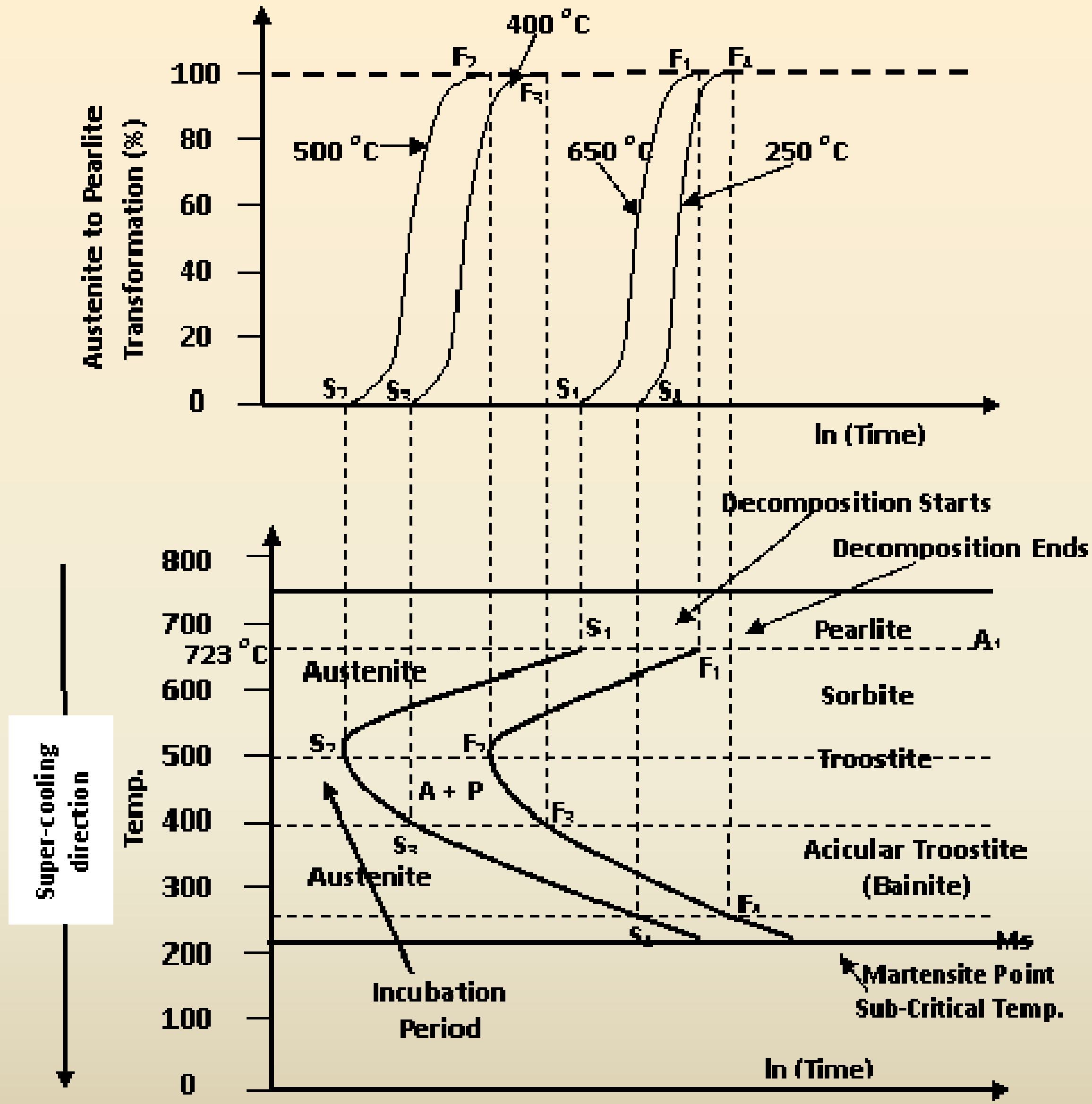
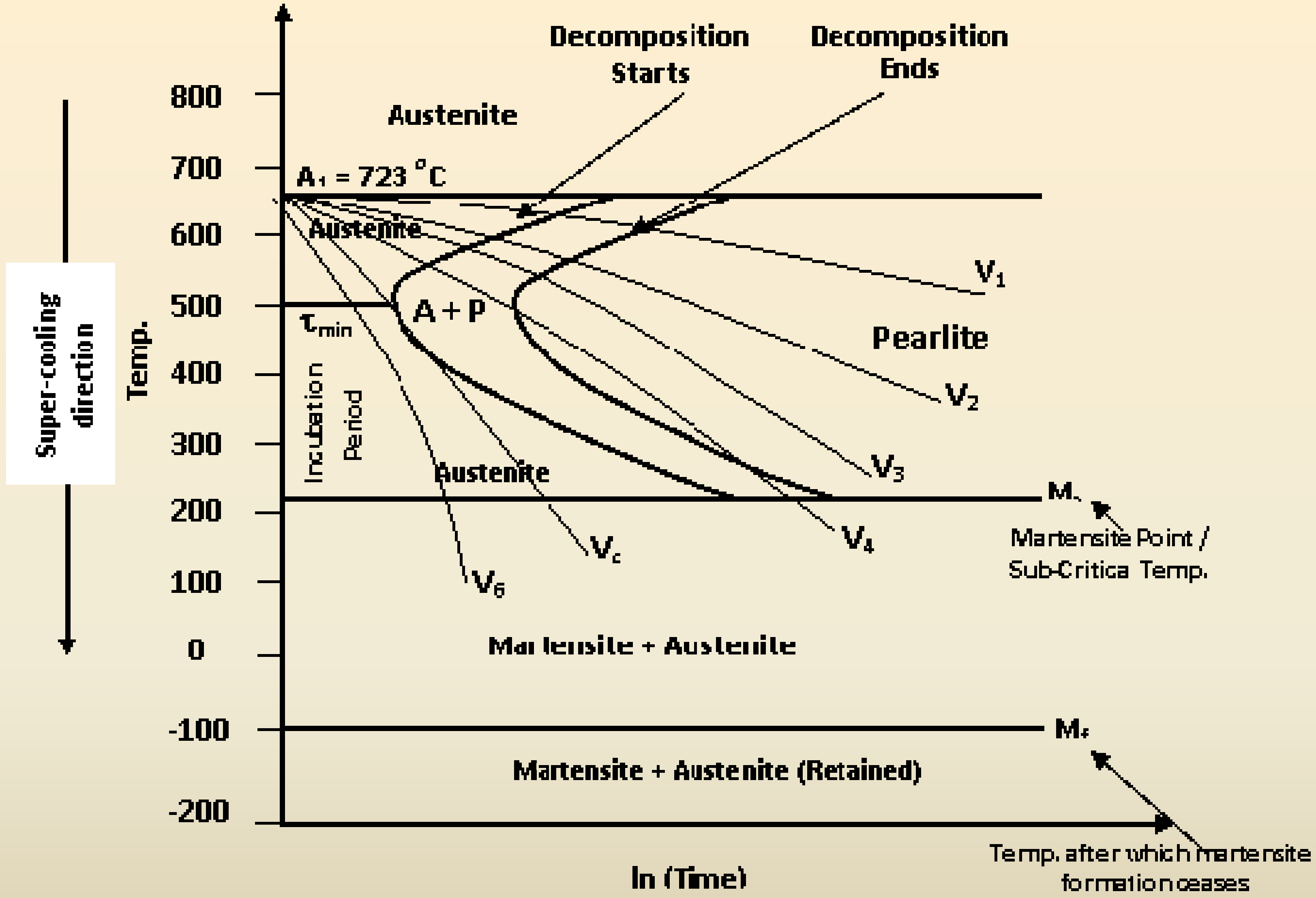
Module 4
Heat Treatment



Isothermal Decomposition of Austenite (TTT Diagram / S / C – Curves)



Continuous Cooling Curves

Pearlite

Martensite

Objectives of Heat Treatment

- To increase the hardness, wear & abrasion resistance and machinability
- To re-soften steels after its hardened by heat-treatment
- To adjust the mechanical, physical & chemical properties
- To reduce / eliminate internal residual stresses
- To induce controlled residual stresses
- To stabilize steels
- To decrease / increase the grain size
- To produce special micro-structures
- To eliminate gases, which embrittle steels
- To change the composition of the surface and case of the material by diffusion mechanism

