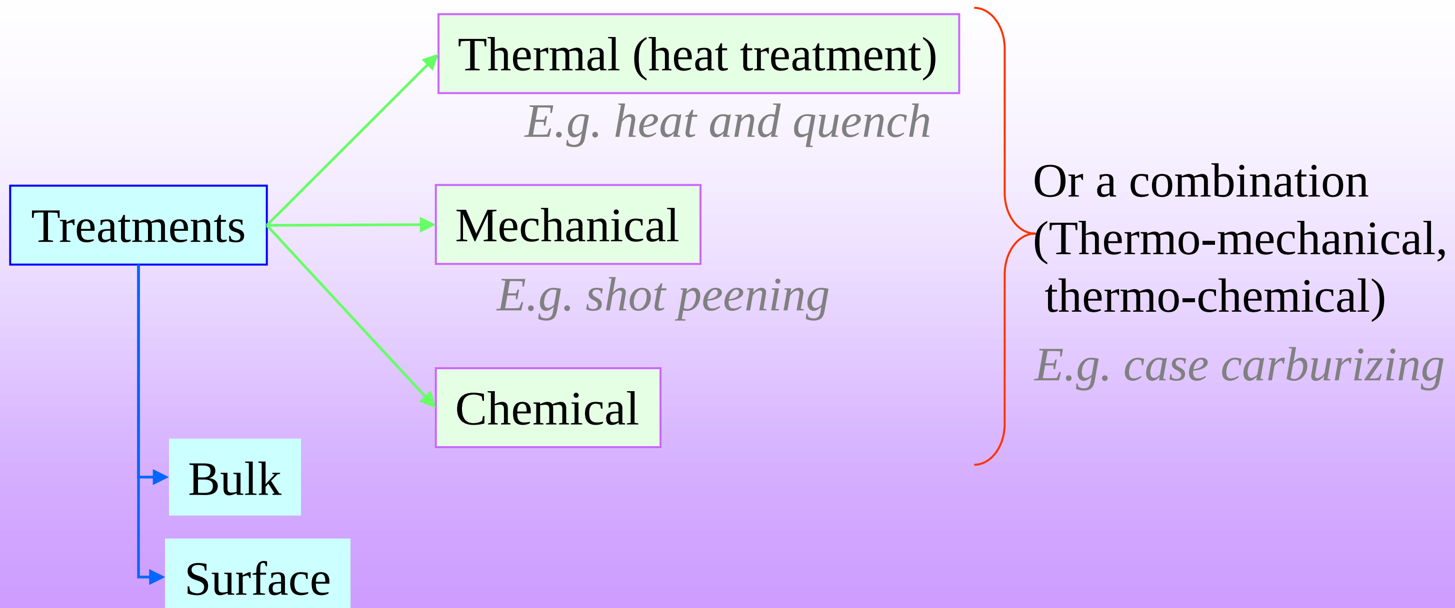
HEAT TREATMENT

- Bulk and Surface Treatments
- Annealing, Normalizing, Hardening, Tempering
- Hardenability

