Heat Treatment

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Heat Treatment

- In the process of forming steel into shape and producing the desired microstructure to achieve the required mechanical properties, it may be reheated and cooled several times.

Steps for all HT (anneals):

1. Heating
2. Holding or “soaking”
3. Cooling

Time and temperature are important at all 3 steps

Heat Treatment

- An operation, or series of operations, involving the heating and cooling of steel in the solid state to develop the required properties.
- Related to the crystalline structure of carbon and iron.

Heat Treatment

- Low carbon steels are generally used as rolled and in most cases do not respond well to heat treating
- High carbon steels and alloys use heat treatment as the means of achieving the ultimate property capabilities on the metals

Types

- Stress Relieving
- Normalizing
- Annealing
- Hardening
- Tempering

Stress Relieving

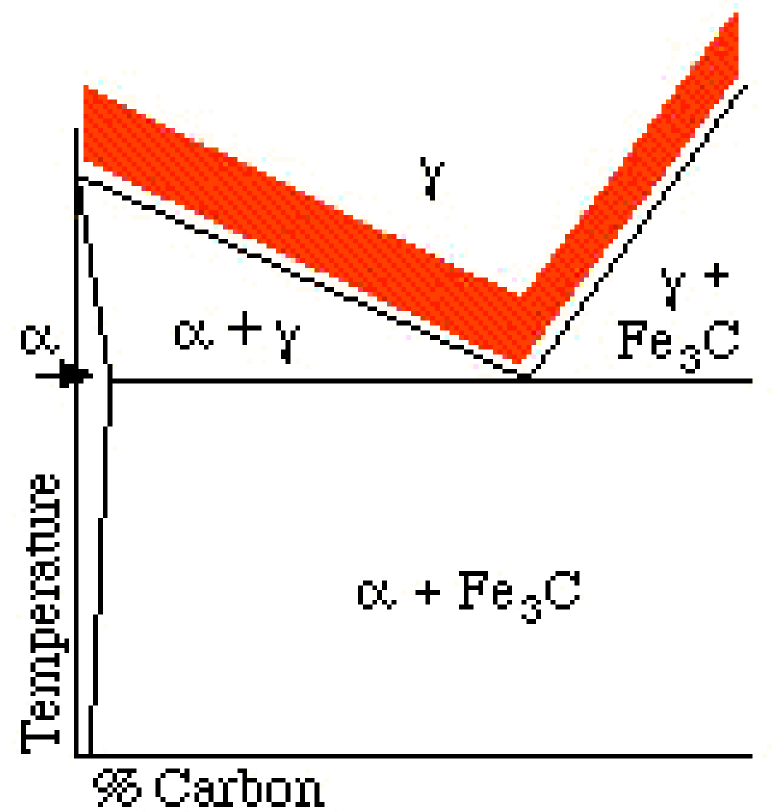
- Reduces internal stresses that may have been caused by machining, cold working or welding.
- Heat the metal to a temperature below the critical range (1100^{o}F)
- Hold until temperature is reached throughout the piece.
- Allow to cool slowly

Normalizing

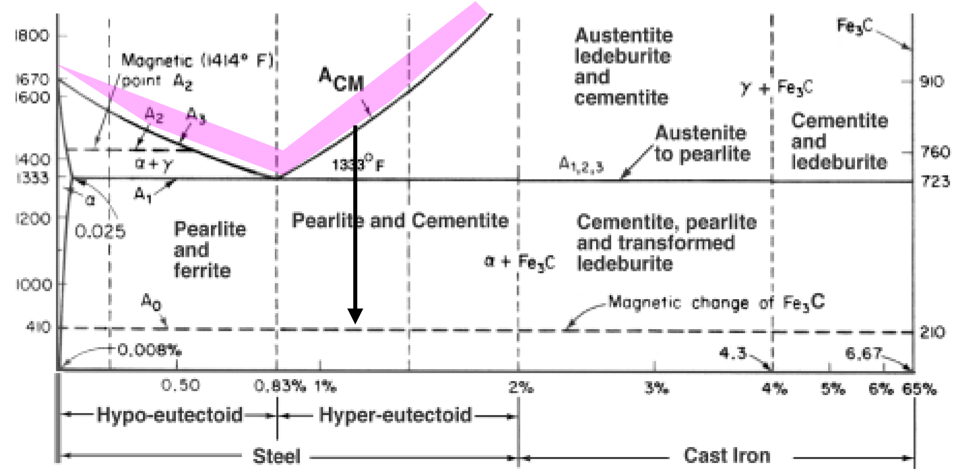
- Promotes uniformity of the structure and alters mechanical properties.
- The steel is heated to a determined temperature above the critical range (1600-1700º F)
- Cooled to below that range in still air.
- Molecular structure changes
- Results in higher strength, hardness, and less ductility
- Cools faster than stress relieving or annealing