Classification of Heat Treatment Processes

Group I: First order Annealing / Re-crystallization Annealing

Group II: Second order Annealing / Full-Annealing

Group III: Hardening

Group IV: Tempering

Types of Heat Treatment Processes

- Hardening
- Annealing
- Normalizing
- Tempering
- Surface Hardening

First order Annealing / Re-crystallization Annealing

- Heating slightly above the re-crystallization temperature to soften the strain-hardened steels
- Employed to relieve internal stresses, reduce hardness and to increase the ductility
- The process consists of 'recovery' and 're-crystallization'
- Process is not associated with phase transformations

Recovery: Eliminating the elastic distortions of the crystal lattice upon slight heating

Re-crystallization: Formation and subsequent growth of new grains upon heating to re-crystallization temperature

Min. Re-crystallization Temp. = 0.4 T_m (T_m: Melting Point)

Hardening

- Hardening is performed to impart strength and hardness impart strength and hardness to alloys by heating up to a certain temperature, depending on the material, and cooling it rapidly.
- Steel is heated 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 is performed to cool hot metal rapidly by immersing it in brine (salt water), water, oil, molten salt, air or gas.
- Quenching sets up residual stresses in the workpiece and sometimes results in cracks
- Residual stresses are removed by another process called annealing.

Annealing

- **Annealing is performed to Annealing is performed to reduce hardness, remove residual stresses, improve toughness, restore ductility, and to alter various mechanical, electrical or magnetic properties of material through refinement of grains.**
- **Cooling rate is very slow around 10^{o}C per hour**
- **Process is carried out in a controlled atmosphere controlled atmosphere of inert gas to avoid oxidation.**
- **Used to achieve ductility in work hardened steels**

Types of Annealing

Full Annealing, Incomplete Annealing, Isothermal Annealing, Spheroidising (to obtain granular cementite), Diffusion Annealing (Homogenizing)

Objectives

- **To obtain softness & improve machinability**
- **To improve / restore ductility & toughness**
- **To relieve internal stresses**
- **To reduce / eliminate structural inhomgeneity**
- **To refine grain size**
- **To prepare steel for subsequent heat –treatment**

Full Annealing

- Heating steels to a temperature 30-50 ^{0}C above Ac_3 (910 ^{0}C), holding at this temperature and cooling slowly (within the furnace) at a rate of 30-200 ^{0}C per hour depending upon the composition of the steel
- The holding time should be about one-half to one hour per tons of the charge
- Heating should be essentially with in the controlled / protective environment to prevent scaling (oxidation) and de-carbonization of the steels
- Slow cooling is required to decompose austenite into pearlite (low degrees of super-cooling)
- Higher the austenite stability, slower the cooling must be to ensure decomposition of the austenite

Incomplete Annealing

- Heating steels to a temperature somewhat above Ac_1 (723 ^0C), holding at this temperature and cooling slowly (within the furnace)
- Employed to relieve internal stresses and to improve machinability of the steels
- Employed generally in case of eutectoid and hyper-eutectoid steels, where heating above Ac_1 causes complete re-crystallization

Isothermal Annealing

- Heating steels similar to ordinary annealing (slightly above the Ac_3) and cooling comparatively rapidly in air or by a blast in the furnace to a temperature (about 50-100 ^{0}C) below Ar_1 and then holding at this temperature isothermally for certain period of time (in accordance with TTT diagram), so that austenite decomposes to pearlite. This is followed by rapid cooling
- Reduced time of heat-treatment
- Process not suitable for large forgings or charges as uneven cooling on the surface and core may result into non-uniform structures

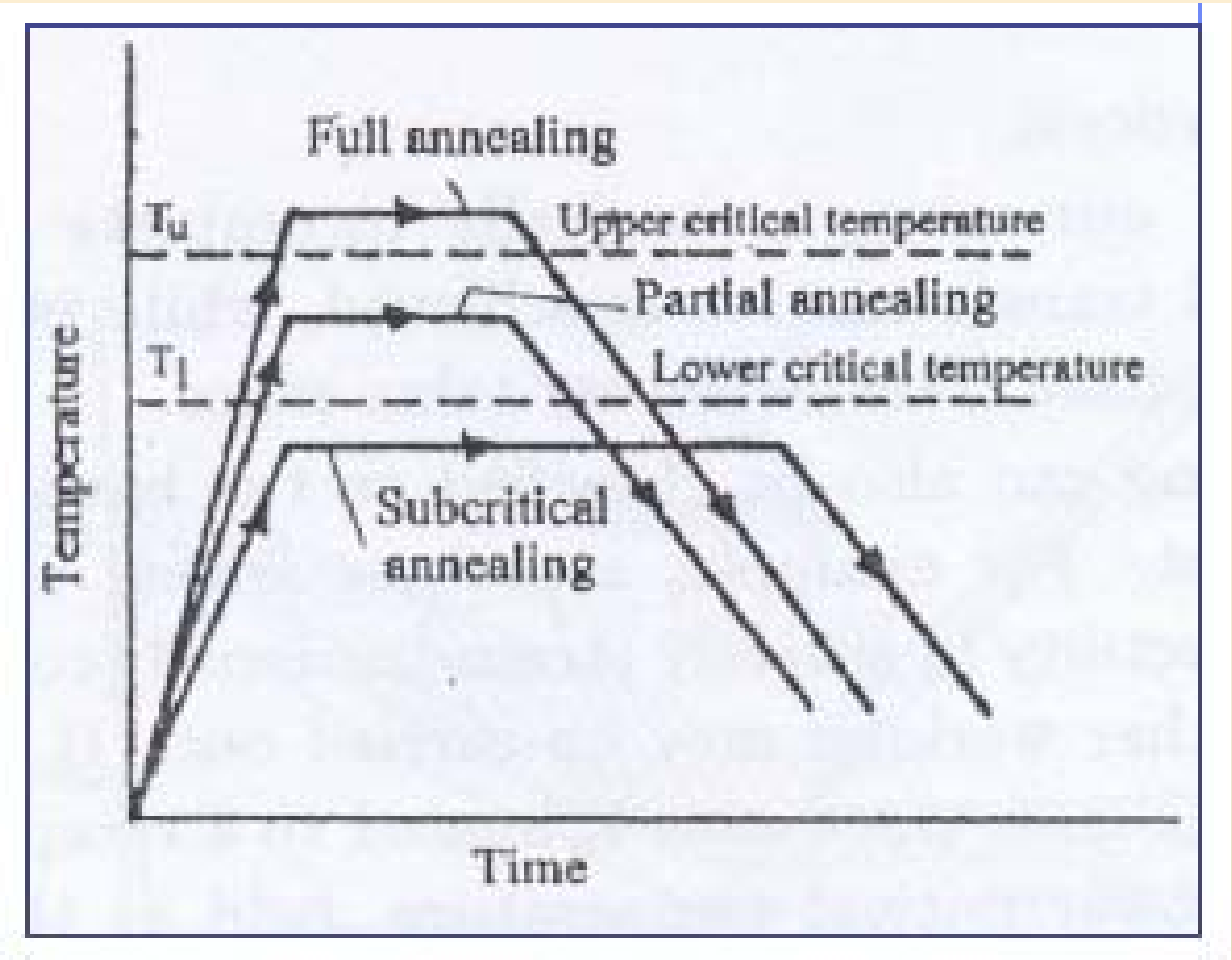
Spheroidizing (to obtain granular cementite)

- **Heating steels to temperature very-slightly above Ac_1 holding at this temperature and cooling slowly (within the furnace) at a rate of 25-30 ^{0}C per hour to a temperature of 600 ^{0}C and then cooling it as usual**
- **Essentially practiced for high-carbon steels and tool steels to transform lamellar pearlite into granular cementite**
- **Caution: steels should be heated very-slightly above , Ac_1 otherwise heating to high temperatures will make granular cementite difficult to obtain and will facilitate formation of lamellar pearlite only**
- **Spheroidized steels will have lower hardness and tensile strength and relatively higher % elongation, reduction in area and machinability as compared to regular annealed steels**
- **Optimum temp:**

	Eutectoid steels:	**750 ^{0}C**
	hyper-eutectoid Steels:	**770 ^{0}C**

Diffusion Annealing (Homogenizing)