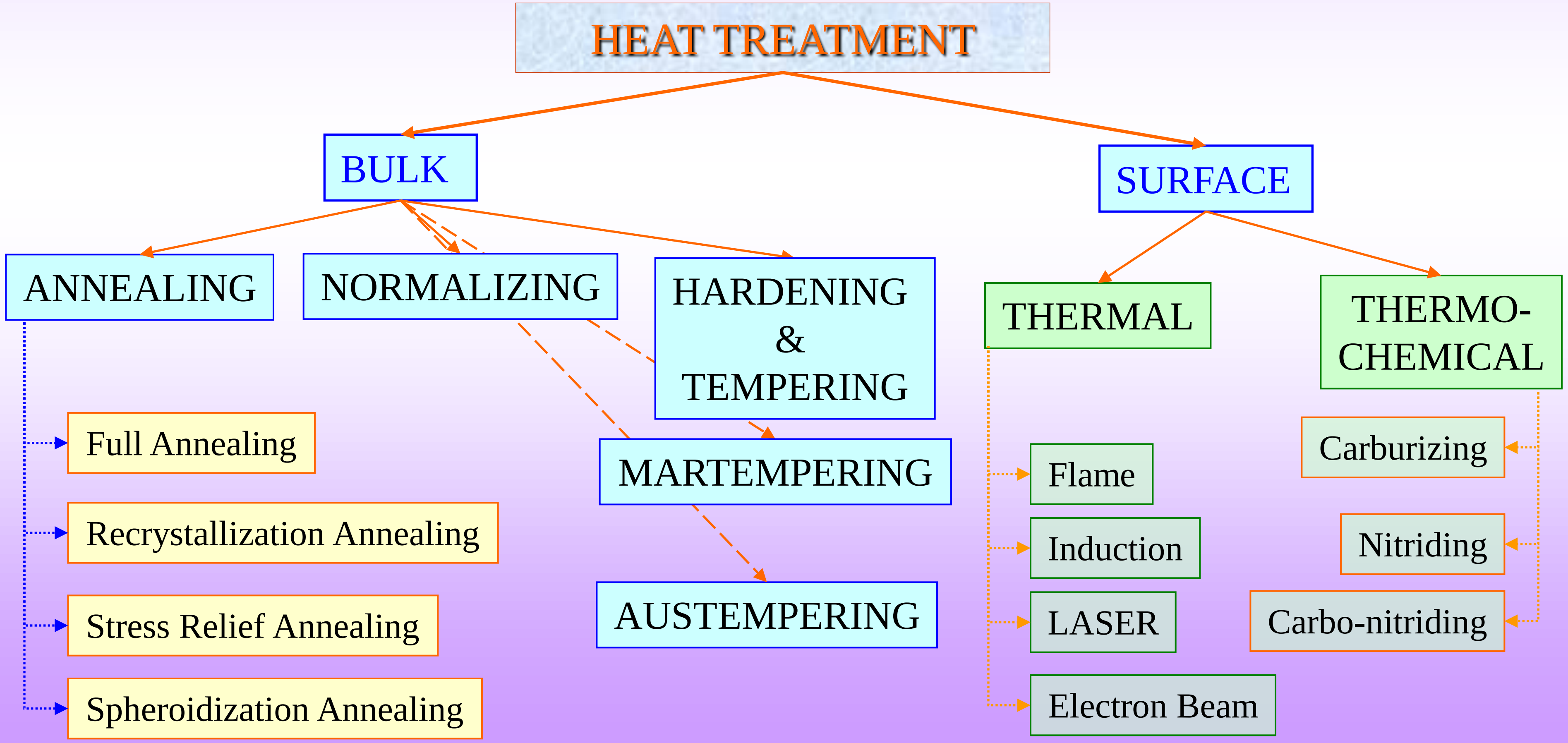
Heat Treatment of Steels

- We have noted that how TTT and CCT diagrams can help us design heat treatments to design the microstructure of steels and hence engineer the properties. In some cases a gradation in properties may be desired (usually from the surface to the interior- a hard surface with a ductile/tough interior/bulk).
- In general three kinds of treatments are: (i) Thermal (heat treatment), (ii) Mechanical (working), (iii) Chemical (alteration of composition). A combination of these treatments are also possible (e.g. thermo-mechanical treatments, thermo-chemical treatments).
- The treatment may affect the whole sample or only the surface.
- A typical industrial treatment cycle may be complicated with many steps (i.e. a combination of the simple steps which are outlined in the chapter).

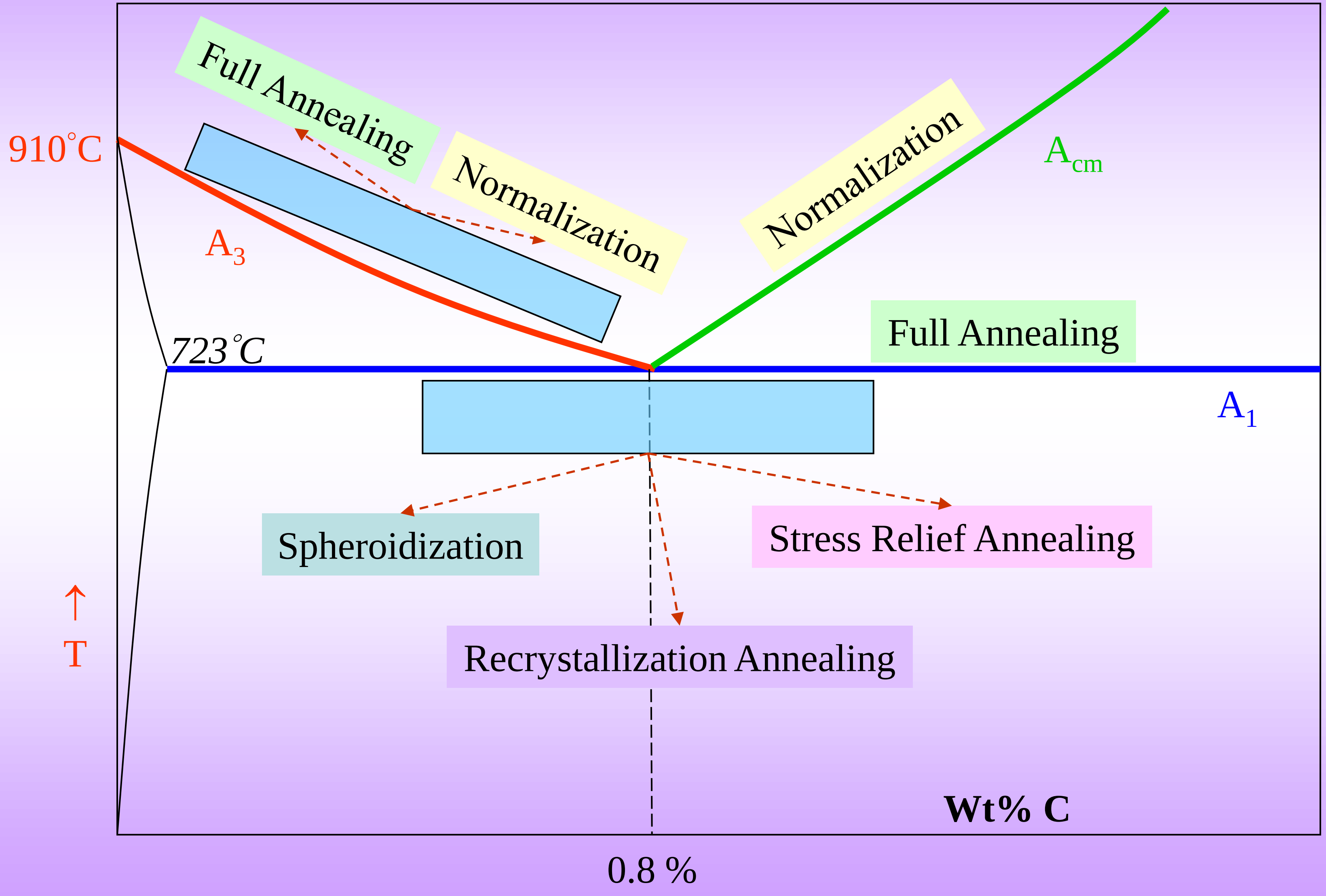


An overview of important heat treatments

- A broad classification of heat treatments possible are given below. Many more specialized treatments or combinations of these are possible.