Normalizing

- Allows steels to cool more rapidly, in air
- Produced structure – fine pearlite
- Faster cooling provides higher strength than at full annealing



Normalizing



- Procedure
  - Heat to above the A_3
  - Held at this temperature
  - Remove from furnace and allowed to cool in still air
- Different of Full annealing with normalizing
  - Full annealing cooling at all locations but
  - Normalizing: the cooling will be different at different locations.

Annealing

- May be used for the following:
  - To soften steel
  - To develop a structure like lamellar pearlite or spheroidized carbide.
  - To improve machinability or facilitate cold shaping
  - To prepare the steel for additional heat treatment

Annealing cont.

- to reduce stress
- to improve or restore ductility
- to modify other properties

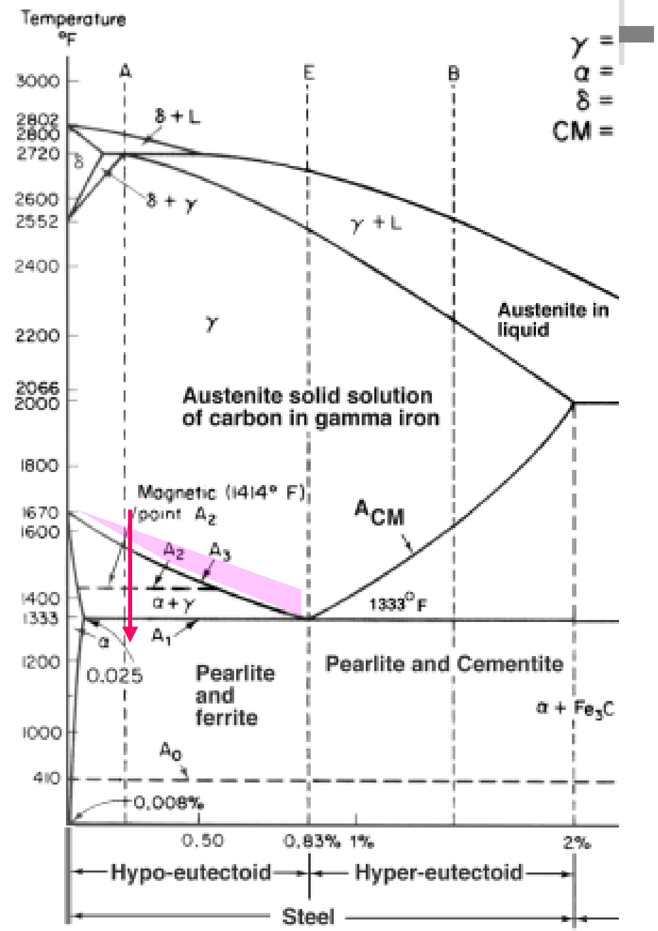
- Steel is heated to a point at or near the critical range (1600-1700ºF)
- Cooled slowly at a predetermined rate.