- Heating steels to temperature 1100-1200 ^{0}C (optimum temperature is 1150 ^{0}C) and holding for very small time (to avoid metal loss due to heavy scaling) followed by cooling within the furnace for 6-8 hours upto temperature of 800-850 ^{0}C and then further cooling in air
- Employed for eliminating chemical inhomgeneity
- Used for alloy steel ingots and heavy complex castings

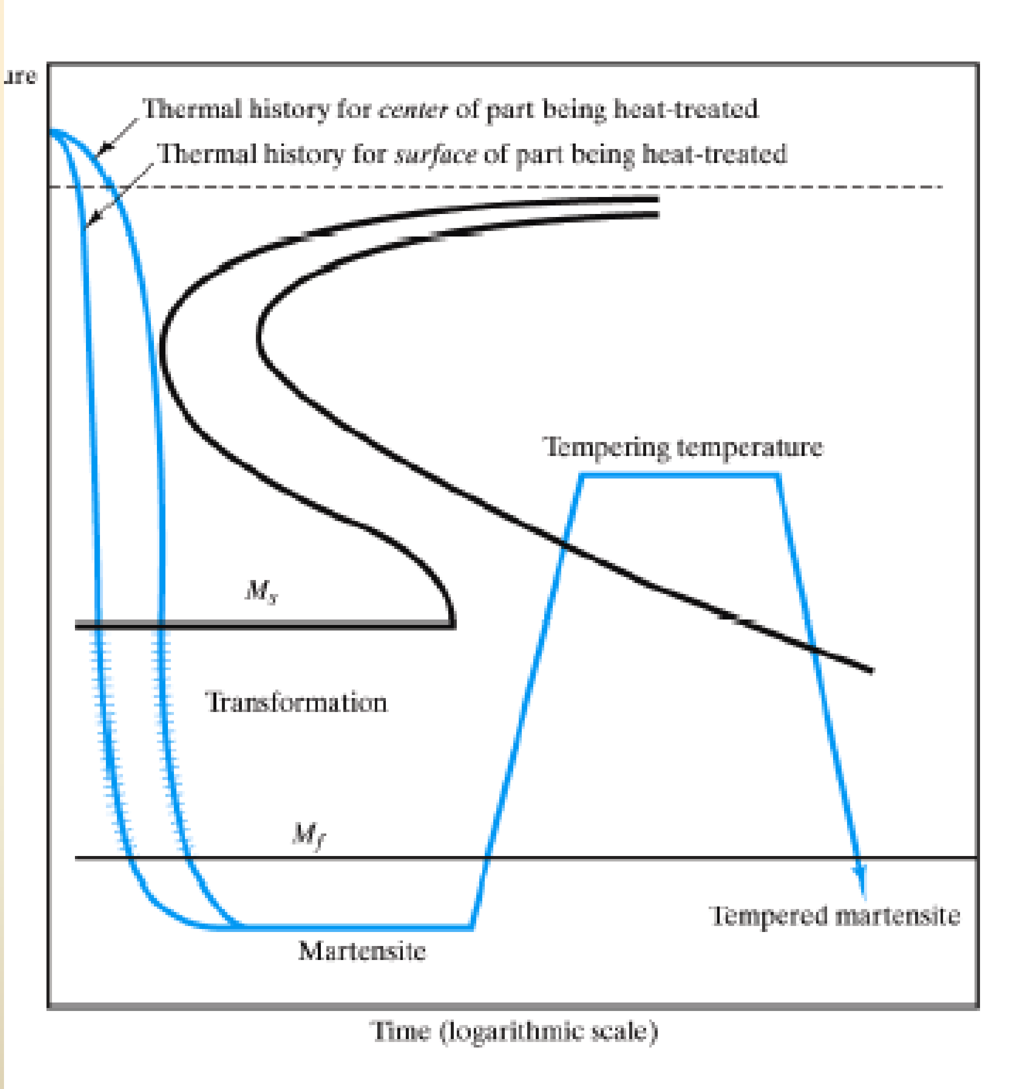

Full annealing
T_u
Upper critical temperature
Partial annealing
T_l
Lower critical temperature
Subcritical
annealing
Temperature
Time