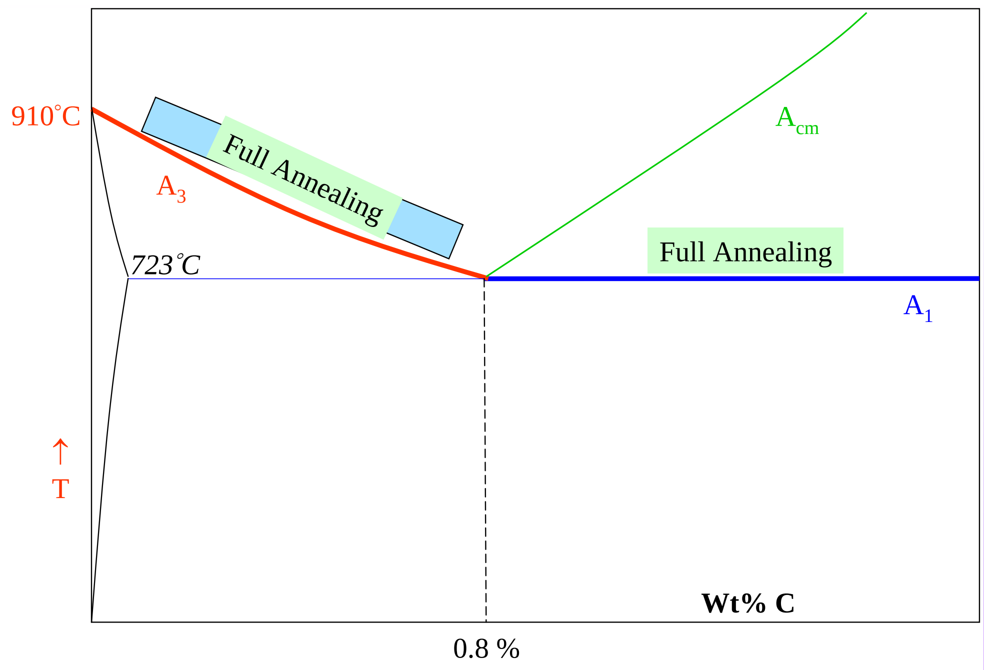


- Ranges of temperature where Annealing, Normalizing and Spheroidization treatment are carried out for hypo- and hyper-eutectoid steels.
- Details are in the coming slides.



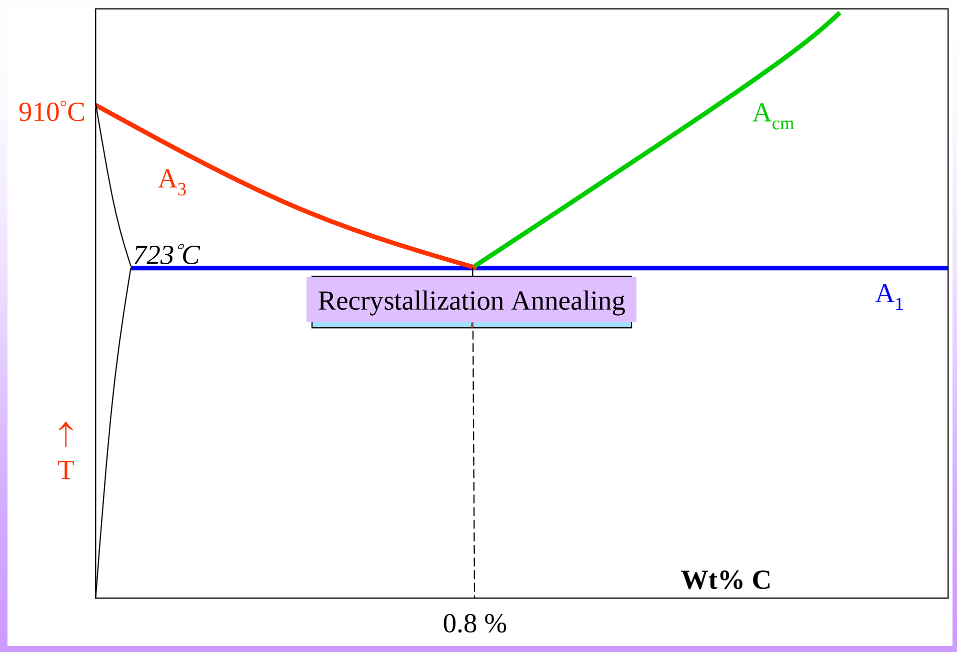
Full Annealing

- The purpose of this heat treatment is to obtain a material with high ductility. A microstructure with coarse pearlite (i.e. pearlite having high interlamellar spacing) is endowed with such properties.
- The range of temperatures used is given in the figure below.
- The steel is heated above A_3 (for hypo-eutectoid steels) & A_1 (for hyper-eutectoid steels) → (hold) → then the steel is furnace cooled to obtain Coarse Pearlite.
- Coarse Pearlite has low (↓) Hardness but high (↑) Ductility.
- For hyper-eutectoid steels the heating is not done above A_{cm} to avoid a continuous network of proeutectoid cementite along prior Austenite grain boundaries (presence of cementite along grain boundaries provides easy path for crack propagation).



