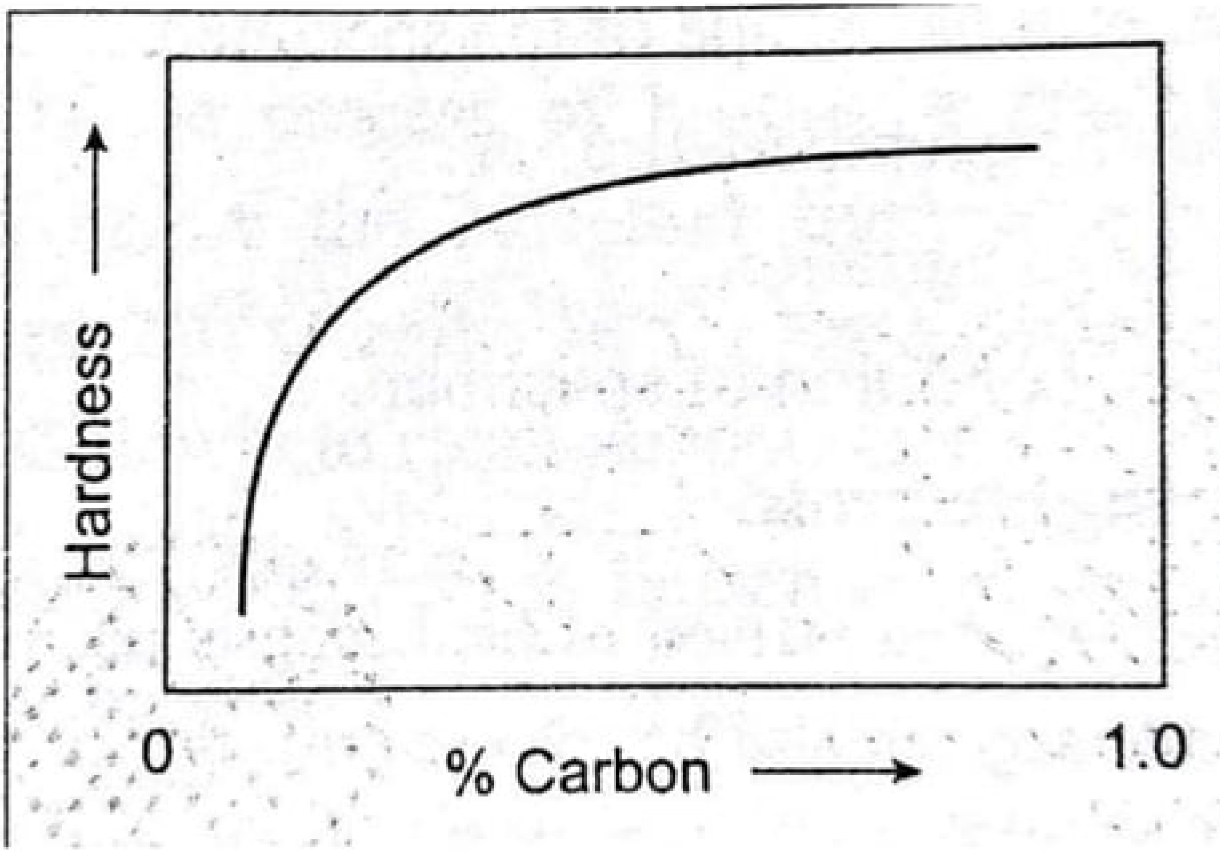
- <u>Carbon content:</u>

when the **% carbon** is less than 0.3% **we cannot do the process**, **It should be 0.3 – 0.7%C**

- <u>Rate of cooling:</u>

To get martensite structure we have to **cool suddenly**

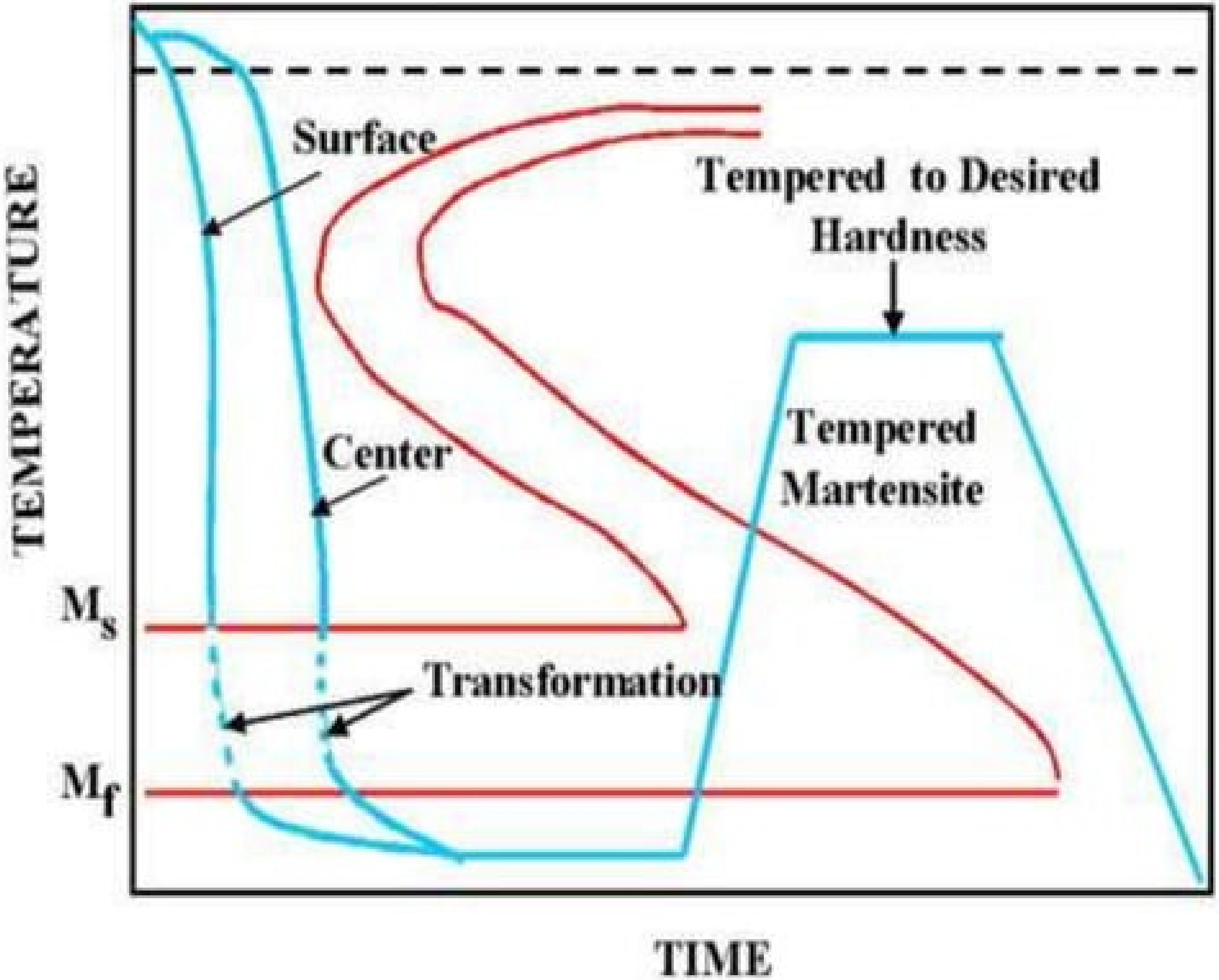
- **<u>SPECIMEN SIZE:</u>**
- **<u>OTHER FACTORS</u>**
  - Geometry
  - Quenching temp
  - Alloying elements