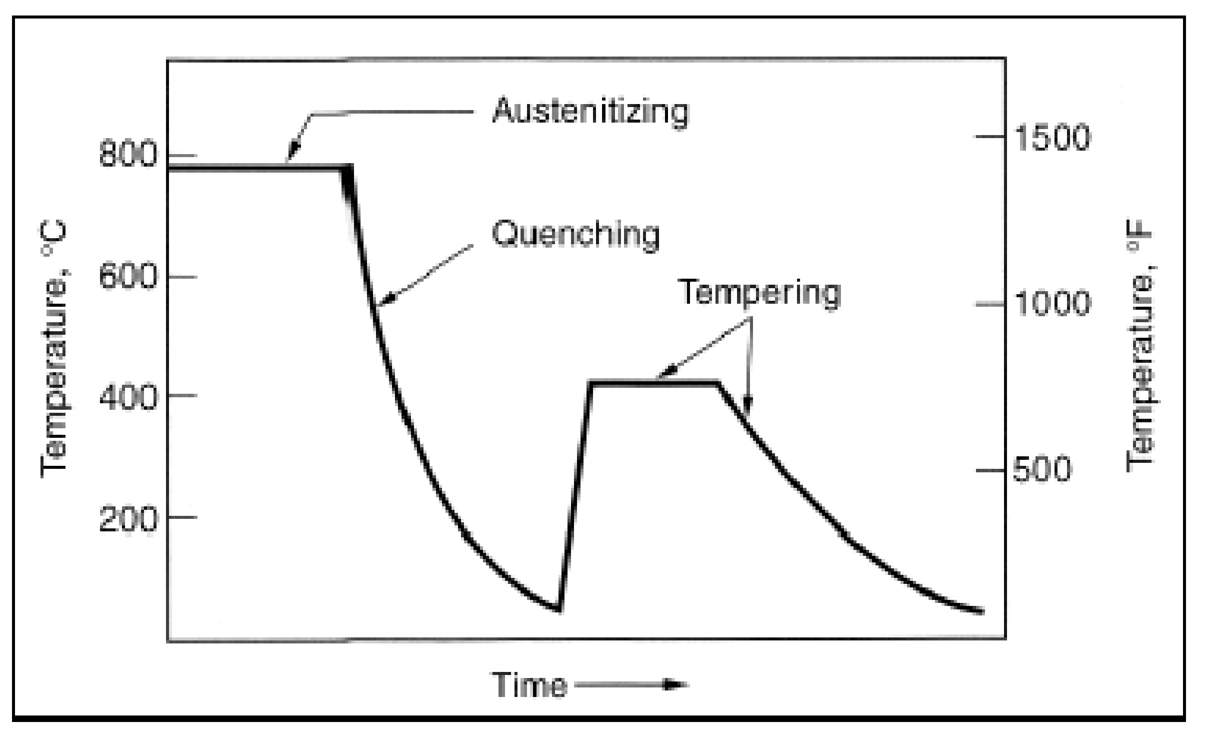
Normalizing

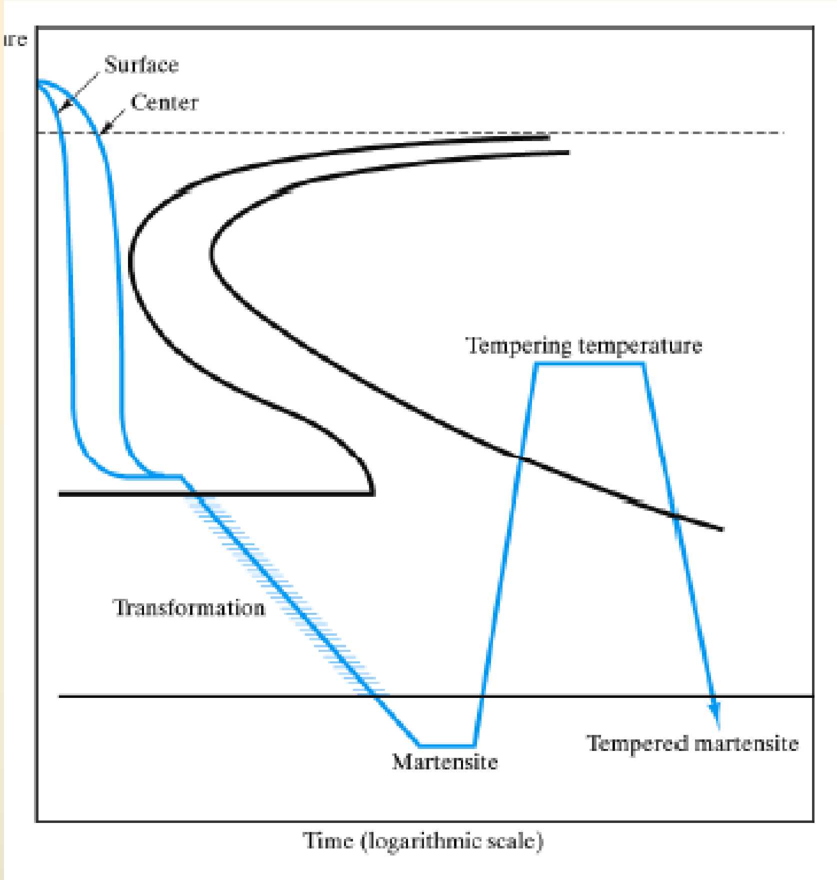
- The process is similar to annealing and is carried out to avoid excessive softness in the material.
- The material is heated above austenitic phase (1100 °C) and then cooled in air. This gives relatively faster cooing relatively faster cooing and hence enhanced hardness and less ductility.
- Normalizing is less expensive less expensive than annealing.
- In normalization variation in properties of different sections of a part is achieved.
- The selection of heat treatment operations is strongly influenced by the carbon content in the steel.

Tempering

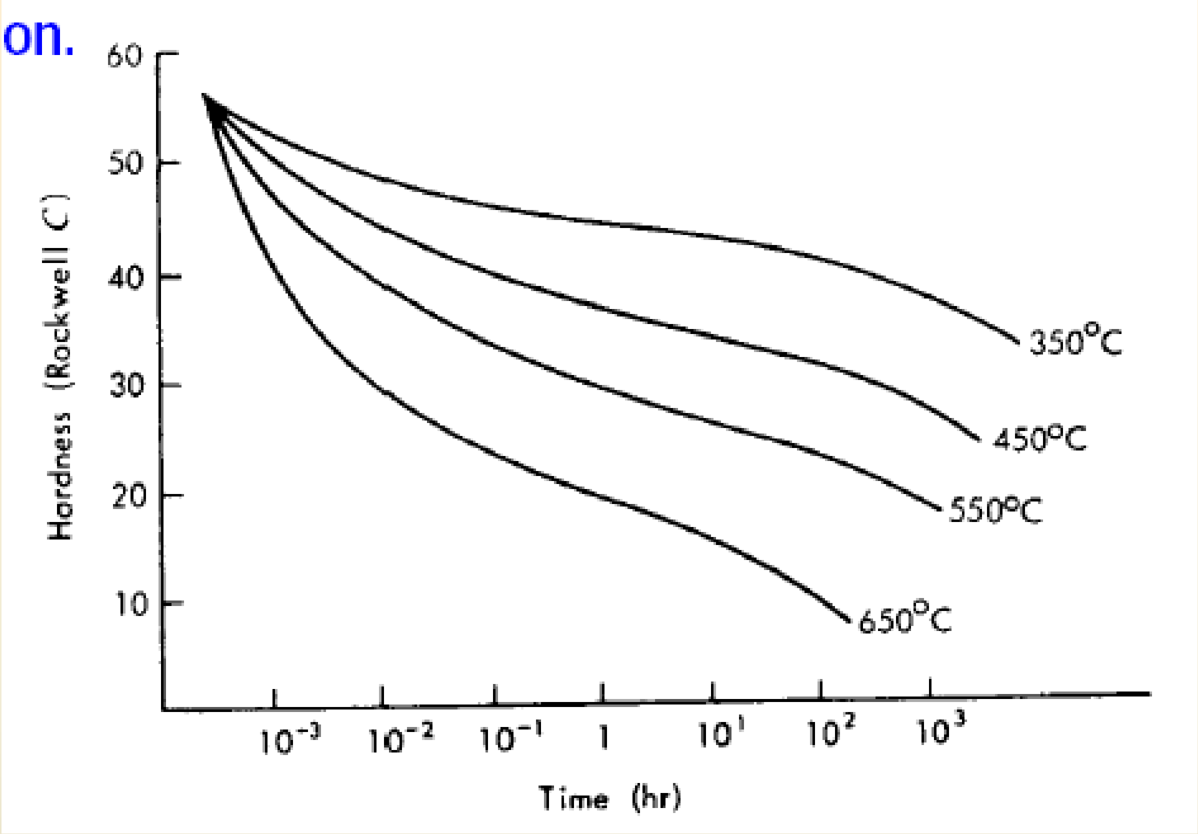
- **Martensite is very hard and brittle.**
- **Tempering is applied to hardened steel to reduce brittleness, increase ductility, and toughness and relieve stresses in martensite structure.**
- **In this process, the steel is heated to lower critical temperature steel is heated to lower critical temperature (350 (350-400 400 °C) C) keeping it there for about one hour and then cooled**
- **slowly at prescribed rate.**
- **This process increases ductility and toughness but also reduces hardness, strength and wear resistance marginally.**
- **Increase in tempering temperature lowers the hardness.**


ure
Thermal history for center of part being heat-treated
Thermal history for surface of part being heat-treated
Tempering temperature
M_s
Transformation
M_f
Tempered martensite
Martensite
Time (logarithmic scale)

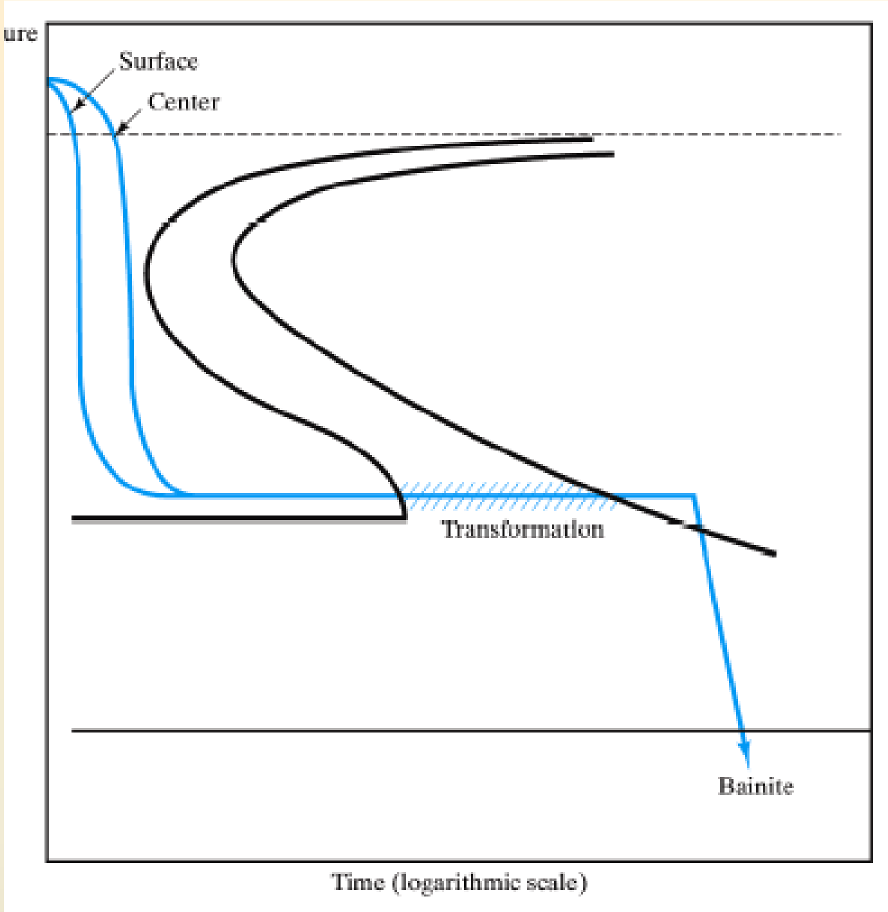

Austenitizing
Quenching
Tempering
800
600
400
200
Temperature, °C
1500
1000
500
Temperature, °F
Time



Martempering: A modified quenching procedure for steels to minimize distortion and cracking upon quenching.