Recrystallization Annealing

- During any cold working operation (say cold rolling), the material becomes harder (due to work hardening), but loses its ductility. This implies that to continue deformation the material needs to be recrystallized (wherein strain free grains replace the 'cold worked grains').
- Hence, recrystallization annealing is used as an intermediate step in (cold) deformation processing.
- To achieve this the sample is heated below A_1 and held there for sufficient time for recrystallization to be completed.

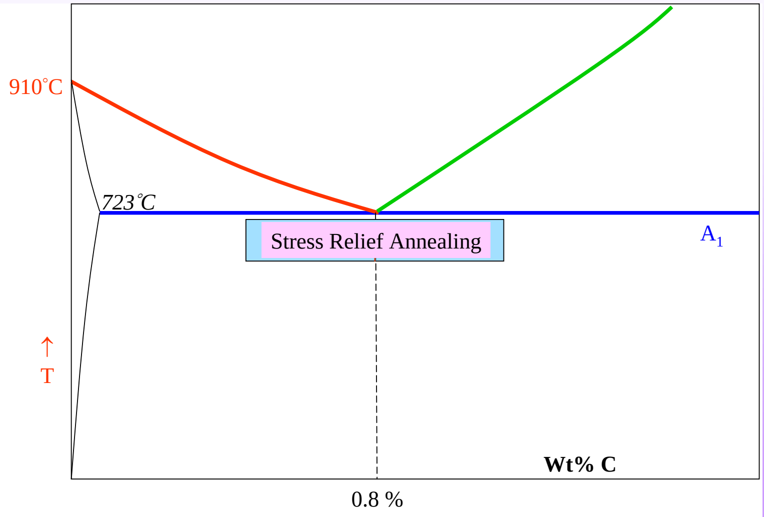


Stress Relief Annealing

- Due to various processes like quenching (differential cooling of surface and interior), machining, phase transformations (like martensitic transformation), welding, etc. the residual stresses develop in the sample. Residual stress can lead to undesirable effects like warpage of the component.
- The annealing is carried out just below A_1 , wherein 'recovery*' processes are active (Annihilation of dislocations, polygonization).

Residual stresses → Heat below A_1 → Recovery → Annihilation of dislocations, polygonization

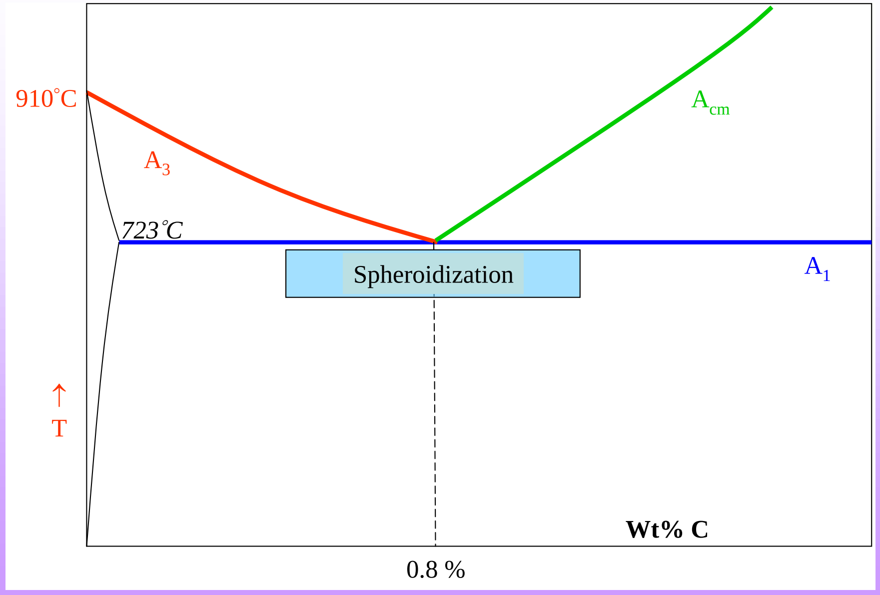
- Differential cooling
- Machining and cold working
- Martensite formation
- Welding