Full Annealing

- heats the steel to a temperature within the austenite (FCC, γ) phase region to dissolve the carbon. (50 deg.F above A_3-A_{cm} line)
- The temperature is kept at the bottom of this range to minimize growth of the austenitic grains. Then, after cooling ferrite (α) and cementite structures will be fine as well

Full annealing: hypoeutectoid steels (less than 0.77% carbon)

- Heat to above the A_3
- Held for sufficient time to convert the structure
- Slowly cooled through the A_1 in furnace
- When all structural change complete, remove and air cooled to room temperature



Resulting microstructure:

- For low-medium carbon steels – coarse pearlite and ferrite
- It is easily machined

Process Stress-relief Annealing

- Heats the steel to just below the eutectoid transformation temperature (A_1) to remove the effects of prior cold work and grain deformation.
- This allows further forging or rolling operations.

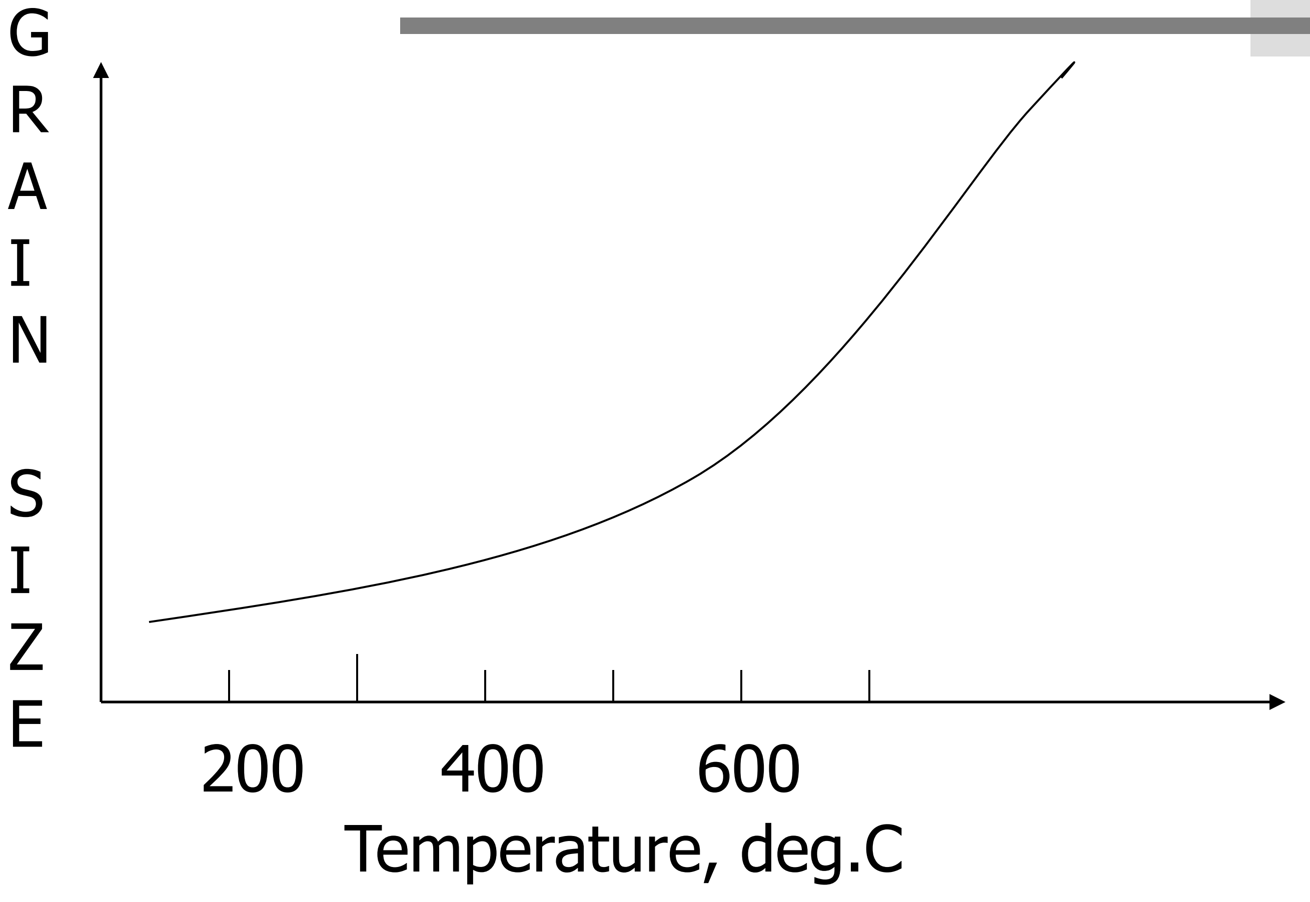
Process Annealing (Recrystallization)