Variation of hardness with tempering temperature



Austempering: Quenching in hot oil or molten salt at a temperature just above M_s followed by moderate cooling (An isothermal treatment which produce a bainite structure in some carbon steels).

Surface Hardening

- **Heat treatment methods in general change the properties of entire material.**
- **Hardening improves wear resistance of material but lowers impact lowers impact resistance and fatigue life resistance and fatigue life. Therefore, sometimes there is requirement of surface hardening**
- **Two subsequent processes are used, first is heating and cooling to get required phase (heat treatment), and second is thermo-chemical treatment (case hardening). Heat treatment can be done by Induction heating, Flame heating, High frequency resistance heating, Laser Beam heating and Electron Beam heating. Case hardening can be done by Carburizing, Cyaniding, Nitriding and Carbonitriding processes.**

Reason to Surface Harden

- Harden surface layers (0.1mm – 5mm)
- Increase wear resistance
- Increase surface strength for load carrying (crush resistance)
- Impart favorable residual compressive stresses
- Improve fatigue resistance
- Produce tough core for resistance to impact

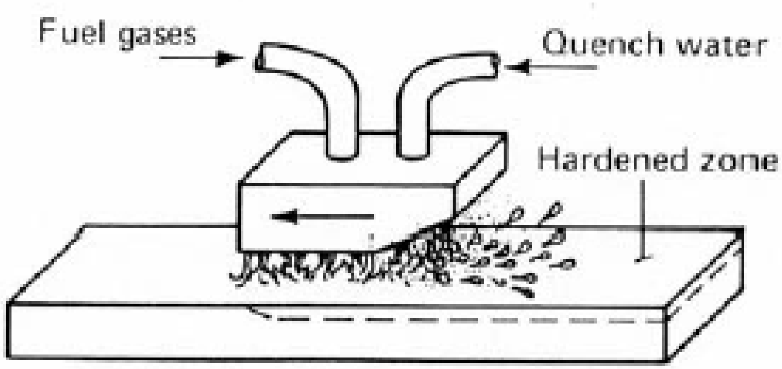
Heat Treatment Characteristics

- **Hardened depth depends on frequency (induction), heat flow (flame) and Frequency, e.g. 1000 Hz results into hardened depth of 4.5-9.0 mm and 10,00,000 Hz results into hardened depth up to 0.25-0.8 mm**
- **Surface hardness is about Rc = 50-60 (martensite or tempered martensite)**
- **Interior hardness is about Rc = 10-20 (pearlite-ferrite-pearlite)**

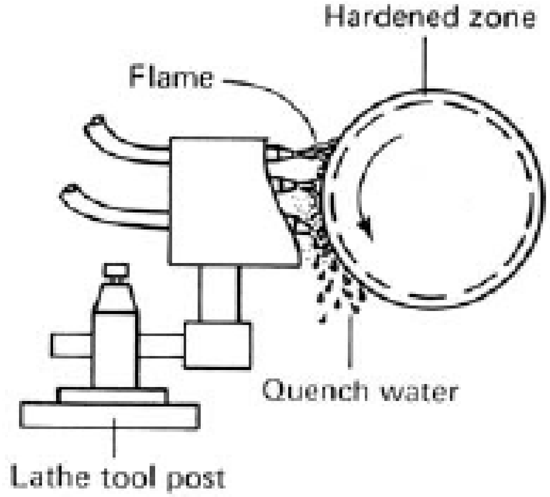
Reasons for Case Hardening

- Easy control of depth (good for quality control)
- Works well for complicated parts
- Cheap – lends itself to mass production
- Low carbon steel starting material –cheaper
- Tougher structure than with medium or high C

Flame hardening plates and rounds

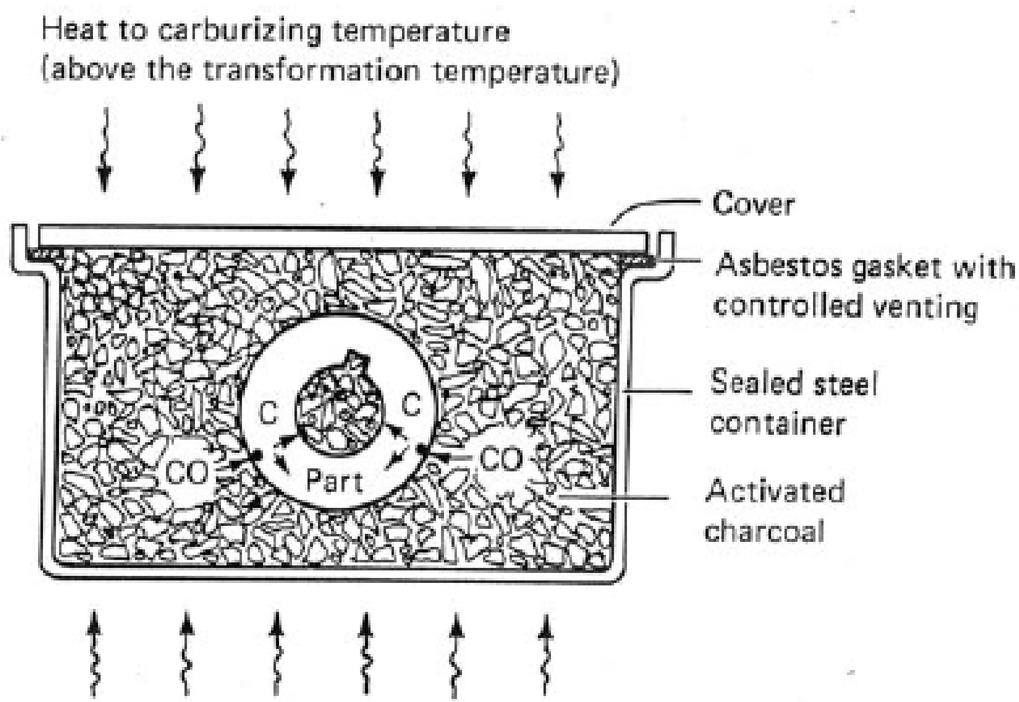


Flame hardening of flat plates



Flame hardening round bars in a lathe

Pack carburizing



- **Carburizing gas mixtures are CO, CO_2, H_2, H_2O and carrier gas N_2**
- **Reactions during carburizing:**