* *It is to be noted that 'recovery' is a technical term.*

Spheroidization Annealing

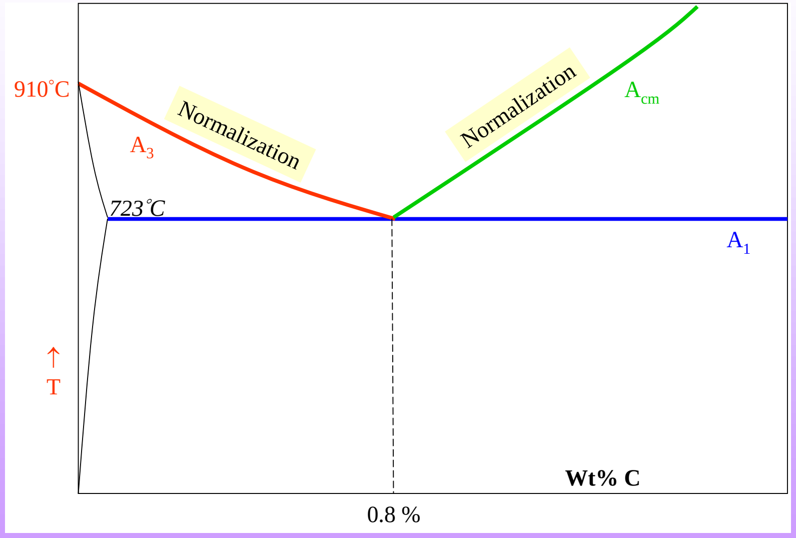
- This is a very specific heat treatment given to high carbon steel requiring extensive machining prior to final hardening & tempering. The main purpose of the treatment is to increase the ductility of the sample.
- Like stress relief annealing the treatment is done just below A_1.
- Long time heating leads cementite plates to form cementite spheroids. The driving force for this (microstructural) transformation is the reduction in interfacial energy.



NORMALIZING

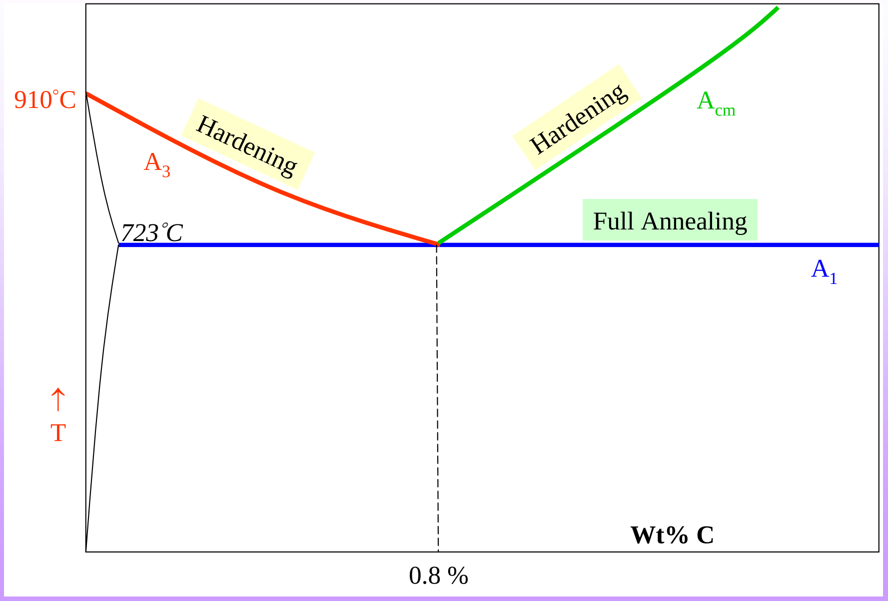
- The sample is heat above A_3 | A_{cm} to complete Austenization. The sample is then air cooled to obtain Fine pearlite. Fine pearlite has a reasonably good hardness and ductility.
- In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature.
- In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB.
- The list of uses of normalizing are listed below.

Purposes
- Refine grain structure prior to hardening
- To harden the steel slightly
- To reduce segregation in casting or forgings



HARDENING

- The sample is heated above A_3 | A_{cm} to cause Austenization. The sample is then quenched at a cooling rate higher than the critical cooling rate (i.e. to avoid the nose of the CCT diagram).
- The quenching process produces residual strains (thermal, phase transformation).
- The transformation to Martensite is usually not complete and the sample will have some retained Austenite.
- The Martensite produced is hard and brittle and tempering operation usually follows hardening. This gives a good combination of strength and toughness.



Severity of quench values of some typical quenching conditions

- Before we proceed further we note that we have a variety of quenching media at our disposal, with varying degrees of cooling effect. The severity of quench is indicated by the 'H' factor (defined below), with an ideal quench having a H-value of ∞.

Severity of Quench as indicated by the heat transfer equivalent H

$$H = \frac{f}{K} \qquad [m^{-1}]$$

f → heat transfer factor

K → Thermal conductivity

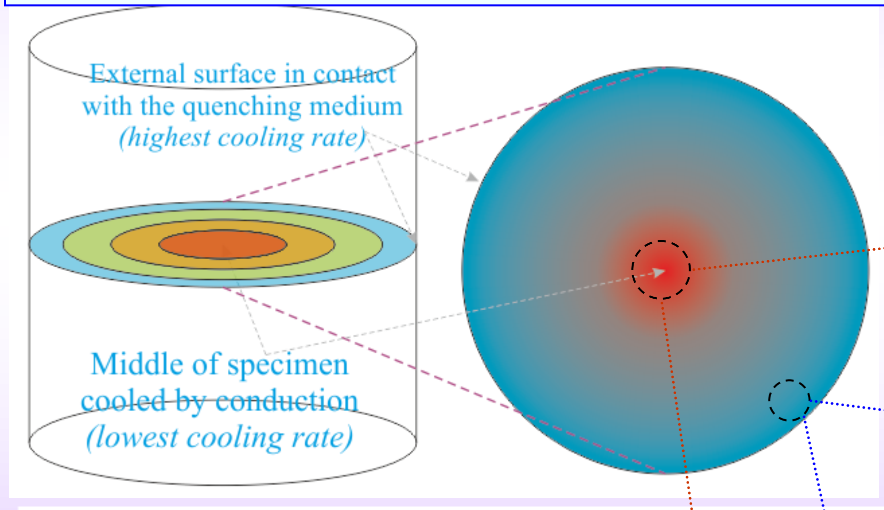
Process	Variable	H
Air	No agitation	0.02
Oil quench	No agitation	0.2
"	Slight agitation	0.35
"	Good agitation	0.5
"	Vigorous agitation	0.7
Water quench	No agitation	1.0
"	Vigorous agitation	1.5
Brine quench (saturated Salt water)	No agitation	2.0
"	Vigorous agitation	5.0
Ideal quench		∞