- Add more heat and wait some more time, and new grains start to grow at the grain boundaries.
- The new grains have not been strain hardened
- The recrystallized metal is ductile and has low strength

Process Annealing (Grain Growth)

- If you keep the metal hot too long, or heat it up too much, the grains become large
- Usually not good
- Low strength

Size of grains vs. temperature



Why hyperetectoid steels are annealed intercritically?

- To prevent formation of brittle cementite network on the grain boundaries
- This is undesirable condition if machining is to be done
- Annealing is performed at temperatures between the critical lines $A_{3,1}$-A_{cm}

Spheroidising

1. Heat to just below Lower Critical Temperature. (about 650-700 deg C)
2. Cool very slowly in the furnace.
3. Structure will now be spheroidite, in which the Iron Carbide has ‘balled up’.
4. Used to improve the properties of medium and high carbon steels prior to machining or cold working.

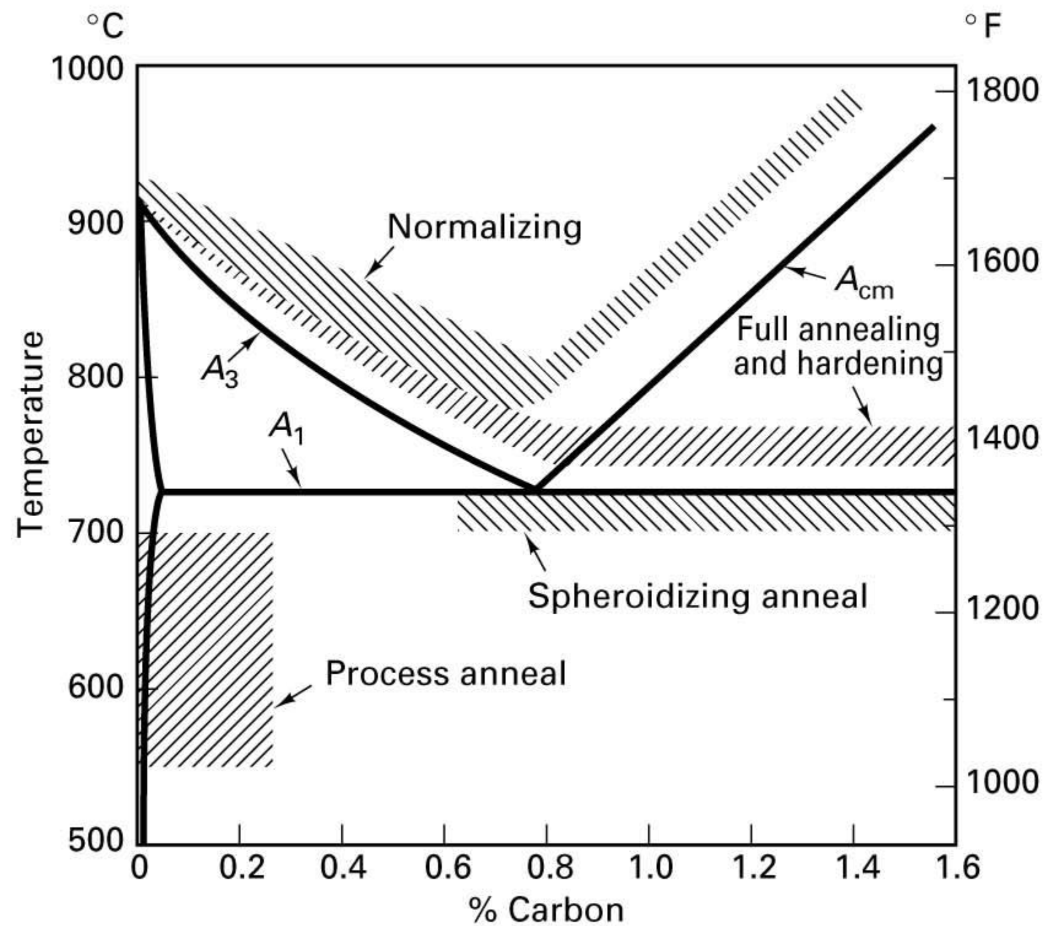
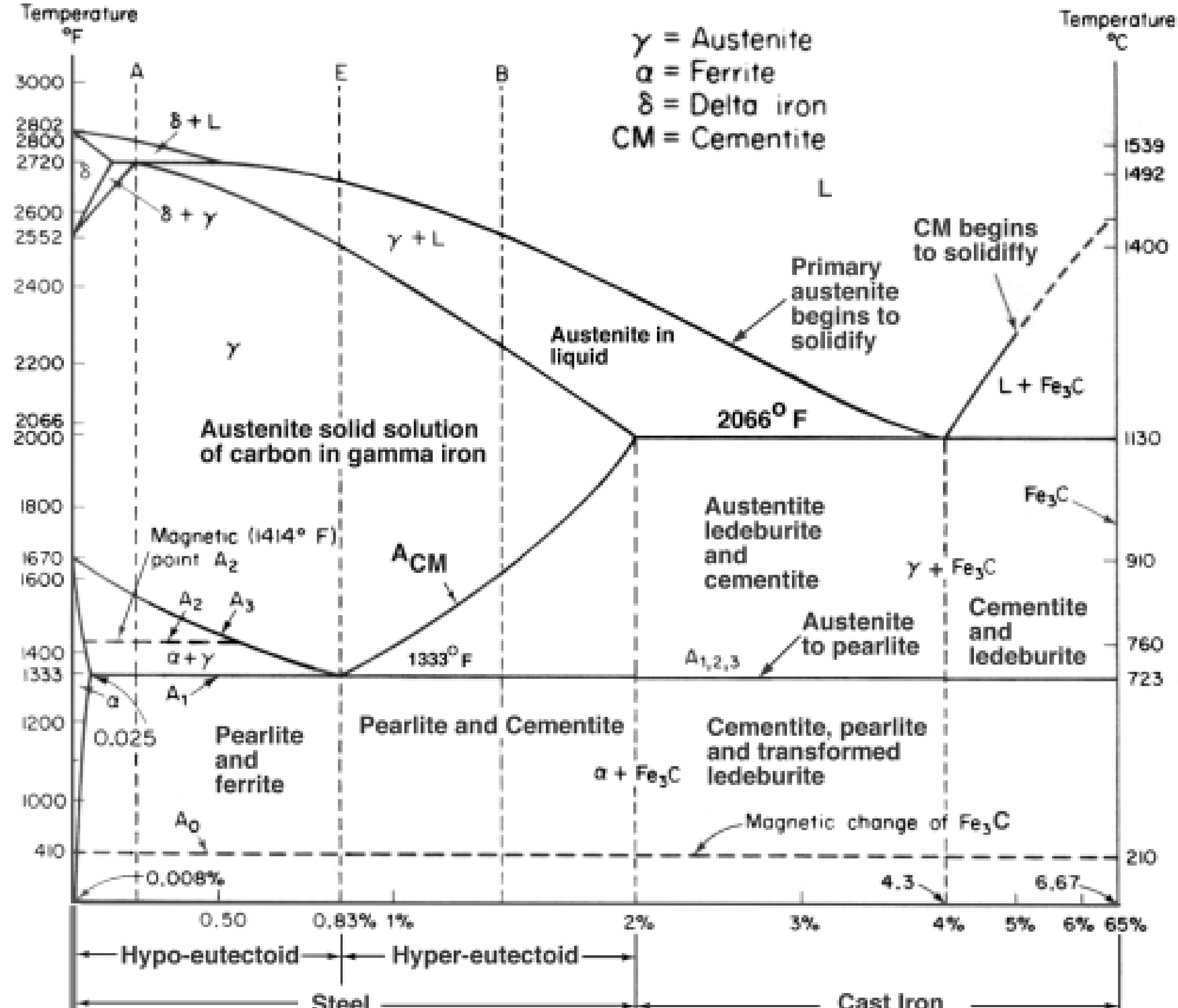


FIGURE 5-2 Graphical summary of the process heat treatments for steels on an equilibrium diagram.