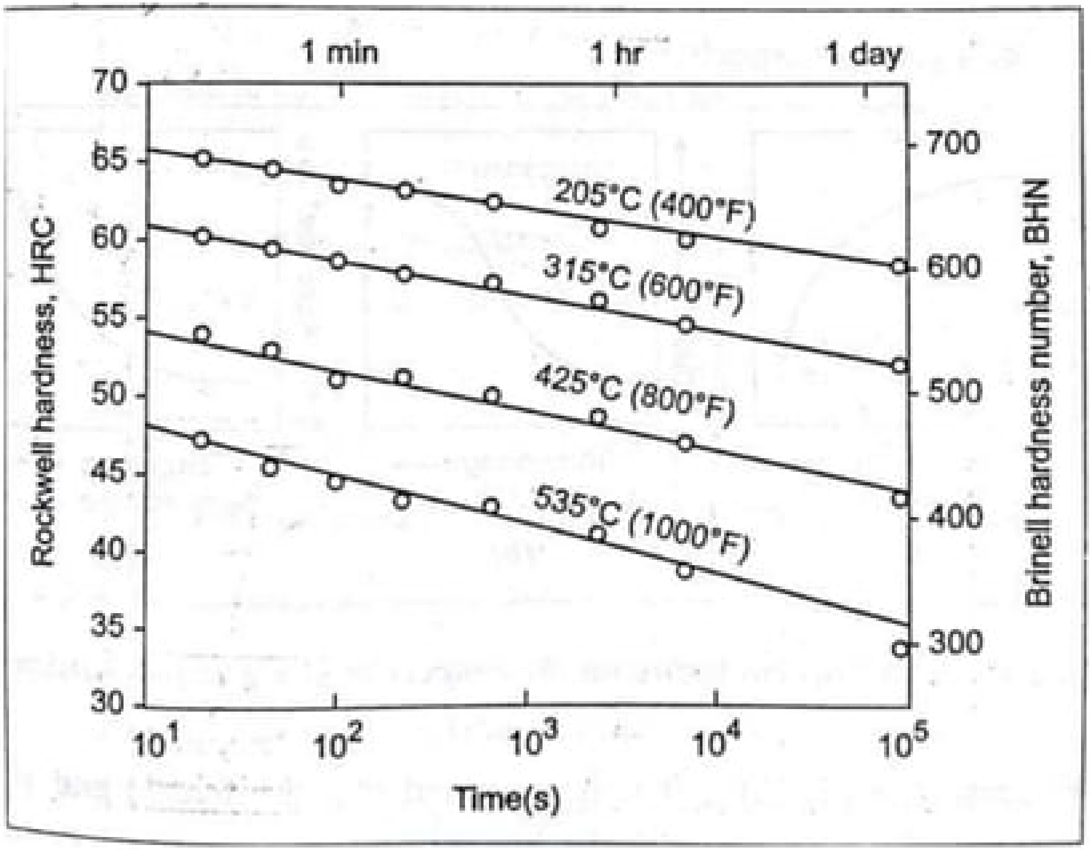

Hardness
0
% Carbon
1.0

TEMPERING

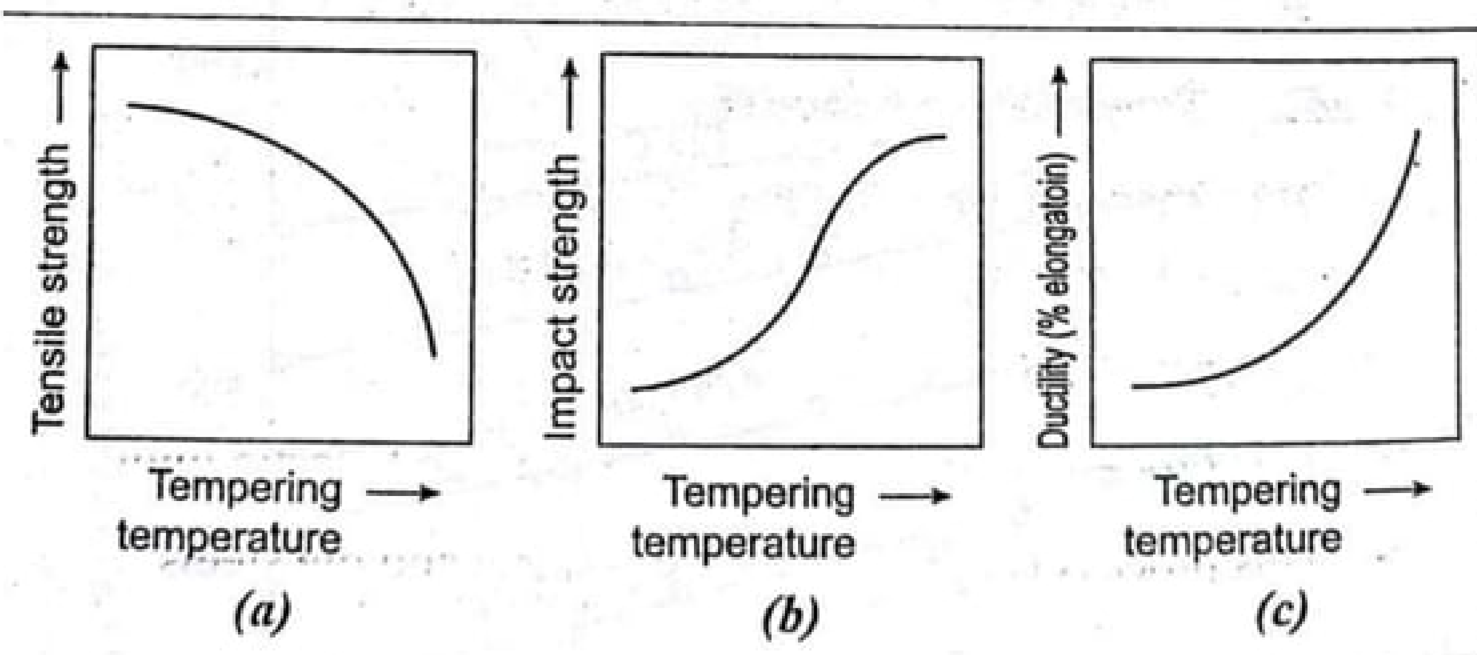
- In the **hardening process** we obtained **martensite structure** . In this structure, the material **having brittle property** and also it has **internal stresses**.
- For minimizing the hardness **and removing** the internal stresses we heat the **metal near to upper critical temp once again after quenching** and let it for some time then cool **slowly** by using salt liquid or oil

CONVENTIONAL QUENCHING AND TEMPERING





1 min
1 hr
1 day
70
65
60
55
50
45
40
35
30
700
600
500
400
300
205°C (400°F)
315°C (600°F)
425°C (800°F)
535°C (1000°F)
Rockwell hardness, HRC
Brinell hardness number, BHN
10^1
10^2
10^3
10^4
10^5
Time(s)


Tensile strength
Tempering temperature
(a)
Impact strength
Tempering temperature
(b)
Ductility (% elongaloin)
Tempering temperature
(c)

TYPES OF TEMPERING

- Low temperature tempering (150 – 250 ‘ c)
- Medium temperature tempering (350 – 450 ‘ c)
- High temperature tempering (500 – 650 ‘ c)

INTERRUPTED QUENCHING

- The **rapid cooling** of molten **metal gives more problems** like

1. induced stresses
2. distortions (warping)
3. crack formation in steel

In order to overcome the disadvantages a modified quenching is to be followed called interrupted quenching

Two forms of modified Quenching are

MARTEMPERING

AUSTEMPERING

MARTEMPERING
(Mar-quenching)

- It’s a **interrupted cooling** procedure for a steel to **reduce the stresses**, distortions and cracking of steels that may develop **during rapid quenching**

Step-1

Heat the metal to obtain Austenite structure level

Step-2

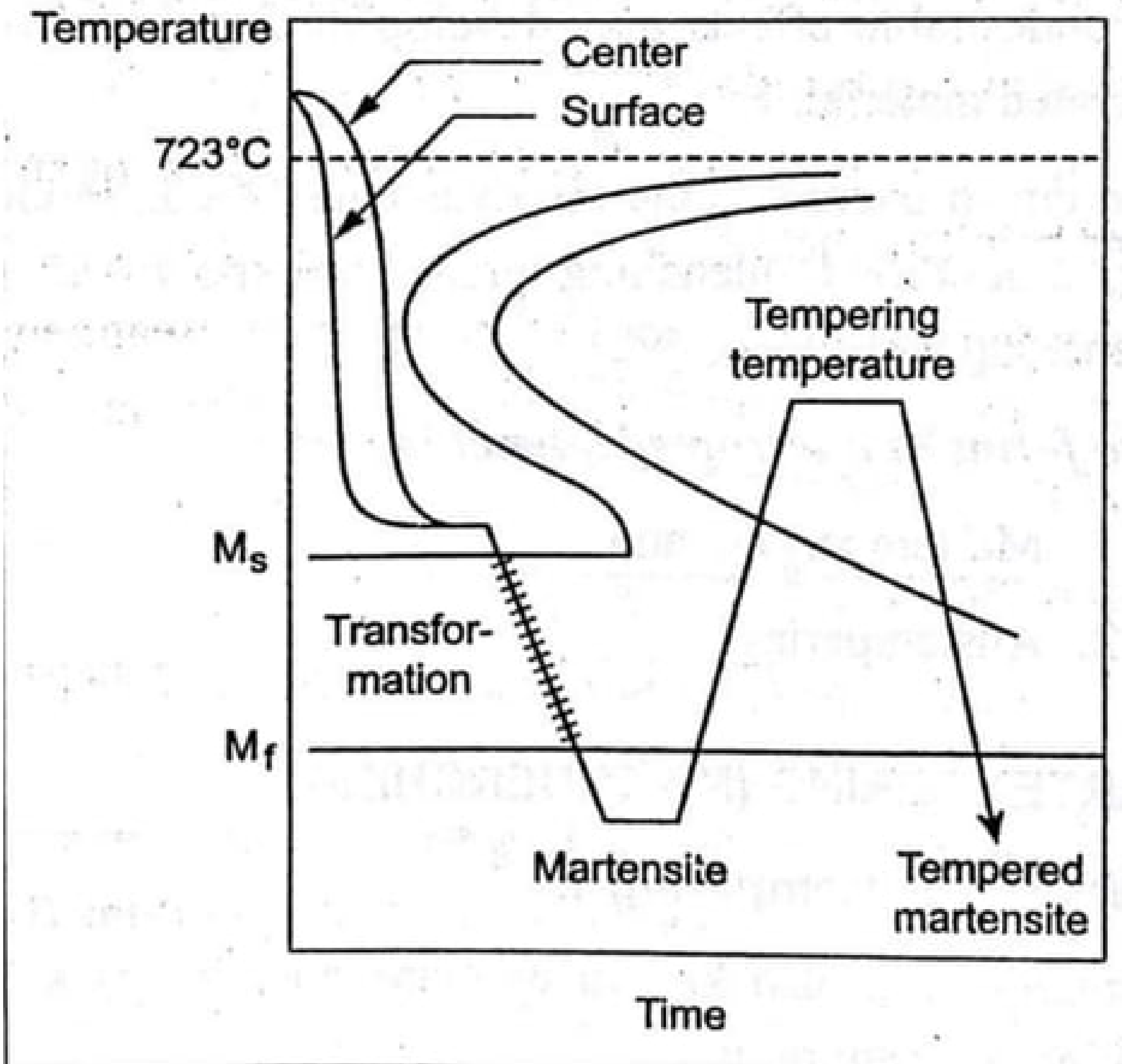
Quench the austenite steel in hot oil or molten salt at a temperature **just above the martensite start temp**.

Step-3

Hold it for some time and **stop the treatment before the transformation of austenite to banite**

Step-4

Cool it in a room air.


Temperature
Center
Surface
723°C
Tempering
temperature
M_s
Transfor-
mation
M_f
Martensite
Tempered
martensite
Time

AUSTEMPERING
(isothermal Quenching)

- It’s a isothermal transformation of steel at a temp below that of pearlite formation and above that of martensite transformation
- **Its usually used to reduce the quenching distortion and to make a tough and strong steel**
- Banite is the structure formed at the end of the process

- ADVANTAGES

Increased ductility , Toughness and reduced distorsion

Step-1

Heat the metal to austenite temperature

Step-2

Then quench the steel in a molten salt bath at a temp just **above the martensite start temp** of the steel.

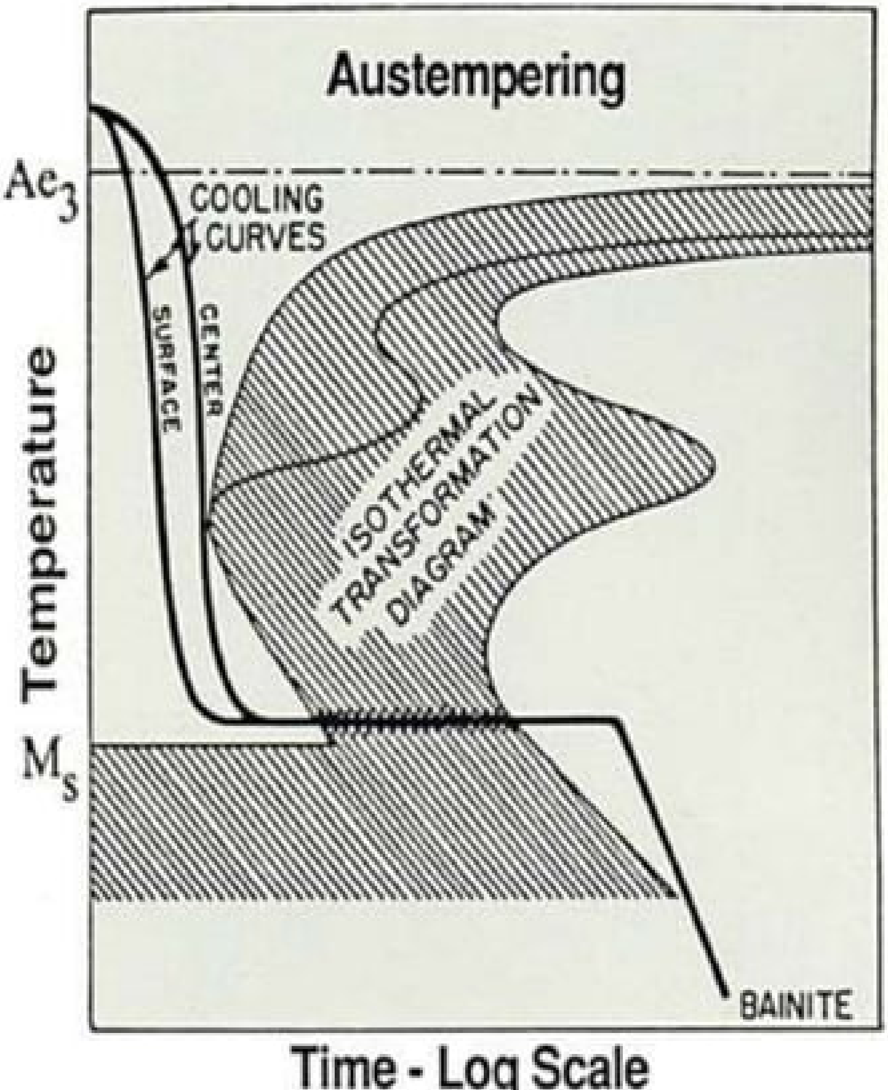
Step-3

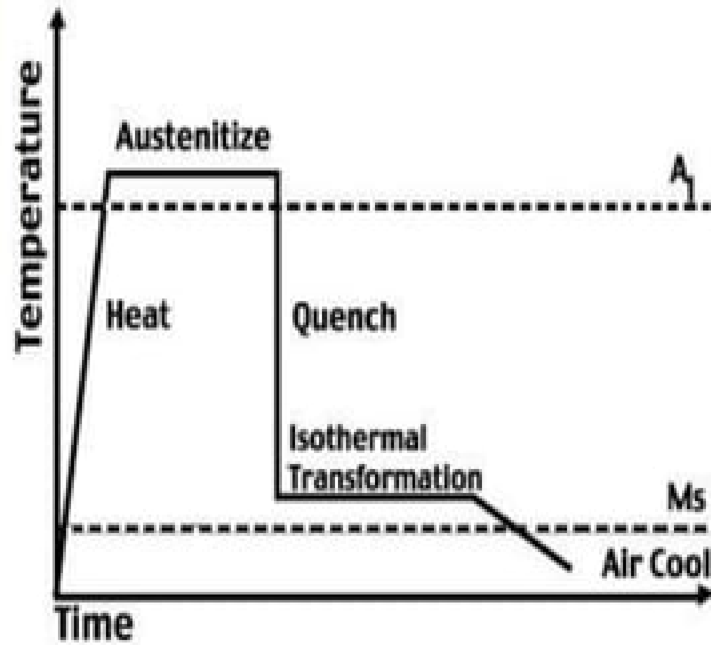
Holding the steel isothermally to **allow the austenite to banite transformation** to take place

Step-4

slow cooling to room temperature in air

AUSTEMPERING





TTT DIAGRAM

WHY – TTT & CCT DIAGRAMS ?