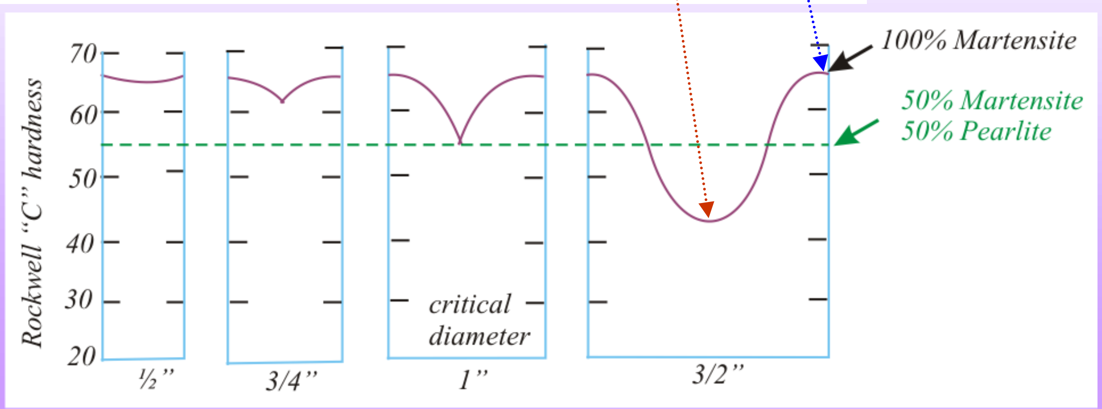
Increasing severity of quench ↓

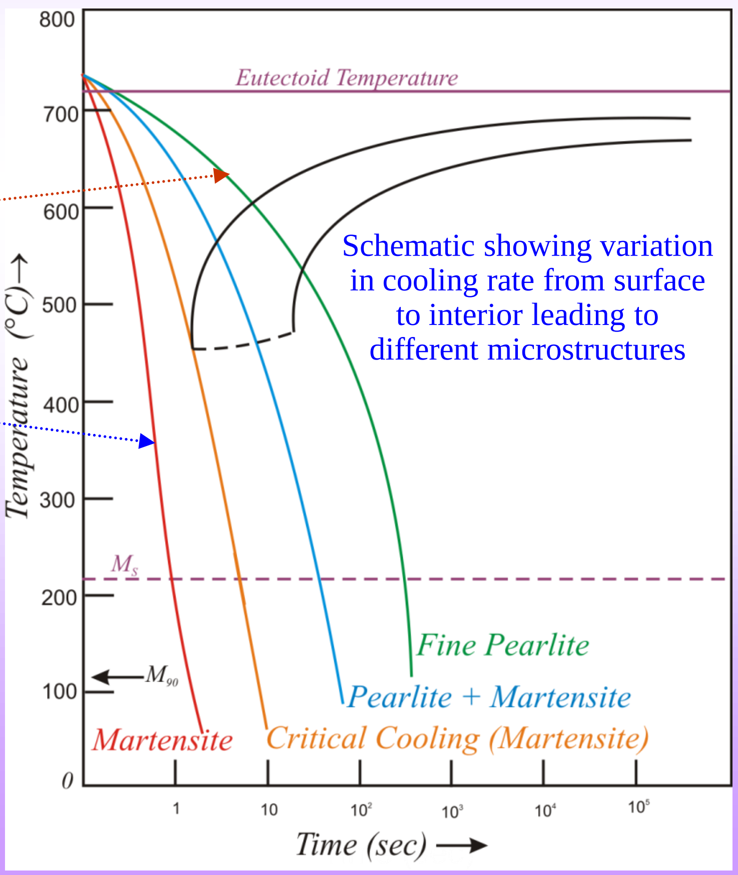
Note that apart from the nature of the quenching medium, the vigorousness of the shake determines the severity of the quench. When a hot solid is put into a liquid medium, gas bubbles form on the surface of the solid (interface with medium). As gas has a poor conductivity the quenching rate is reduced. Providing agitation (shaking the solid in the liquid) helps in bringing the liquid medium in direct contact with the solid; thus improving the heat transfer (and the cooling rate). The H value/index compares the relative ability of various media (gases and liquids) to cool a hot solid. Ideal quench is a conceptual idea with a heat transfer factor of ∞ (⇒ H = ∞).