$CH_4 + CO_2 = 2CO + 2H_2$

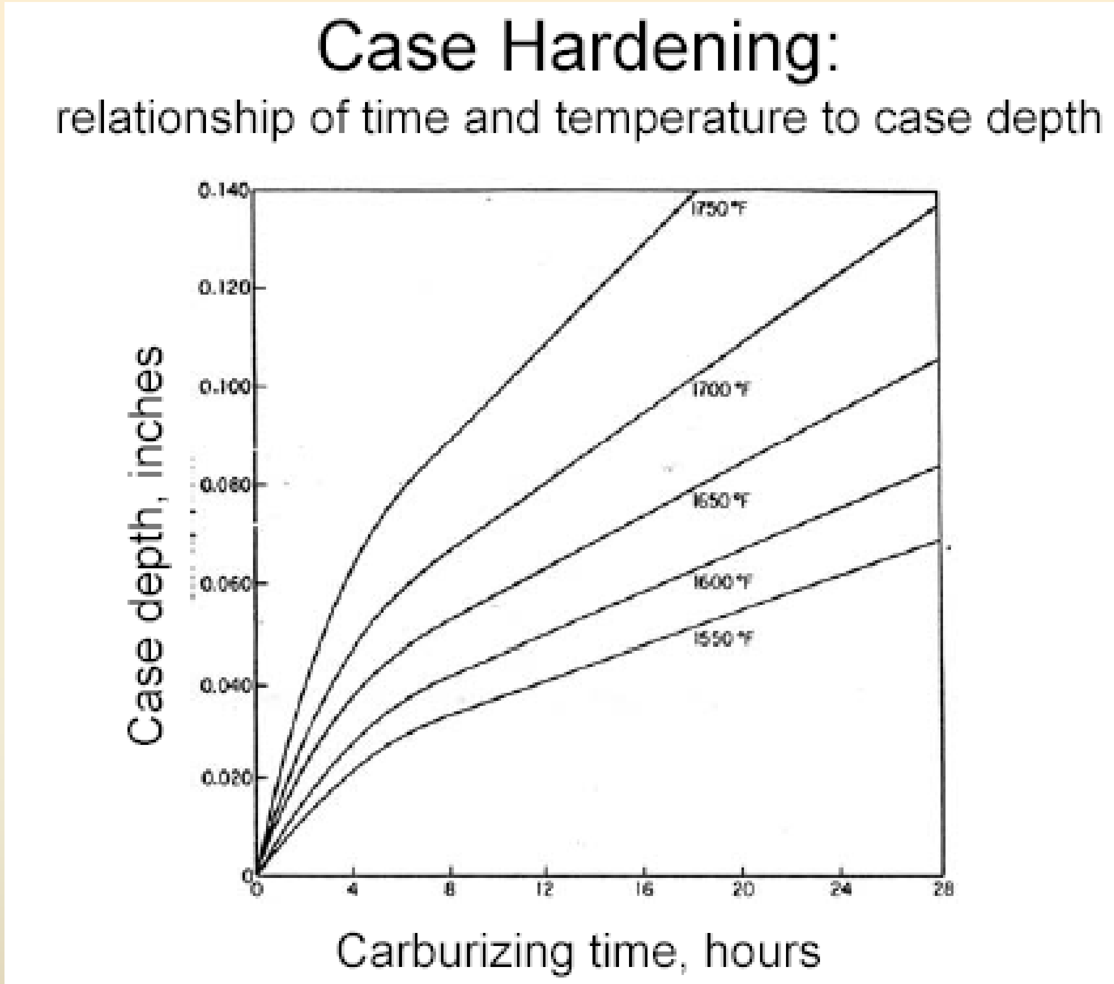
$CH_4 + H_2O = CO + 3H_2$

Natural Gas Produces $CO + H_2$

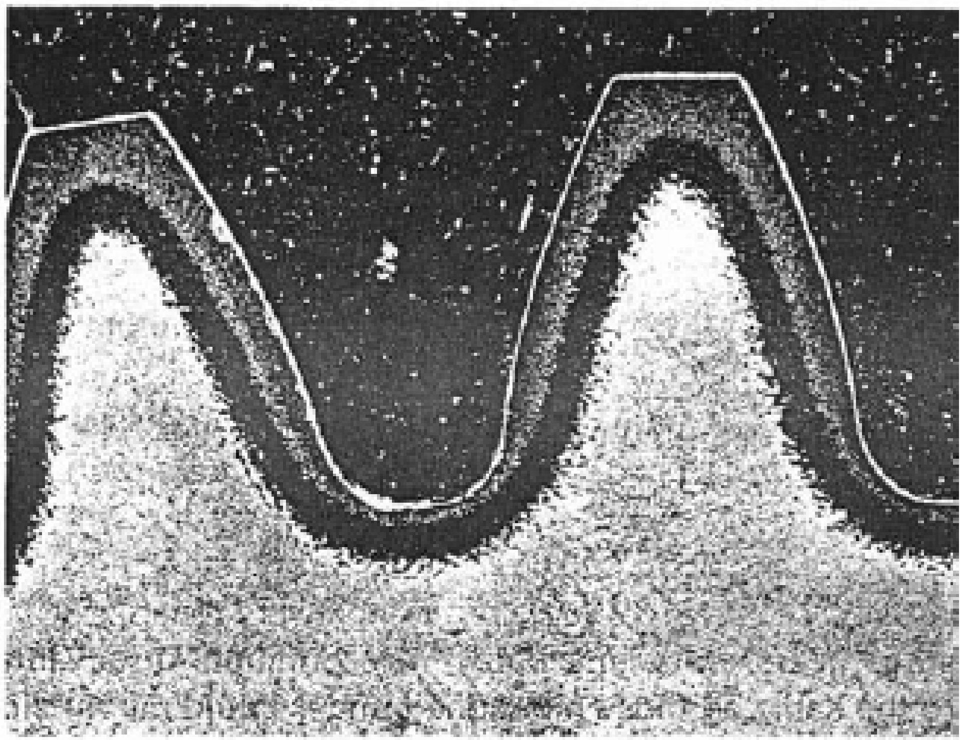
$2CO = C$ (in Fe) $+ CO_2$

$CO + H_2 = C$ (in Fe) $+ H_2O$

- **Control $CO/CO_2 + H_2/H_20$ ratio to carburize or decarburize (or neutral conditions)**


Case Hardening:
relationship of time and temperature to case depth
Case depth, inches
Carburizing time, hours
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0
0
4
8
12
16
20
24
28
1750 °F
1700 °F
1650 °F
1600 °F
1550 °F

Properly carburized gear teet



Case Hardening - Nitriding

- Base: Special steels with strong nitride forming elements Al, Cr, Mo, V (4140 ^{O}K)
- Quench and temper part (temper to 650°C)
- Heat and hold in atmosphere of atomic nitrogen, i.e. 500-600°C for 1-100 hrs.
- N dissolves in á to form nitrides
- Very thin layer – diffusion is slow at these low temperatures
- Slow cool – therefore no distortion from cooling or phase transformation
- Cases are harder than carburized cases
- Excellent wear resistance and fatigue resistance

	Heat treatment	Case hardening
%C	0.4-0.6	0.2
Austenized	surface	all
Speed of procedure	Fast (secs)	Slow (~10hrs)
Surface chemistry	No change	0.8-1.0%C (or N)
Depth	1-10mm	0.5-2mm
Surface hardness	R_c 57-60	R_c 65
Microstructure	martensite (may be through part)	surface martensite; centre pearlite
Control	difficult	easy
Residual stress	Surface compressive	Surface compressive
Core toughness	Medium (high C)	Good (low C)
Cost		Cheap $/part

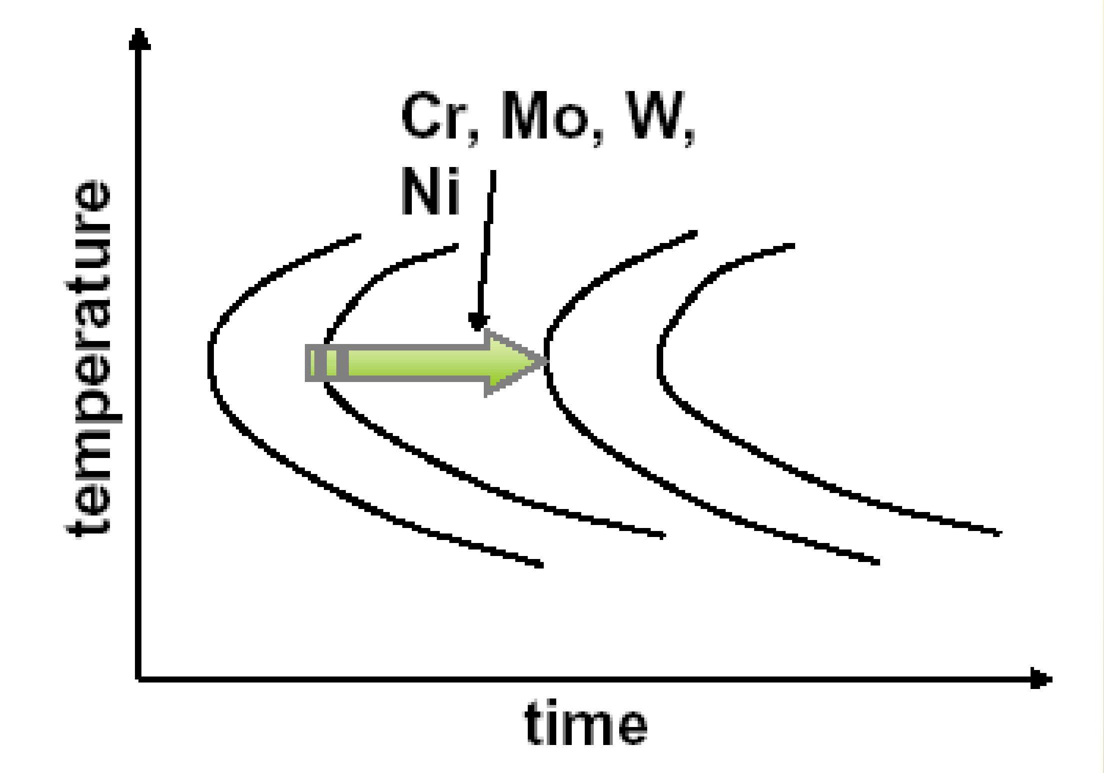
21

Hardenability

- Relative ability of a steel to be hardened in depth by quenching.
- Depends on :

1. Alloy composition : Cr, Ni, V, Mo → increase hardenability
2. Austenite grain size

- Hardenability of a steel increases with an addition of alloying elements such as Cr, Mo, Ni, W, → C
- Curve moves to the right direction in the TTT diagram.