- The phases **martensite and bainite** are **non-equilibrium phase that do not appear in fe-fe3 c** (iron-iron carbon) phase diagram

- also **strengthening treatment like hardening and tempering are non-equilibrium process**.

- In order to show the influence of varying cooling rates, that is time, on the transformation of austenite other types of diagrams are necessary.

- The time temperature transformation or TTT diagram and the continuous cooling transformation or CCT diagram are used to explain the things in the cooling operation

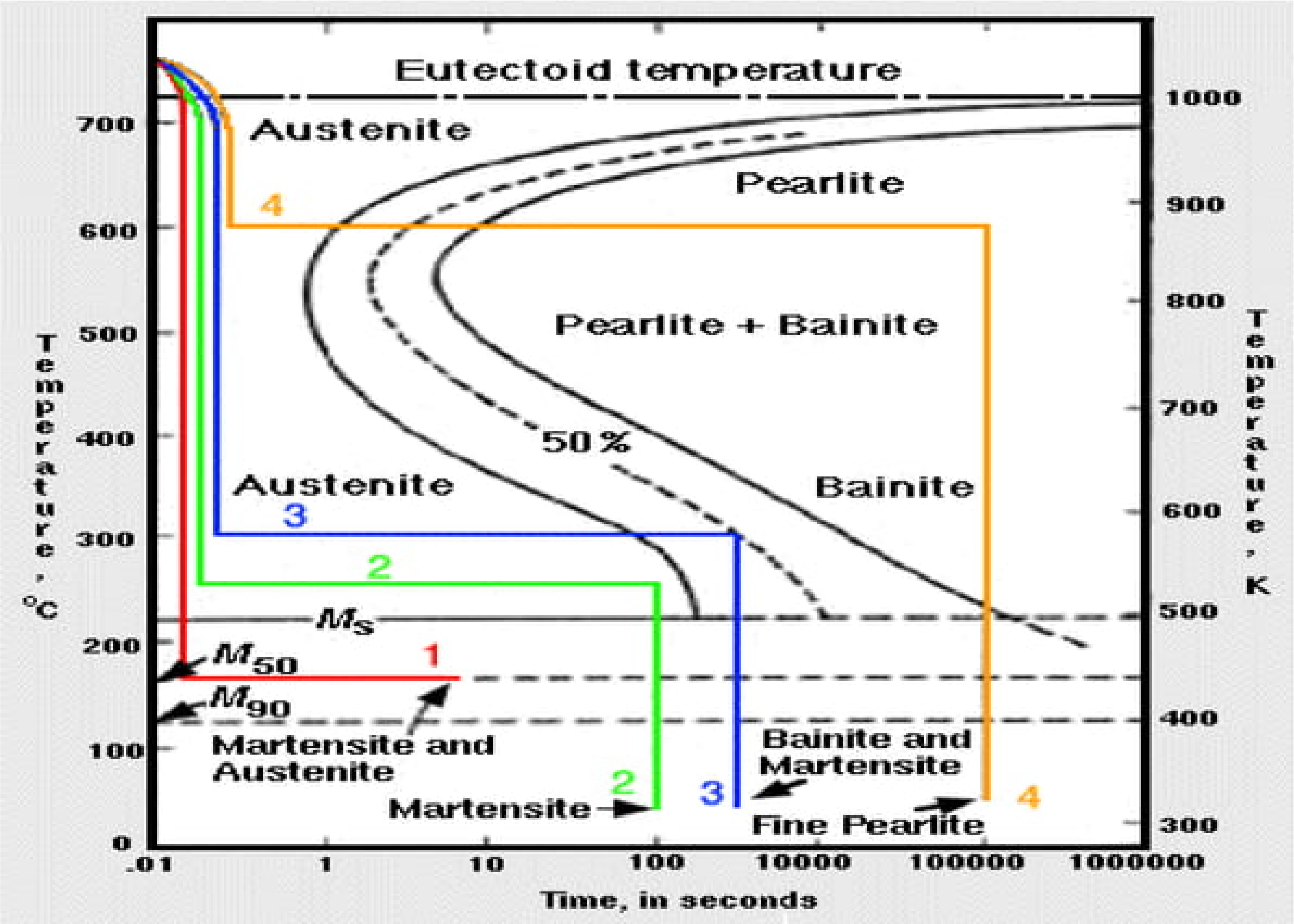
- **Non-equilibrium cooling** will result in different microstructures hence **altered properties**.

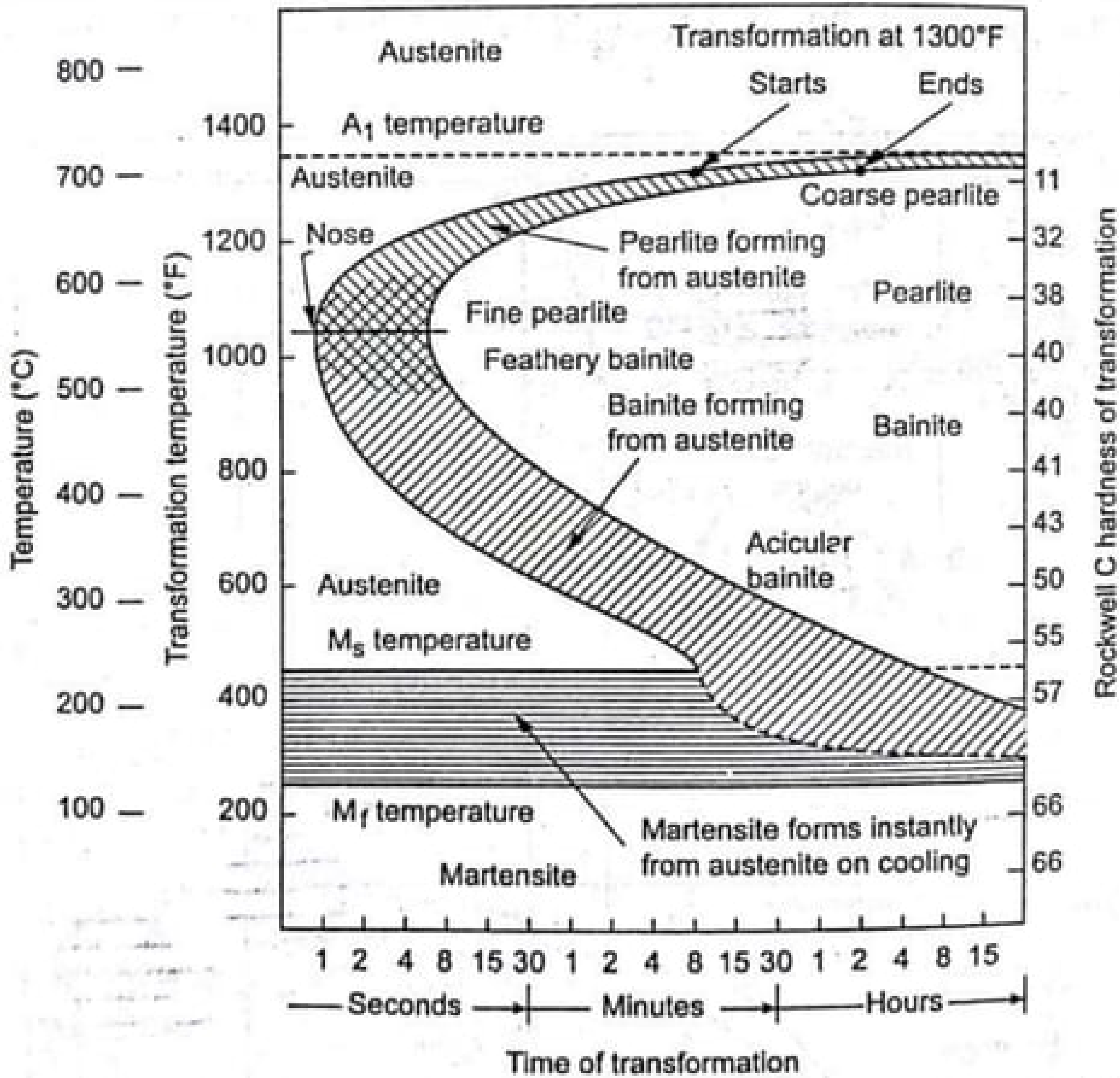
- **TTT diagrams** are the tools that we can use to take into account the **kinetics of the transformation**.

- **They show the relationship between time, temperature and (percent) transformation**.

- There are two types of TTT diagrams:
  - Isothermal transformation (IT) TTT diagrams
  - continuous cooling transformation (CCT) TTT diagrams

TIME TEMPERATURE PATH ON ISOTHERMAL TRANSFORMATION DIAGRAM





Austenite
Transformation at 1300°F
Starts
Ends
A1 temperature
Austenite
Coarse pearlite
Nose
Pearlite forming from austenite
Pearlite
Fine pearlite
Feathery bainite
Bainite forming from austenite
Bainite
Acicular bainite
Austenite
Ms temperature
Mf temperature
Martensite forms instantly from austenite on cooling
Martensite
Temperature (°C)
800
700
600
500
400
300
200
100
Transformation temperature (°F)
1400
1200
1000
800
600
400
200
Rockwell C hardness of transformation
11
32
38
40
40
41
43
50
55
57
66
66
1 2 4 8 15 30 1 2 4 8 15 30 1 2 4 8 15
Seconds
Minutes
Hours
Time of transformation

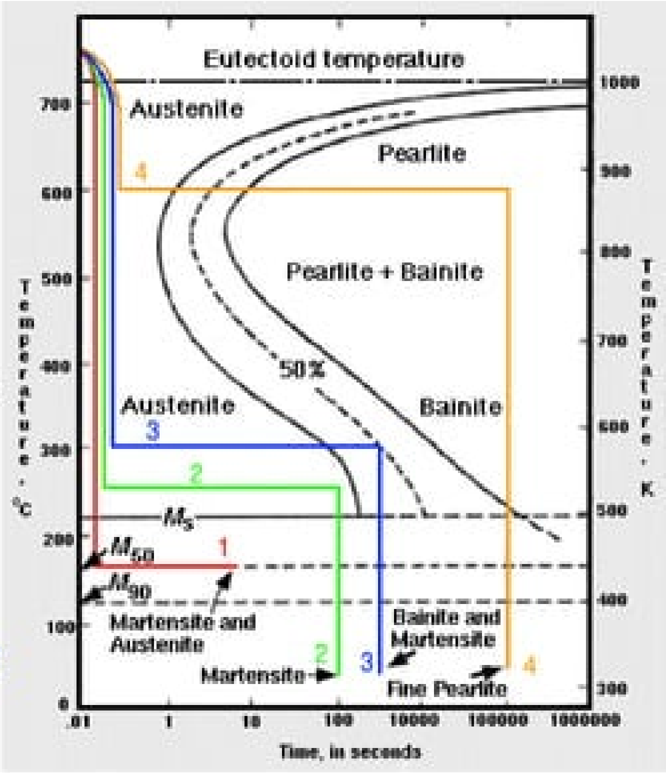
PATHS

what transformations happen in:

– a. Path 1 **(Red line)**
– b. Path 2 **(Green line)**
– c. Path 3 **(Blue line)**
– d. Path 4 **(Orange line)**

PATH I - (RED)

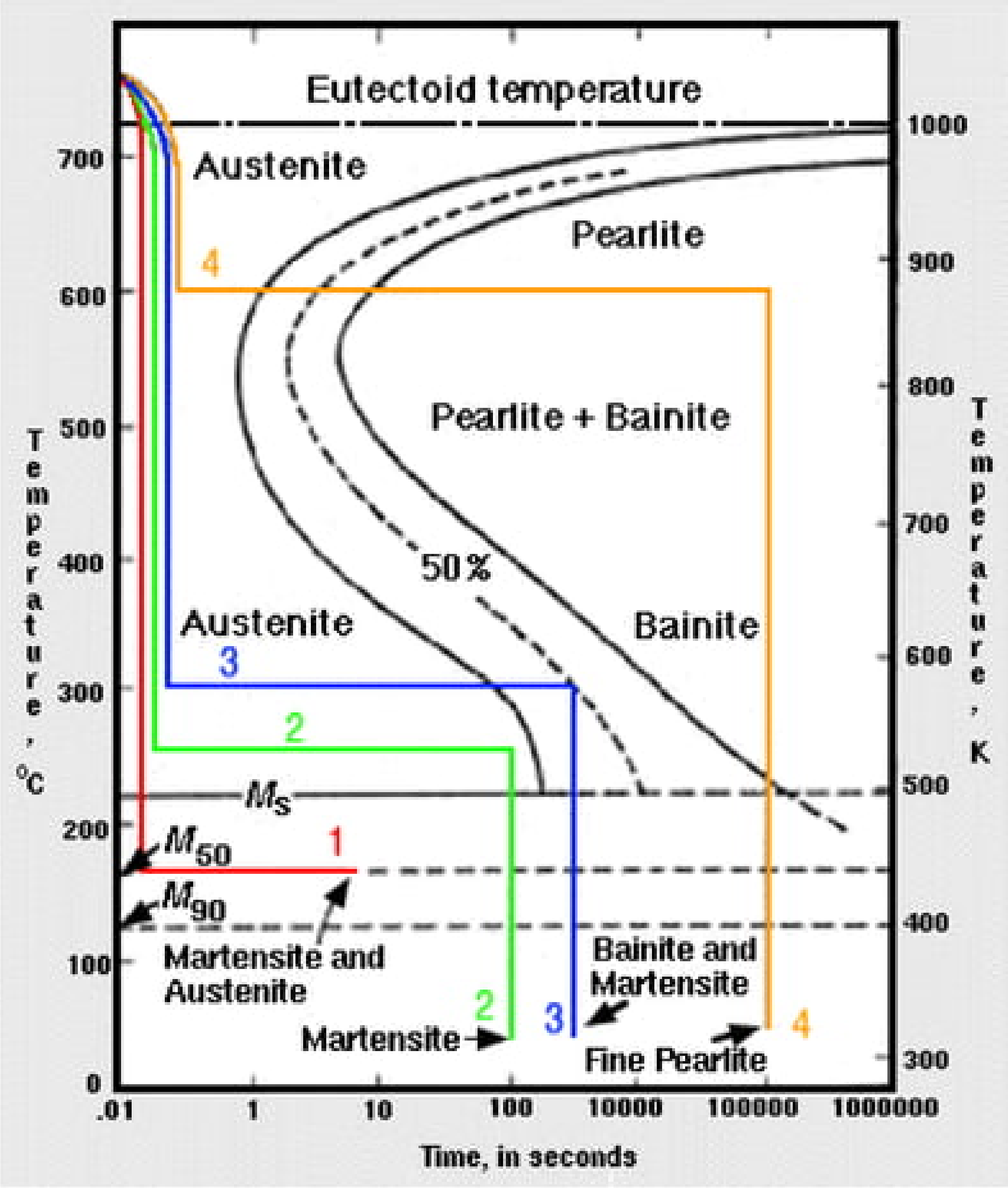
- a. (Red) The **specimen is cooled rapidly to 150 Degree Celcius and let for 20 minutes**. The cooling rate is too rapid for **pearlite** to form at higher temperatures; therefore, the steel remains in the austenitic phase until the Ms temperature is passed, where martensite **begins to form.**
- **Since 150 Degree Celcius is the temperature at which half of the austenite transforms to martensite, the direct quench converts 50% of the structure to martensite.**
- **Holding at 150 Degree Celcius forms only a small quantity of additional martensite, so the structure can be assumed to be half martensite and half retained austenite.**



PATH 2 - (GREEN LINE)

- b. (Green) The specimen is held at 250 Degree Celcius for 100 seconds, which is not long enough to form bainite.

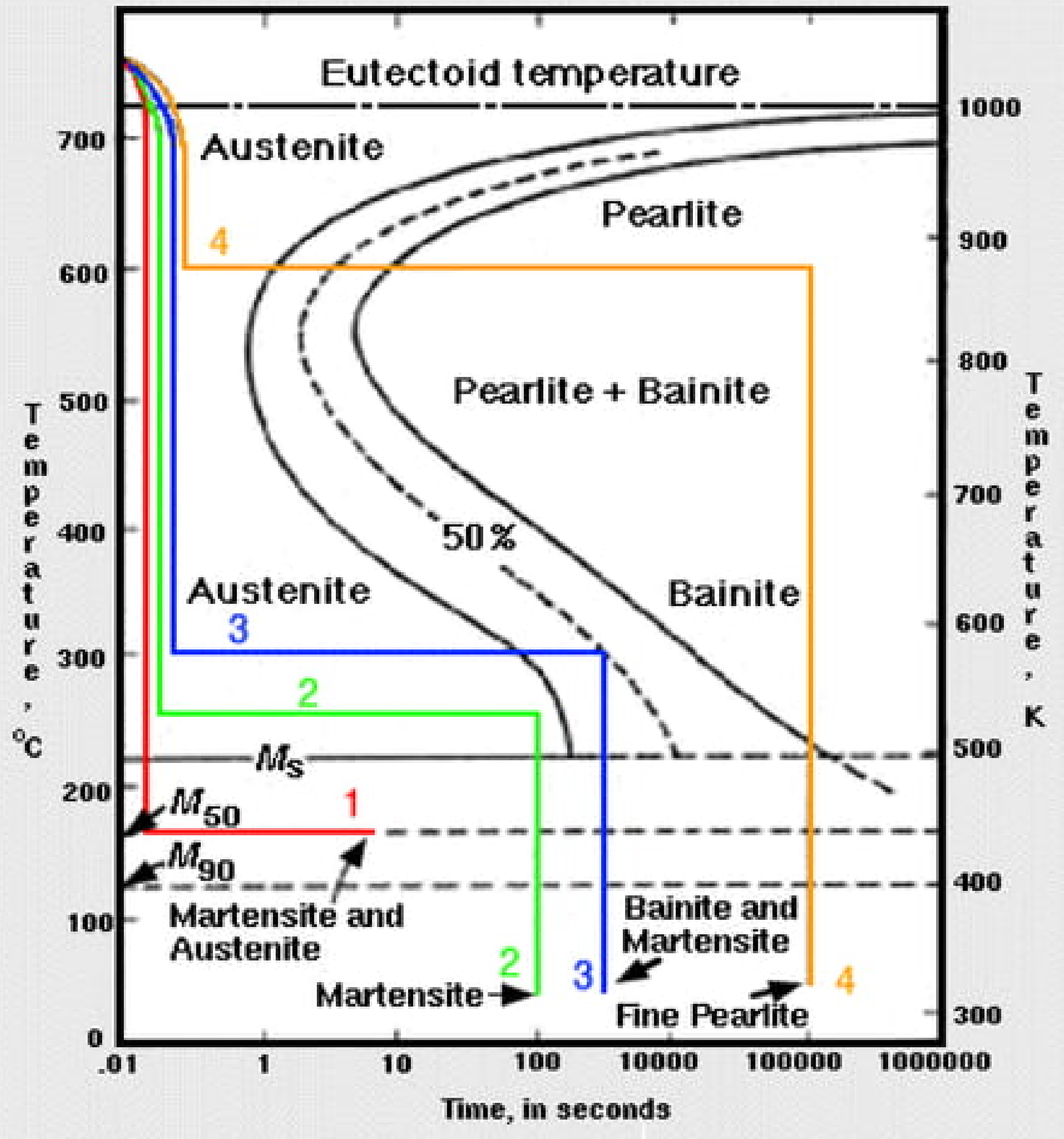
- Therefore, the second quench from 250 Degree Celcius to room temperature develops a martensitic structure.



Path 3 – (Blue line)

- c. (Blue) An isothermal hold at 300 Degree Celcius for 500 seconds produces a half-bainite and half-austenite structure.

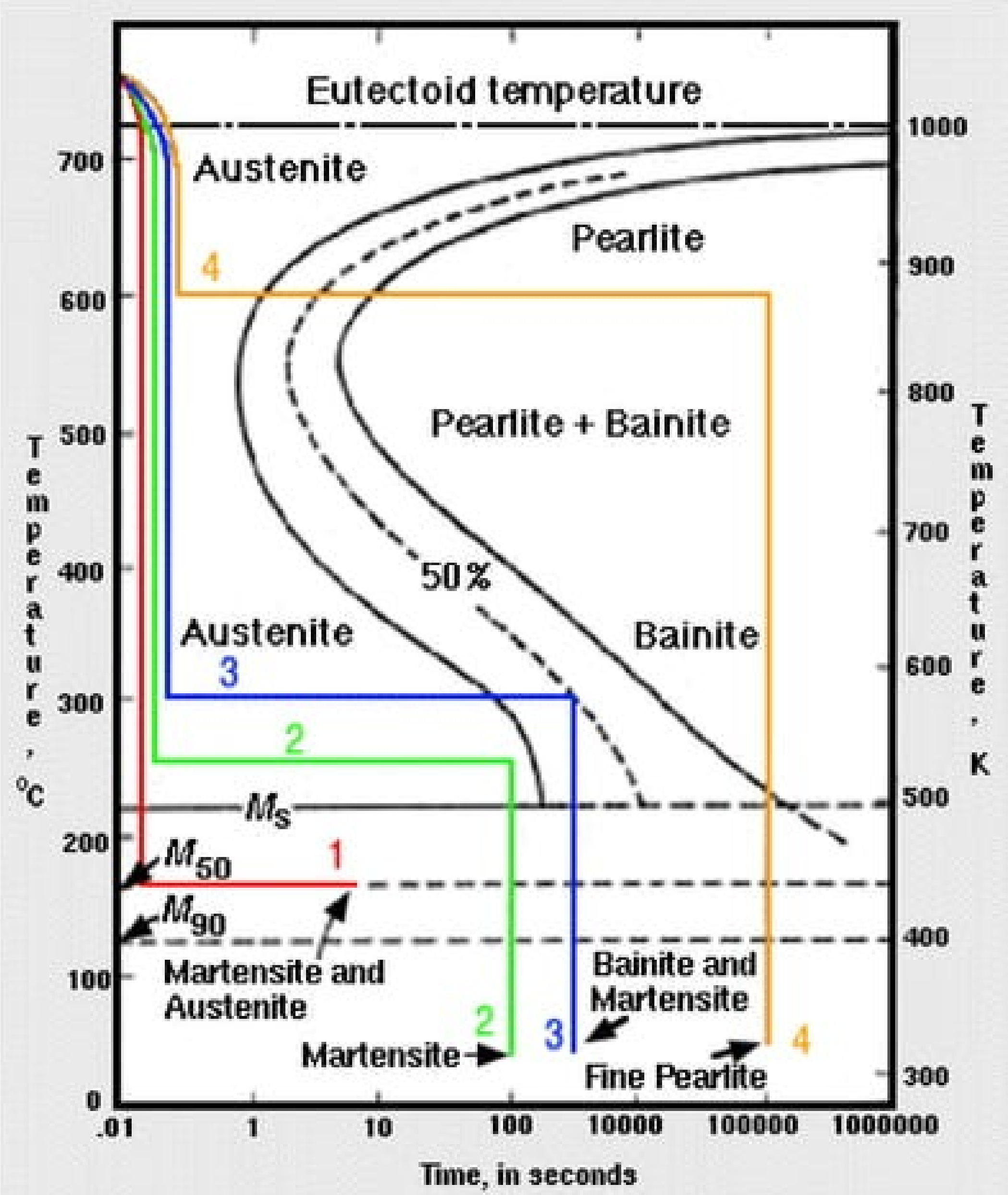
- Cooling quickly would result in a final structure of martensite and bainite.