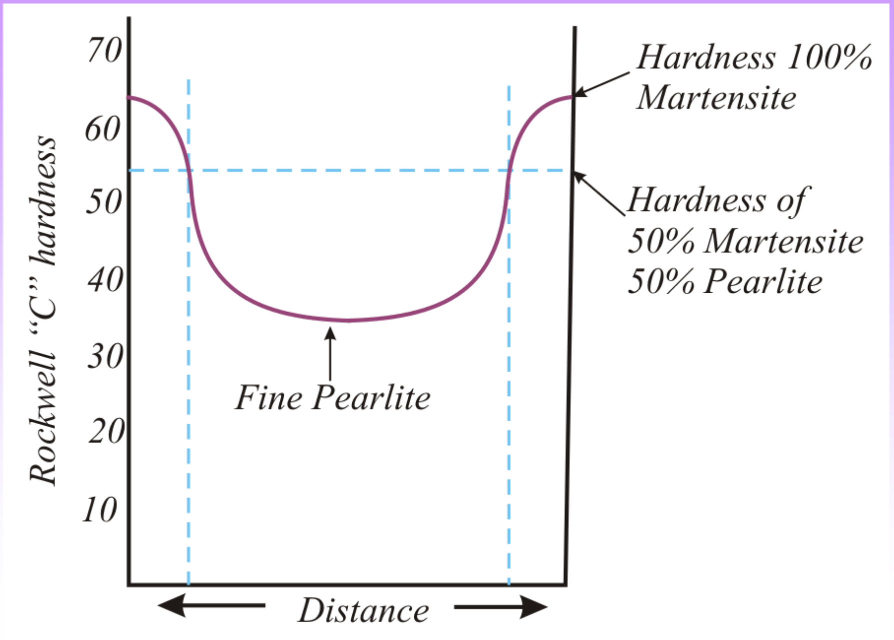
Through hardening of the sample

- The surface of is affected by the quenching medium and experiences the best possible cooling rate. The interior of the sample is cooled by conduction through the (hot) sample and hence experiences a lower cooling rate. This implies that different parts of the same sample follow different cooling curves on a CCT diagram and give rise to different microstructures.
- This gives to a varying hardness from centre to circumference. Critical diameter (d_c) is that diameter, which can be through hardened (i.e. we obtain 50% Martensite and 50% pearlite at the centre of the sample).