The Phase Diagram



HARDENING OF STEEL

Hardening Temperatures

- The temperatures for hardening depend on the carbon content.
- Plain carbon steels below 0.4% will not harden by heat treatment.
- The temperature decreases from approx 820 deg C as carbon content increases from 0.4% up to 0.8%, where temperature is approx 780 deg C.
- Above 0.8% the temperature remains constant at 780 deg C.

Austenite

- This is the structure of irons and steels at high temperatures (over 800 deg C).
- For quench hardening all the material must start as Austenite.
- Quenching causes the Austenite to be partially or totally transformed to Martensite.

Martensite

- Only formed by very rapid cooling from the austenitic structure.
- Needs to be above the *Critical Cooling Rate*.

Quenching Media

Four commonly used quenching media:

- Brine – the fastest cooling rate
- Water – moderate cooling rate
- Oil – slowest cooling rate
- Gas – used in automatic furnaces, usually liquid nitrogen, can be very fast cooling.

Too rapid cooling can cause cracking in complex and heavy sections.

Surface Hardening

- Refers to a “thermo chemical” treatment whereby the surface is altered by the addition of carbon, nitrogen, or other elements.
- Sometimes called CASE HARDENING.
- Commonly applied to low carbon steels
  - Get a hard wear resistant shell
  - Tough inner core

Surface Hardening

- Benefits
  - Resists wear and deformation
  - Two zones result, avoiding brittleness
  - Surface hardness is increased without sacrificing desirable mechanical properties

Surface Hardening

1. Flame Hardening
   - Heating steel to above the critical temperature by use of a flame
   - Followed by quenching
   - Can harden small areas (i.e., push rod ends)

Surface Hardening

2. Induction Hardening

- Heat is generated by electrical induction
- Frequency between 1000 to 3,000,000 cycles per second used
- Maximum hardness by these two processes is a function of the carbon content
- Used on: gears (teeth), shafts, cams, crankshafts, cylinders, and levers

Surface Hardening

3. Carburizing

- Hardening the surface in the presence of a carbonaceous material as a gas, solid, or liquid
- Surface is hardened and the core remains as original material
- The depth of the case acquired is governed by temperature, time, activity of carburizing medium, and the analysis of the ferrous alloy used.
- Since hardness increases with carbon content, increasing the carbon content of the surface of a low carbon steel (by diffusion) results in high hardness at the surface and toughness at the core

Surface Hardening

(I) Pack or Box Carburizing

- Work is placed in a pack or box filled with a solid carburizing agent
- Heated to 1550 - 1750º F
- CO reacts with steel and dissolves into austenite
- Quench harden after heating, or let cool slowly and reheat and quench after working

Surface Hardening

(II) Liquid carburizing

- Molten salts containing cyanides and chlorides
- Heat to 1600-1750º F and place work in cyanide salt solution
- Length of time determines thickness of surface hardened
- Quench in oil or brine after removing from salt solution
- No moisture can be on metal when placed in salt solution or an explosion could result

4. Nitriding

- Nitrogen is diffused in the surface of special alloy steels at temperatures around ~510°C.
  - Steel must contain elements that will form nitride compounds.
    - Aluminum
    - Chromium
  - Forms a thin hard case without quenching
    - Thicknesses 0.001 in – 0.020 in.

TEMPERING

Tempering

The brittleness of martensite makes hardened steels unsuitable for most applications.

This requires the steel to be tempered by re-heating to a lower temperature to reduce the hardness and improve the toughness. This treatment converts some of the martensite to another structure called bainite.