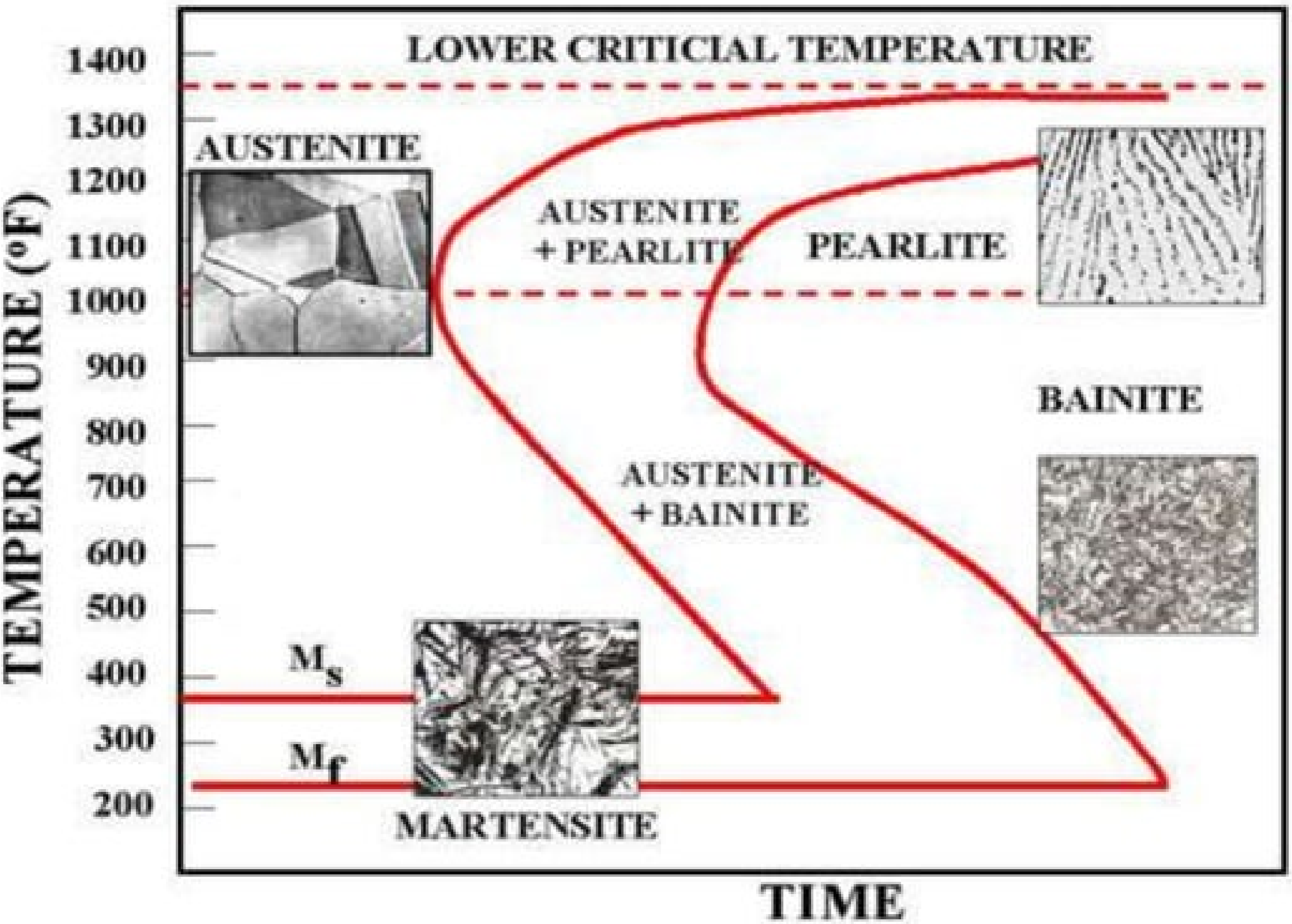
PATH 4 – (Orange Line)

- d. (Orange) Austenite converts completely to fine pearlite **after eight seconds at 600 Degree Celcius This phase is stable and will not be changed on holding for 100,000 seconds at 600 Degree Celcius .**

- **The final structure obtained while cooling is fine pearlite.**



TTT – MICRO STRUCTURES



CCT diagram for Fe-C system

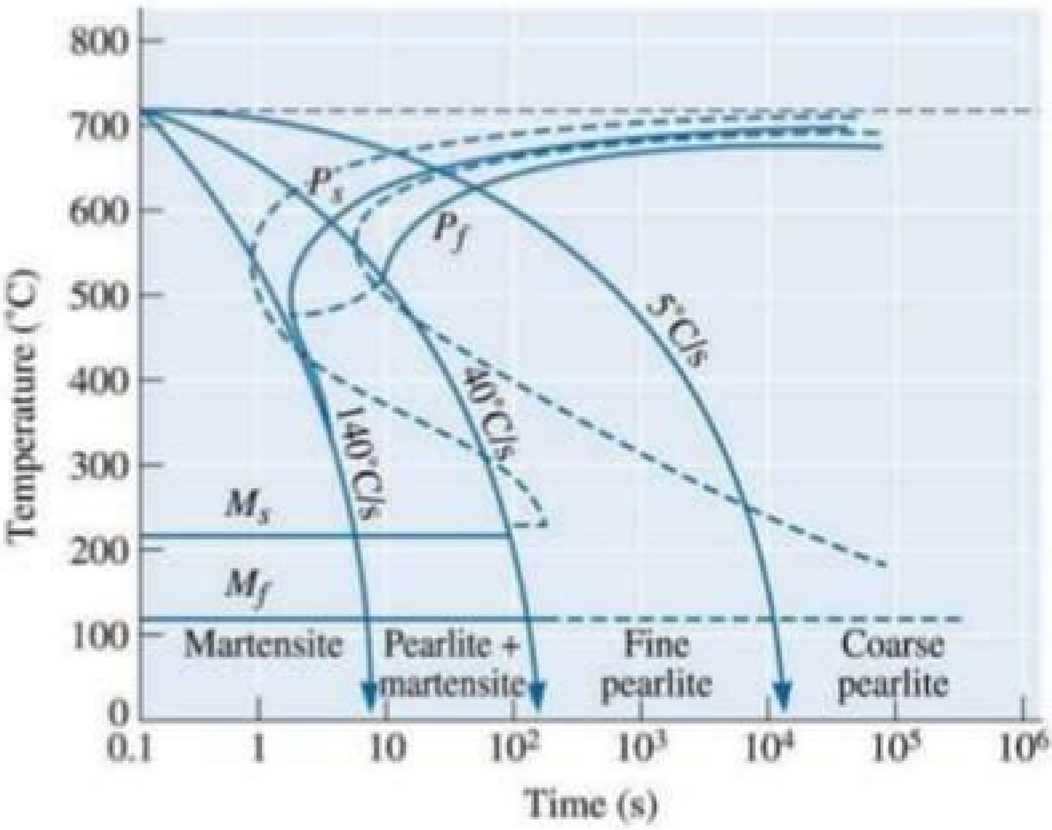
- It measure the extent of transformation as **a function of time for a continuously decreasing temperature.**

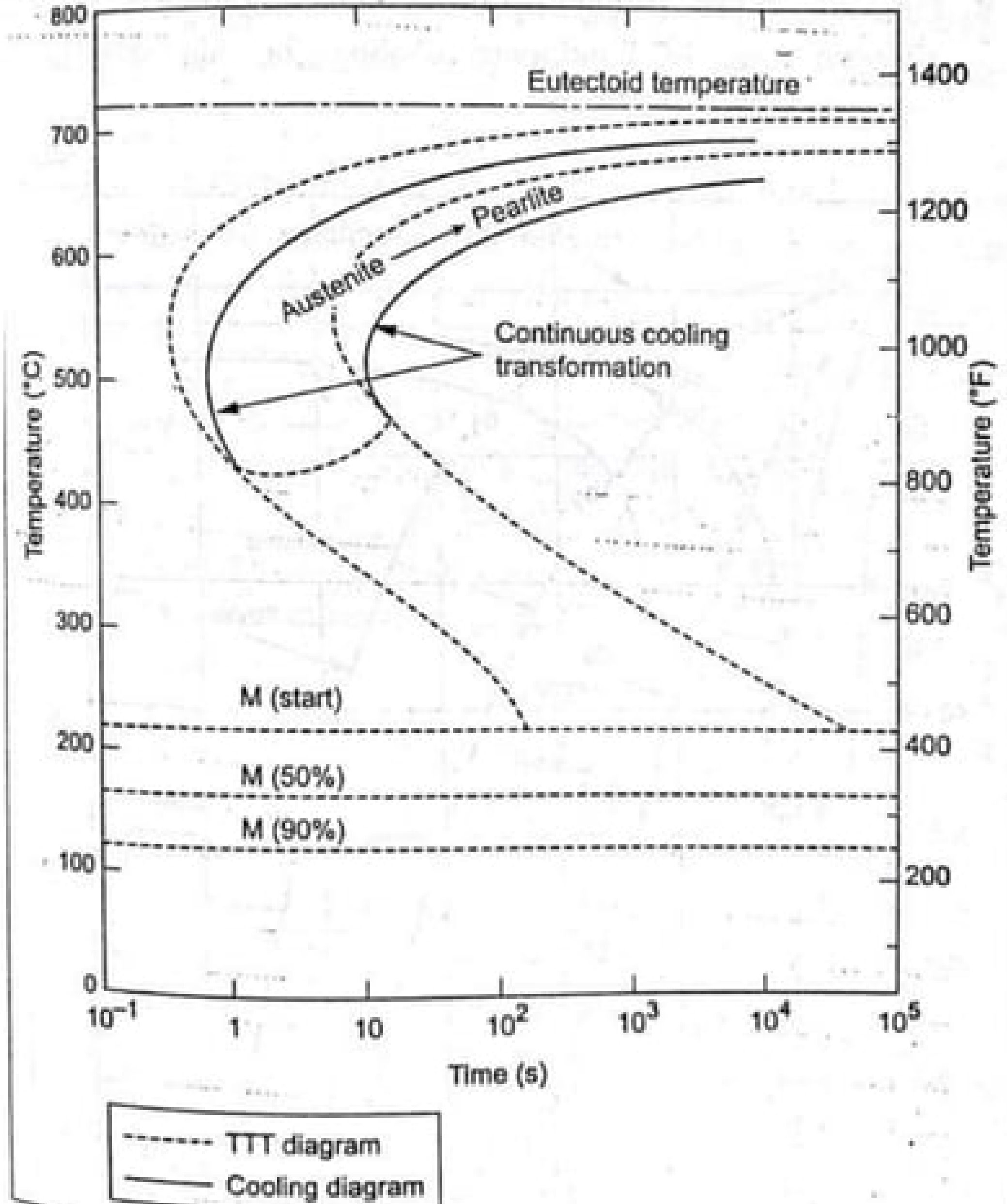
- Usually materials are cooled continuously, thus **Continuous Cooling Transformation diagrams** are appropriate.