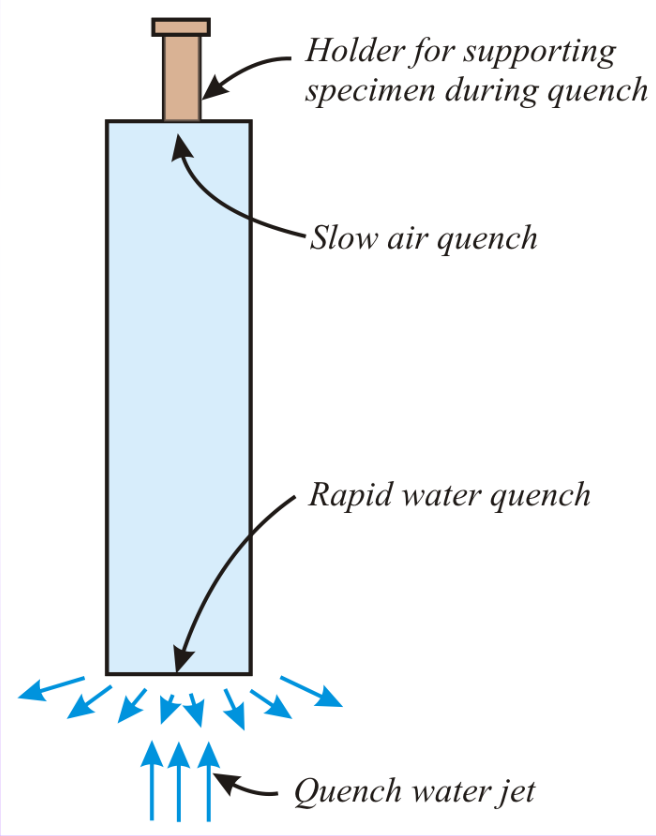


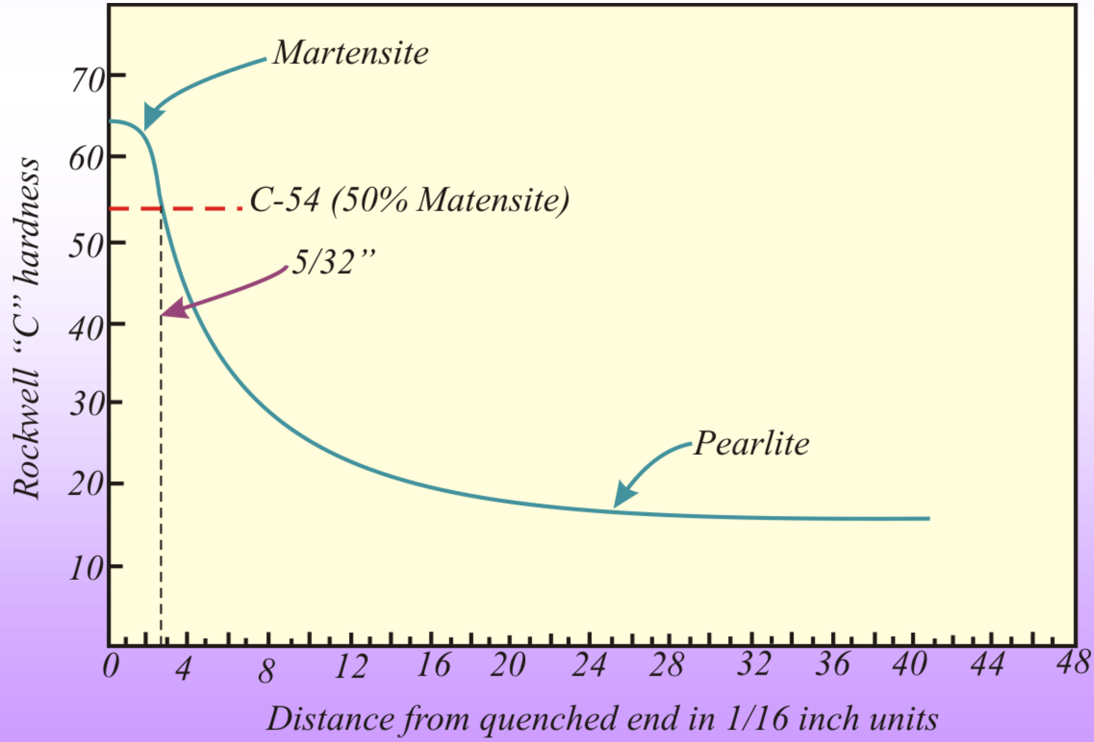




Typical hardness test survey made along a diameter of a quenched cylinder

Schematic of Jominy End Quench Test





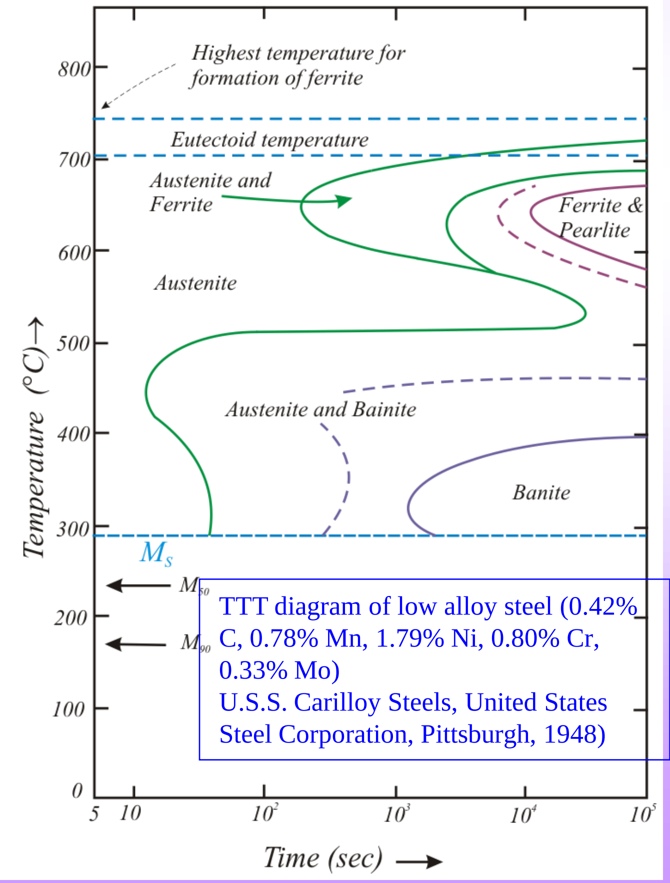
3. Grossman, M. A., *Elements of Hardenability*, ASM, Cleveland, 1952.

Q & A

How to increase hardenability?

- Hardenability should not be confused with the ability to obtain high hardness. A material with low hardenability may have a higher surface hardness compared to another sample with higher hardenability.
- A material with a high hardenability can be cooled relatively slowly to produce 50% martensite (& 50% pearlite). A material with a high hardenability has the 'nose' of the CCT curve 'far' to the right (i.e. at higher times). Such a material can be through hardened easily.

- Hardenability of plain carbon steel can increased by alloying with most elements (it is to be noted that this is an added advantage as alloying is usually done to improve other properties).
- However, alloying gives two separate 'C-curves' for Pearlitic and Bainitic transformations (e.g. figure to the right).
- This implies that the 'nose' of the Bainitic transformation has to be avoided to get complete Martensite on quenching.



TTT diagram of low alloy steel (0.42% C, 0.78% Mn, 1.79% Ni, 0.80% Cr, 0.33% Mo)
U.S.S. Carilloy Steels, United States Steel Corporation, Pittsburgh, 1948)

Tempering

$$\underset{Martensite}{\alpha'(BCT)} \xrightarrow{Temper} \underset{Ferrite}{\alpha(BCC)} + \underset{Cementite}{Fe_3C(OR)}$$

- A sample with martensitic microstructure is hard but brittle. Hence after quenching the sample (or component) is tempered. Maternsite being a metastable phase decomposes to ferrite and cementite on heating (providing thermal activation).
- Tempering is carried out just below the eutectoid temperature (heat → wait→ slow cool).
- In reality the microstructural changes which take place during tempering are very complex.
- The time temperature cycle for tempering is chosen so as to optimize strength and toughness. E.g. tool steel has a as quenched hardness of R_c65, which is tempered to get a hardness of R_c45-55.

MARTEMPERING & AUSTEMPERING

- These processes have been developed to avoid residual stresses generated during quenching.
- In both these processes Austenized steel is quenched above M_s (say to a temperature T_1) for homogenization of temperature across the sample.
- In Martempering the steel is then quenched and the entire sample transforms simultaneously to martensite. This is followed by tempering.
- In Austempering instead of quenching the sample, it is held at T_1 for it to transform to bainite.