Cr, Mo, W,
Ni
temperature
time

Hardenability of Steels

"it is the property which determines the depth of the hardened zone on the material induced during hardening process (quenching)"

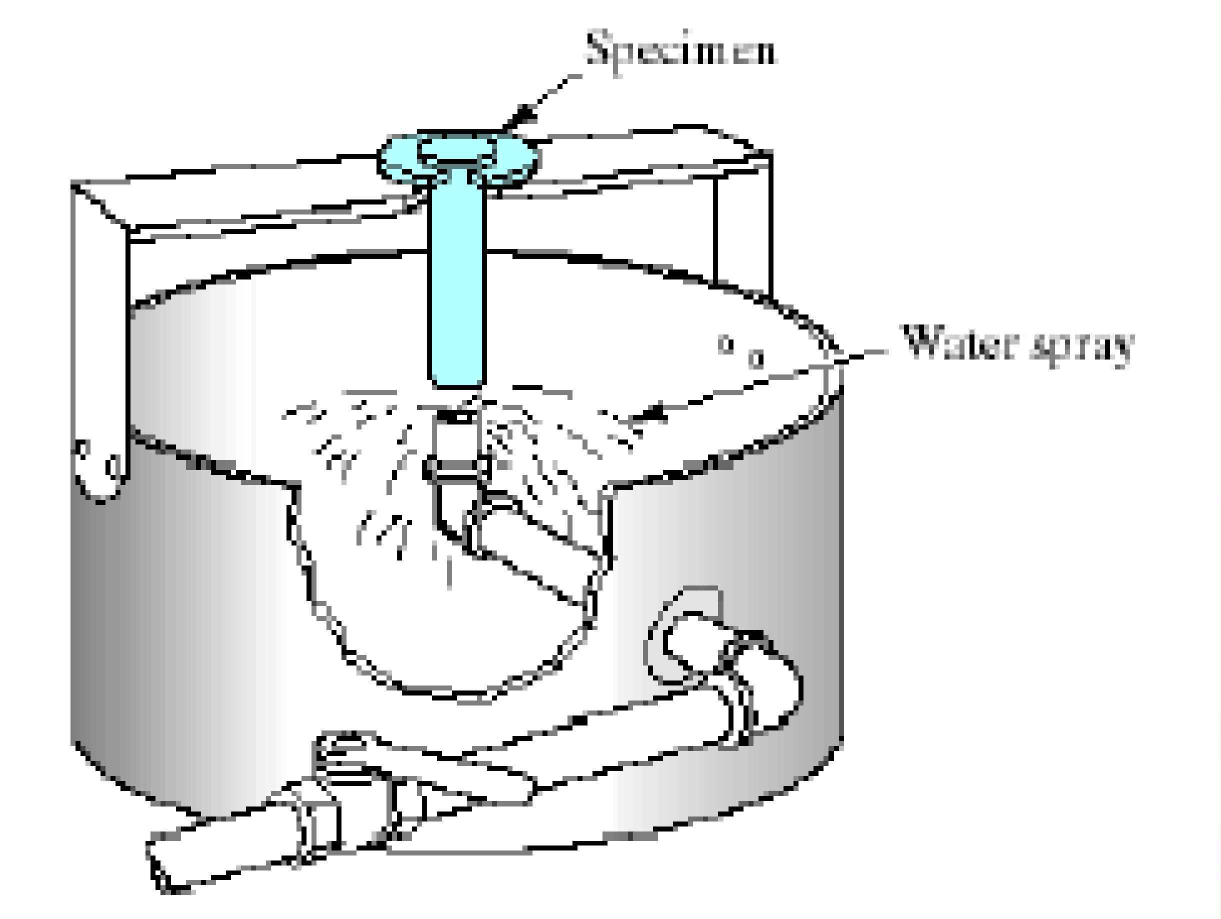
- **Hardening depth depends upon the cooling rate, which should be more than the critical cooling rate**
- **Cooling rate is not same for the entire c/s of the material (higher at s/f and lower at core). If cooling rate at core is less than the critical cooling rate, then only s/f will be hardened and core will still remain soft (core will consists essentially of troosite, sorbite and pearlite inspite of martensite**
- **Hardenability is determined by following ways:**
  - ***(a). Appearance of fracture***
  - ***(b). Distribution of hardness along c/s area***
  - ***(c). Jominy End-Quench Test***

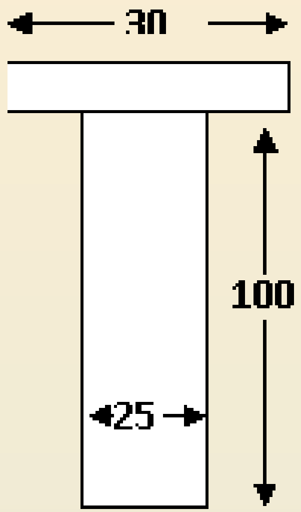
Jominy End Quench Test

- **Measures the hardenability of a steel**
- **Specimen : 25 dia X 100 mm dia. long steel bar**
- **Procedure**

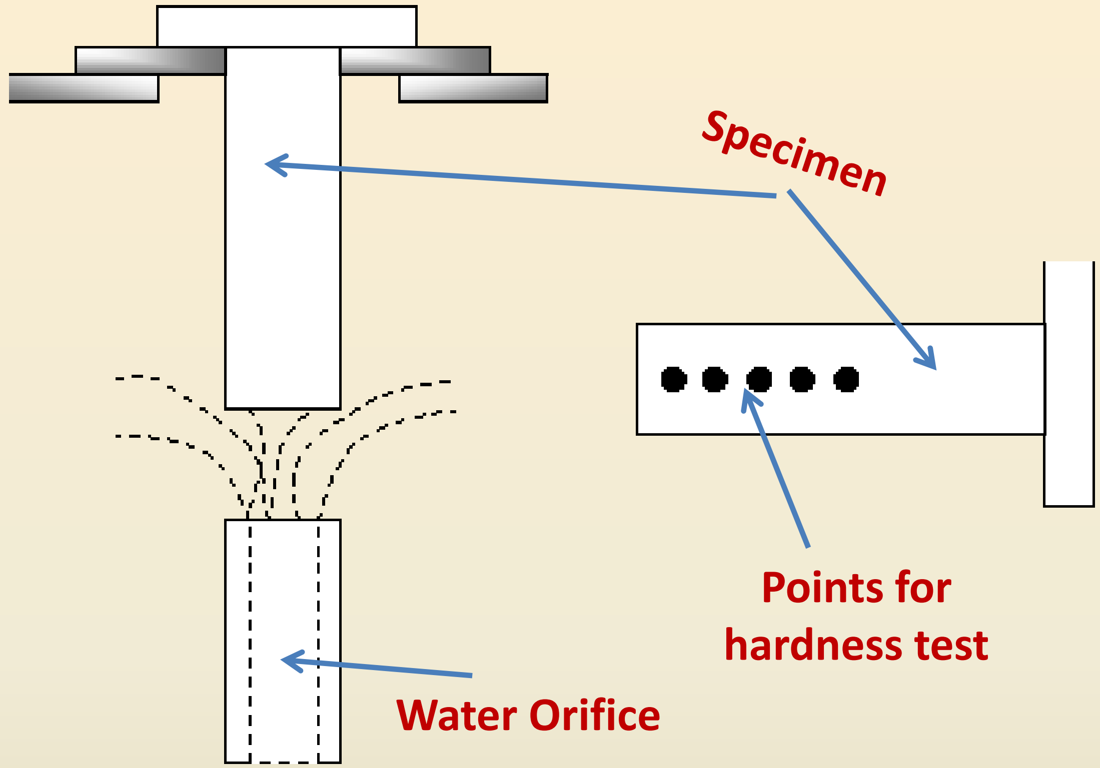
➢ **The cylindrical specimen with fixed dimensions is heated to a specified temperature and then quenched from one end in a special fixture as shown in the figure**