- For continuous cooling, the time required for a reaction to begin and end is delayed, thus the isothermal curves are shifted to longer times and lower temperatures

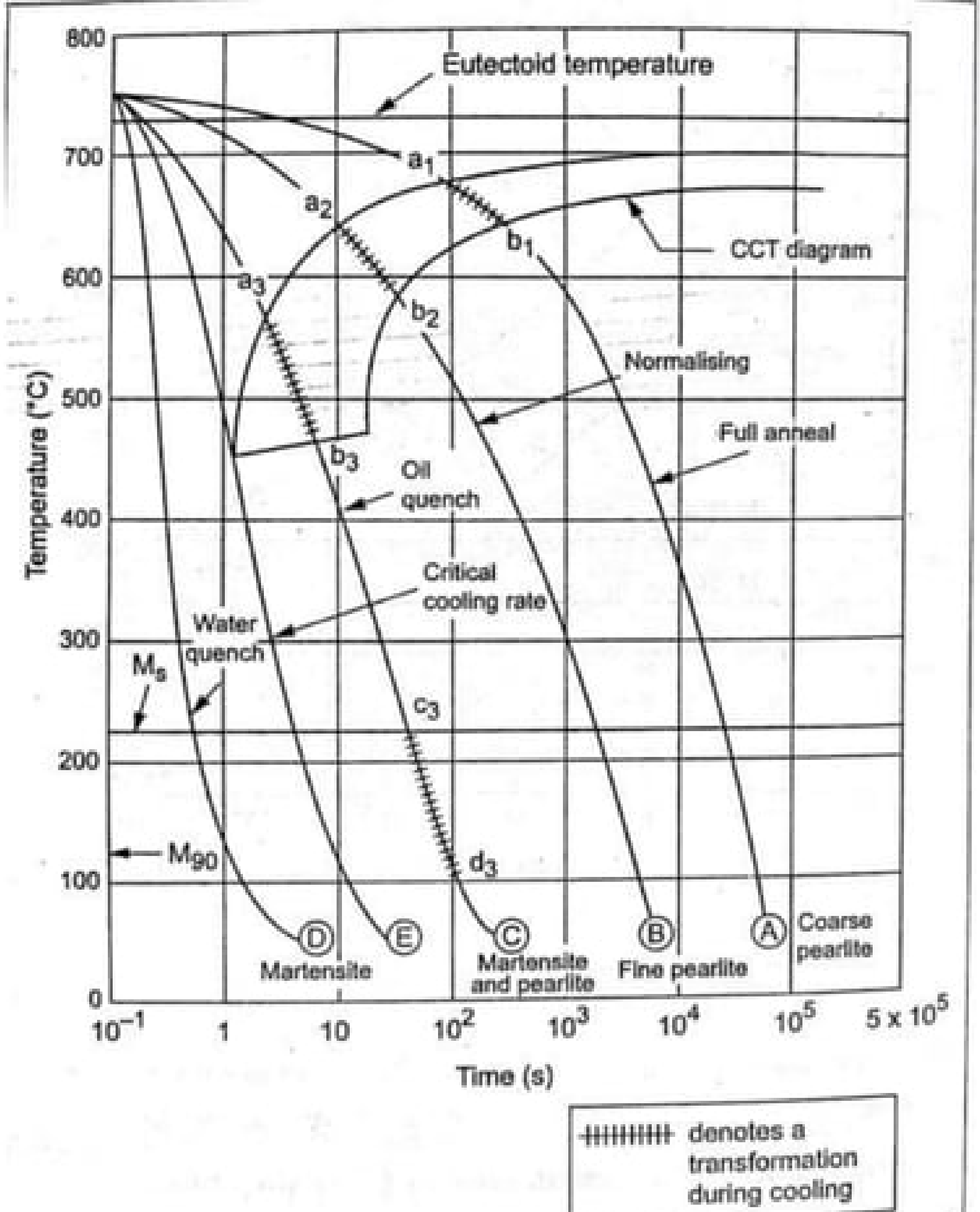
- **Main difference between TTT and CCT diagrams: no space for bainite in CCT diagram as continuous cooling always results in formation of pearlite.**

The CCT diagram (solid lines) for a 1080 steel compared with the TTT diagram (dashed lines).

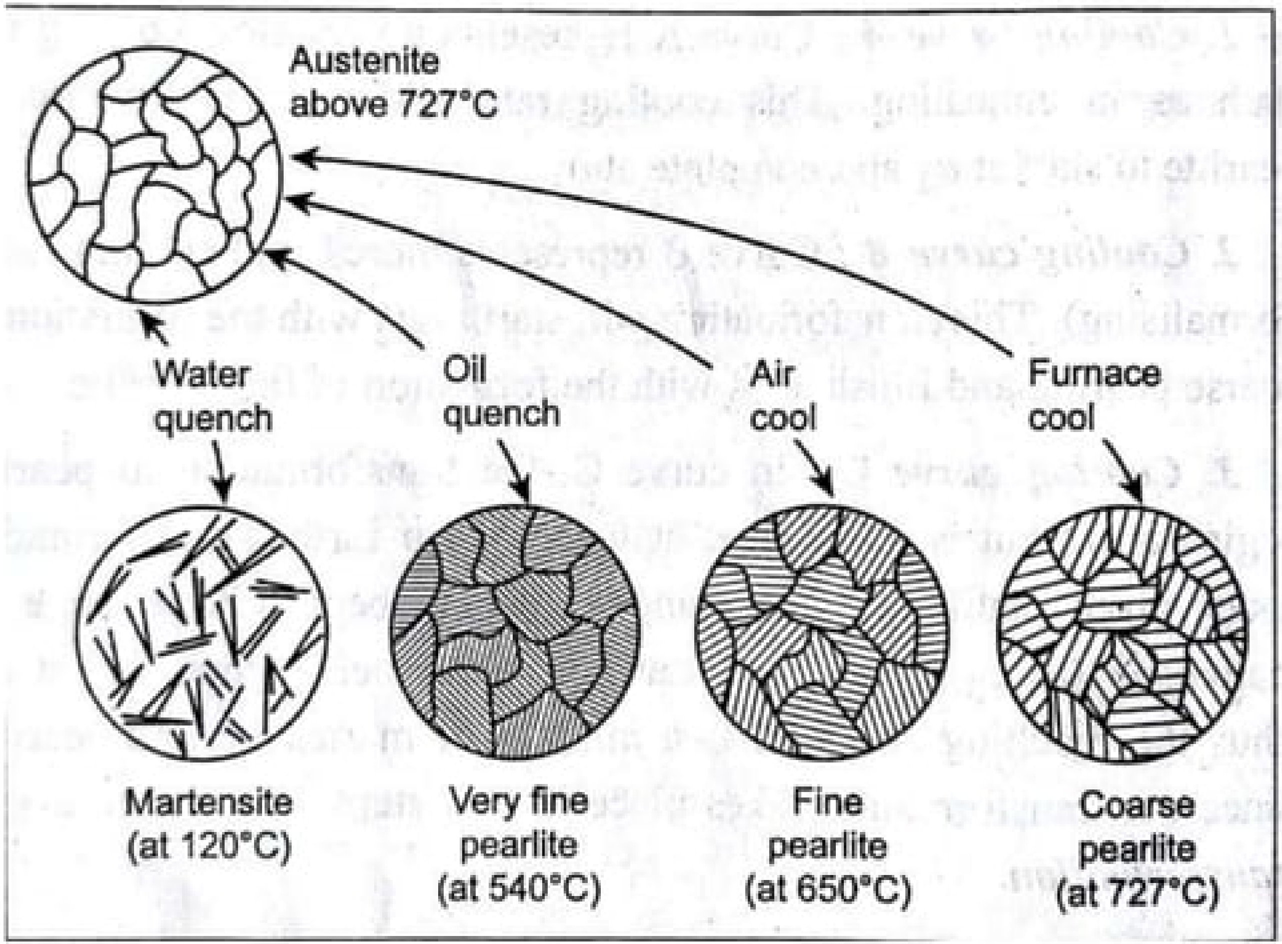




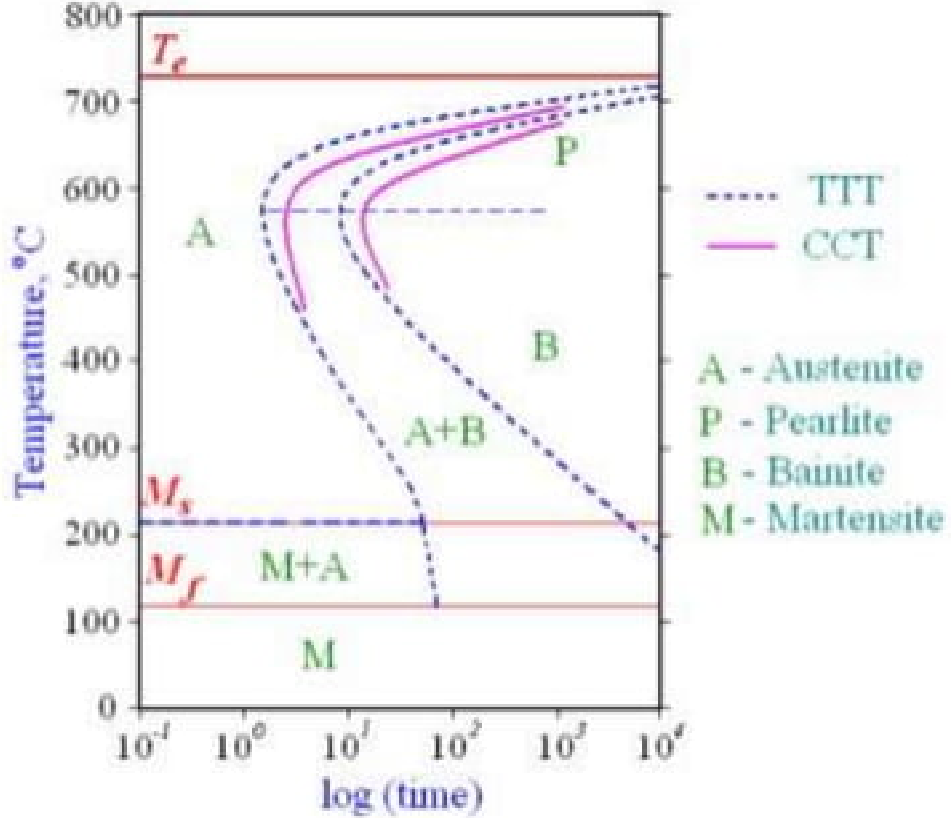
800
700
600
500
400
300
200
100
0
Temperature (°C)
1400
1200
1000
800
600
400
200
Temperature (°F)
Eutectoid temperature
Austenite
Pearlite
Continuous cooling transformation
M (start)
M (50%)
M (90%)
10^{-1}
1
10
10^2
10^3
10^4
10^5
Time (s)
TTT diagram
Cooling diagram



Eutectoid temperature
a1
a2
a3
b1
b2
b3
c3
d3
CCT diagram
Normalising
Full anneal
Oil quench
Critical cooling rate
Water quench
Ms
M90
D
E
C
B
A
Martensite
Martensite and pearlite
Fine pearlite
Coarse pearlite
Temperature (°C)
800
700
600
500
400
300
200
100
0
10−1
1
10
10²
10³
10⁴
10⁵
5 x 10⁵
Time (s)
denotes a transformation during cooling


Austenite
above 727°C
Water
quench
Oil
quench
Air
cool
Furnace
cool
Martensite
(at 120°C)
Very fine
pearlite
(at 540°C)
Fine
pearlite
(at 650°C)
Coarse
pearlite
(at 727°C)

Superposition of TTT and CCT Diagrams for Eutectoid Steel



HARDENABILITY

HARDENABILITY

- Hardenability of steel is defines as that property which determines the depth and distribution of hardness induced by quenching by austenite condition.

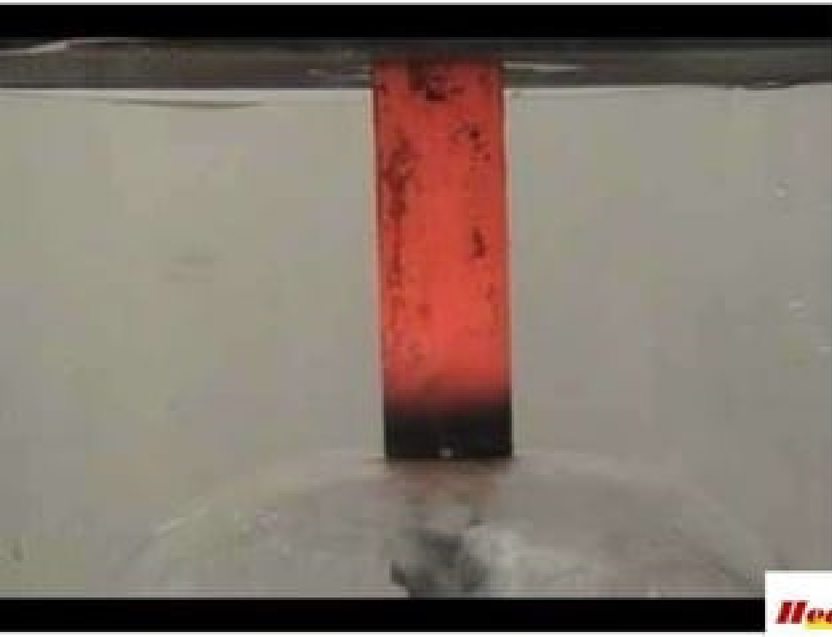
- **METHOD OF DETERMINING HARDENABILITY :**
  - **Jominy end quench test**

JOMINY END QUENCH TEST

- The Jominy end **quench test** is used to **measure the hardenability** of a steel.
- This describes the ability of the steel to be **hardened in depth by quenching**.
- steel to partially or completely **transform from austenite** to some **fraction of martensite** at a given depth below the surface

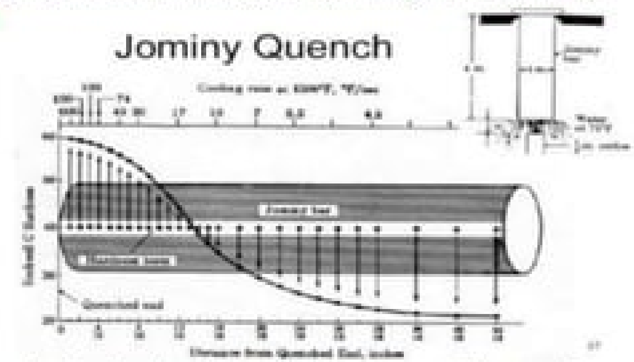
- High hardenability allows slower quenches to be used (e.g. oil quench), which reduces the distortion and residual stress.
- The test sample is a cylinder with a length of 111.6 mm (4 inches) and a diameter of 25.4 mm (1 inch).

- This is usually at a temperature of 800 to 900°C.
- The test sample is quickly transferred to the test machine,
- where it is held vertically and sprayed with a controlled flow of water onto one end of the sample.
- This cools the specimen from one end,



ardenability: Jominy End Quench Test

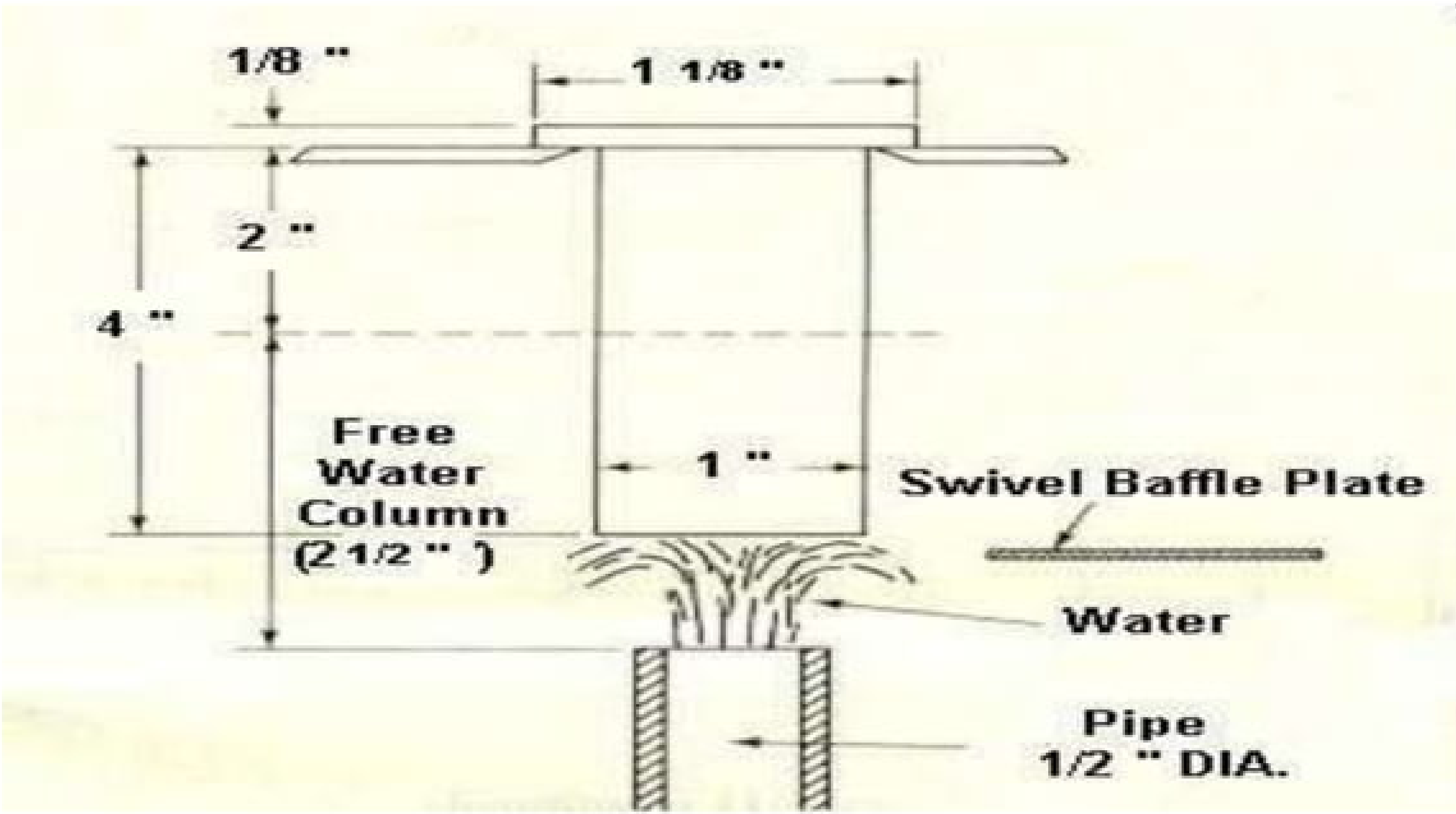
➢ The most simple and convenient method of determining the Hardenability is the Jominy End Quench Test.



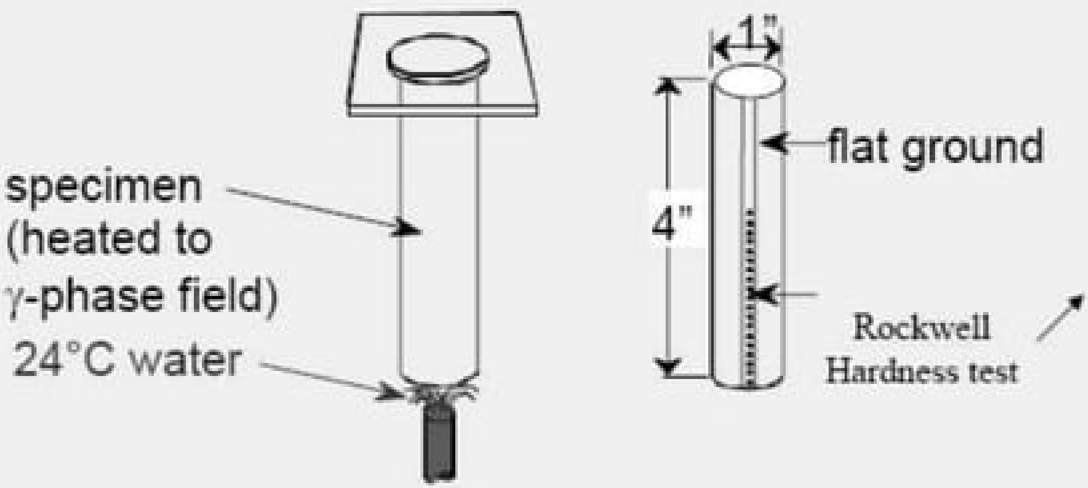
➢ The Jominy test involves heating a standard test piece of diameter 25 mm and length 100 mm to the austenite state, fixing it to a frame in a vertical position and then quenching the lower end by means of a jet of water.

- The hardness is measured at intervals from the quenched end. The interval is typically 1.5 mm for alloy steels and 0.75 mm for carbon steels.
- High hardness occurs where high volume fractions of martensite
- Lower hardness indicates transformation to bainite or ferrite/pearlite microstructures