➢ **Hardness values are measured along the length of the bar and expressed in terms of 'Hardenability Number (L*C)', where, 'L' is the distance from the quenched end to the point with a semi-martensite structure (50% martensite) and 'C' is the hardness value on Rockwell Hardness Tester**

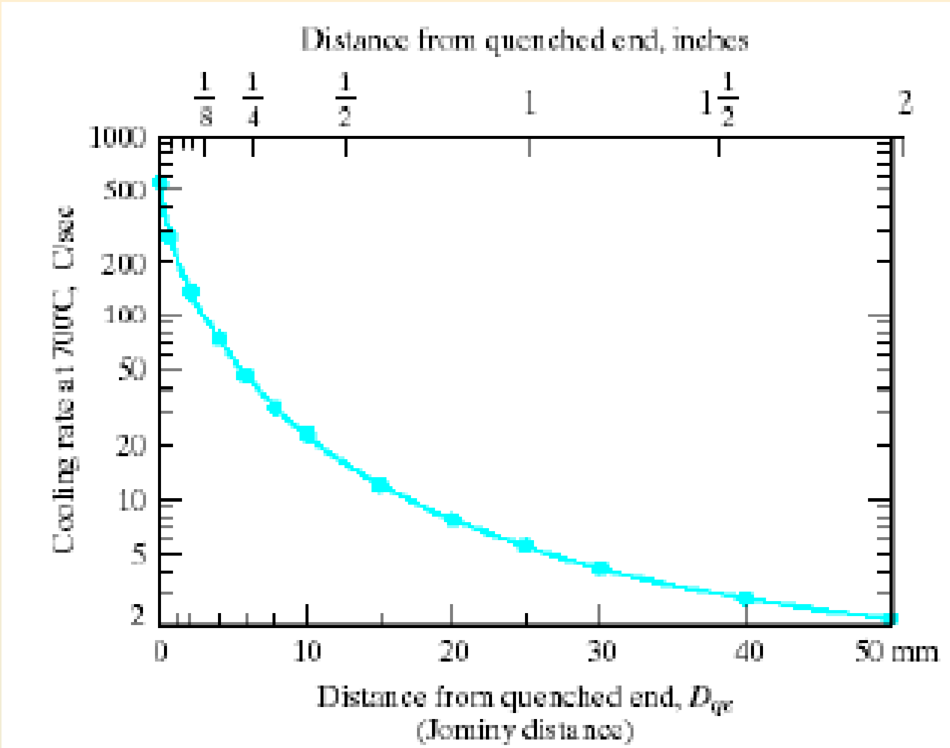

Specimen
Water spray

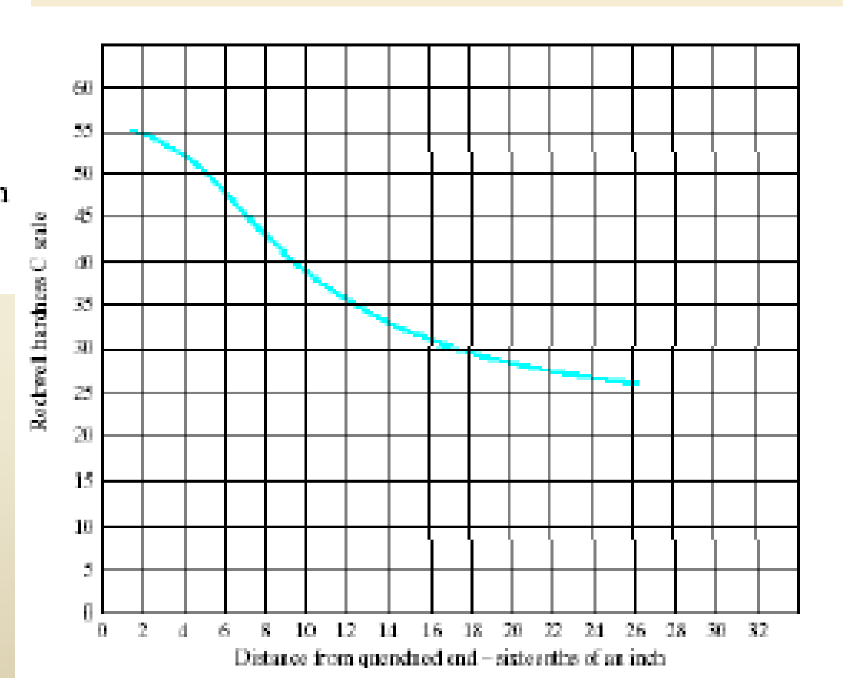


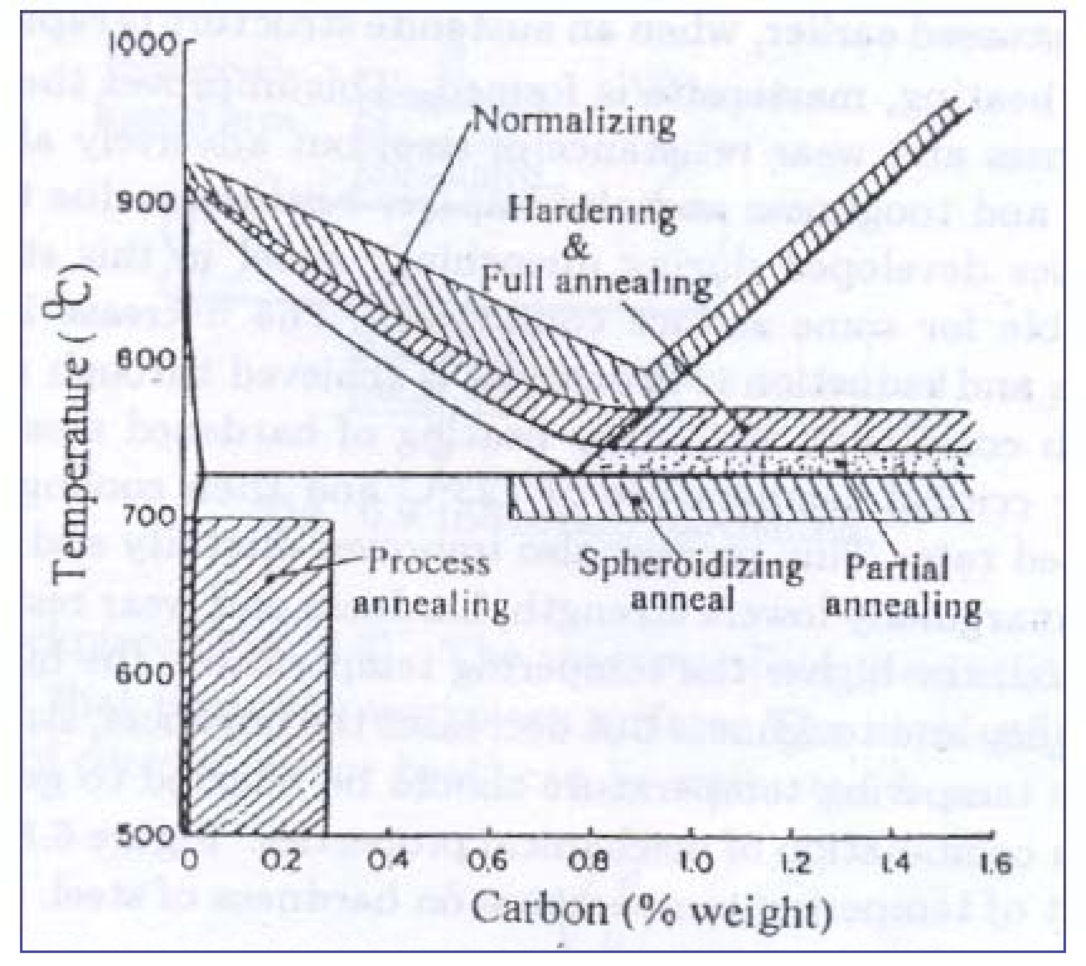
JOMINY TEST SAMPLE



JOMINY HARDNESS TEST


Distance from quenched end, inches
1/8 1/4 1/2 1 1 1/2 2
1000 500 200 100 50 20 10 5 2
Cooling rate at 700C, C/sec
0 10 20 30 40 50 mm
Distance from quenched end, D_{qe}
(Jominy distance)


Rockwell hardness C scale
60 55 50 45 40 35 30 25 20 15 10 5 0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Distance from quenched end – sixteenths of an inch



Heat treatment on phase diagrams of the steels