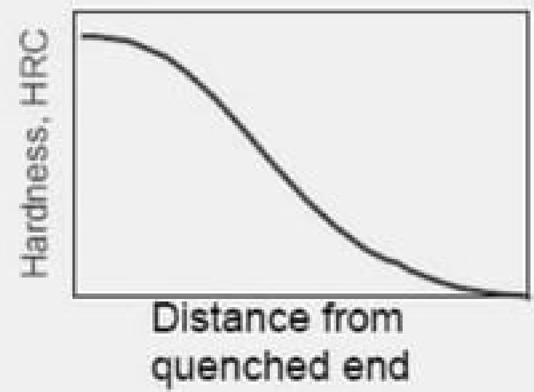
Jominy End Quench Test

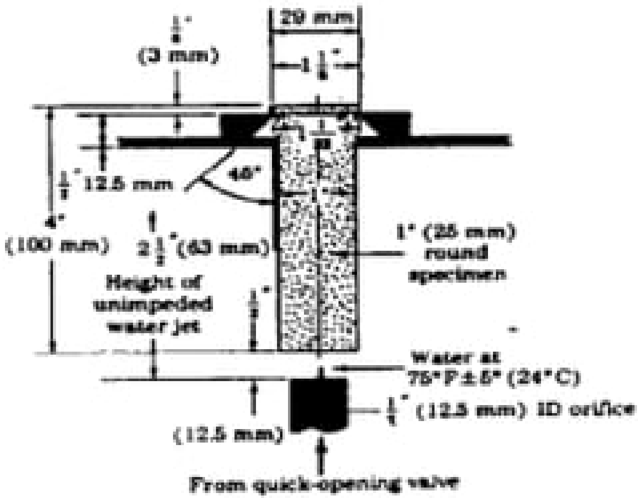


Jominy end-quenching test

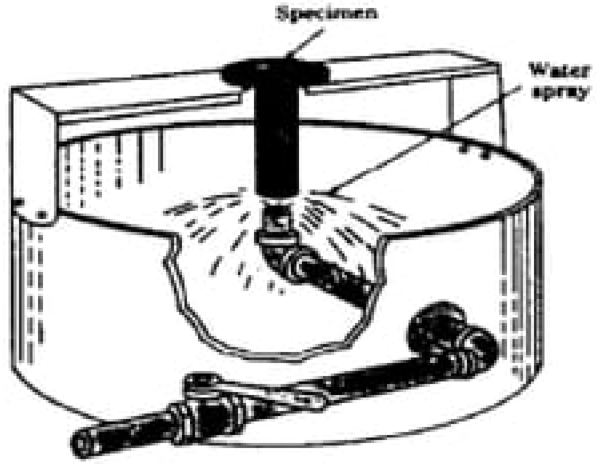


Hardness versus distance from the quenched end

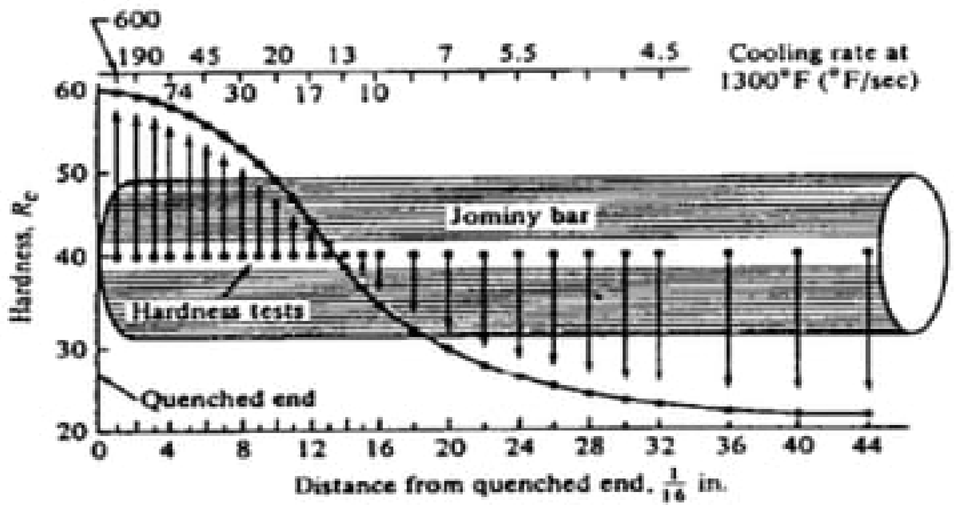




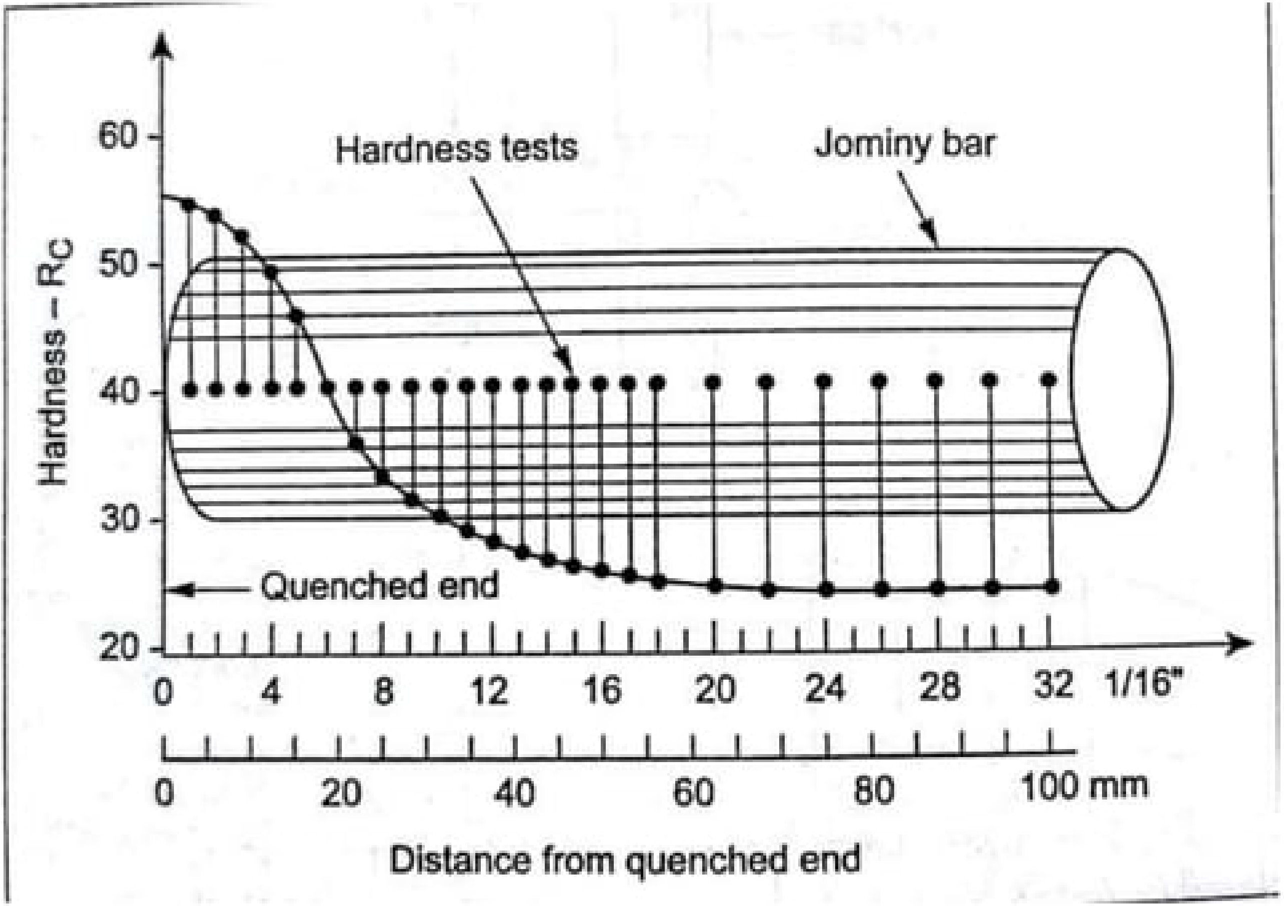
29 mm
(3 mm)
12.5 mm
45°
4" (100 mm)
2½" (63 mm)
Height of unimpeded water jet
1" (25 mm) round specimen
Water at 75°F±5° (24°C)
½" (12.5 mm) ID orifice
(12.5 mm)
From quick-opening valve



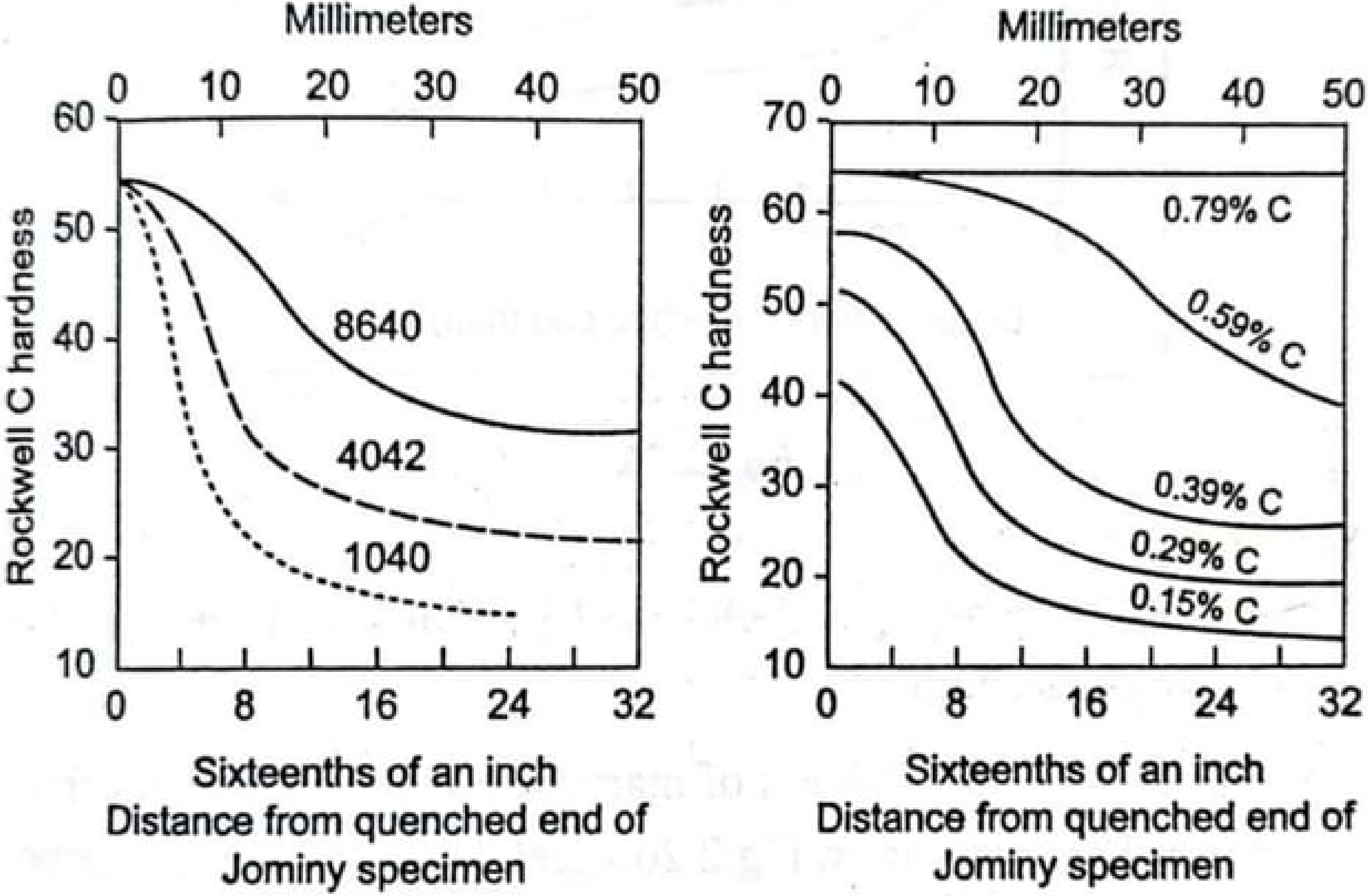
Specimen
Water spray



600
190 45 20 13 7 5.5 4.5
74 30 17 10
Cooling rate at 1300°F (°F/sec)
Hardness, R_c
Jominy bar
Hardness tests
Quenched end
Distance from quenched end, $\frac{1}{16}$ in.
0 4 8 12 16 20 24 28 32 36 40 44
20 30 40 50 60



Hardness – R_C
60
50
40
30
20
Hardness tests
Jominy bar
Quenched end
0
4
8
12
16
20
24
28
32
1/16"
0
20
40
60
80
100 mm
Distance from quenched end


Millimeters
0
10
20
30
40
50
60
50
40
30
20
10
Rockwell C hardness
8640
4042
1040
0
8
16
24
32
Sixteenths of an inch
Distance from quenched end of
Jominy specimen
Millimeters
0
10
20
30
40
50
70
60
50
40
30
20
10
Rockwell C hardness
0.79% C
0.59% C
0.39% C
0.29% C
0.15% C
0
8
16
24
32
Sixteenths of an inch
Distance from quenched end of
Jominy specimen