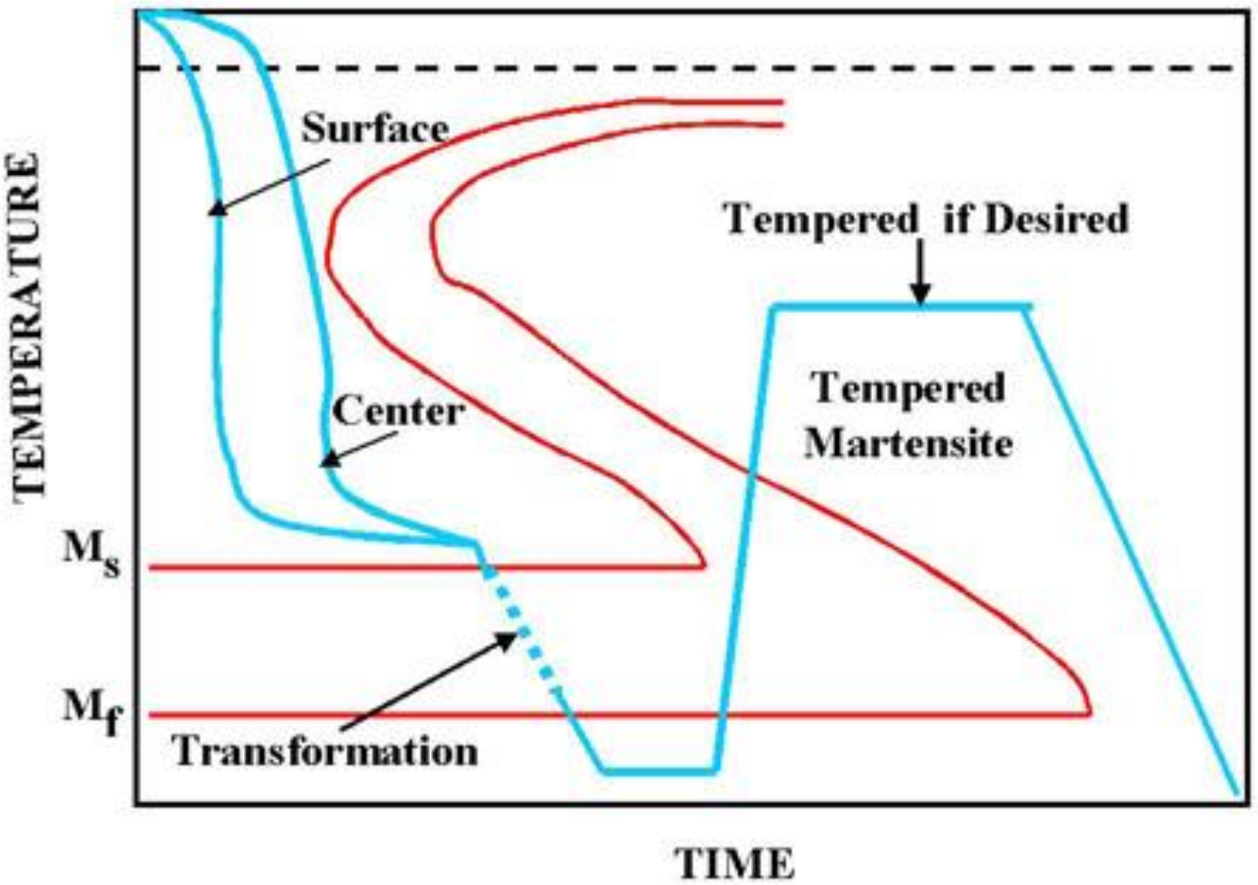
Tempering (drawing)

- Heating and holding steel below A_1 line and slow cooling to room temperature (1 temper cycle)
- Done in the range 150-650˚C
- Temper brittleness should be avoided (loss of toughness at higher tempering temperature). Can be avoided by quenching from the tempering temperature

1. Martempering (Martquenching)

- Martempering permits the transformation of Austenite to Martensite to take place at the same time throughout the structure of the metal part.
- By using interrupted quench, the cooling is stopped at a point above the martensite transformation region to allow sufficient time for the center to cool to the same temperature as the surface.
- Then cooling is continued through the martensite region, followed by the usual tempering.

MARTEMPERING



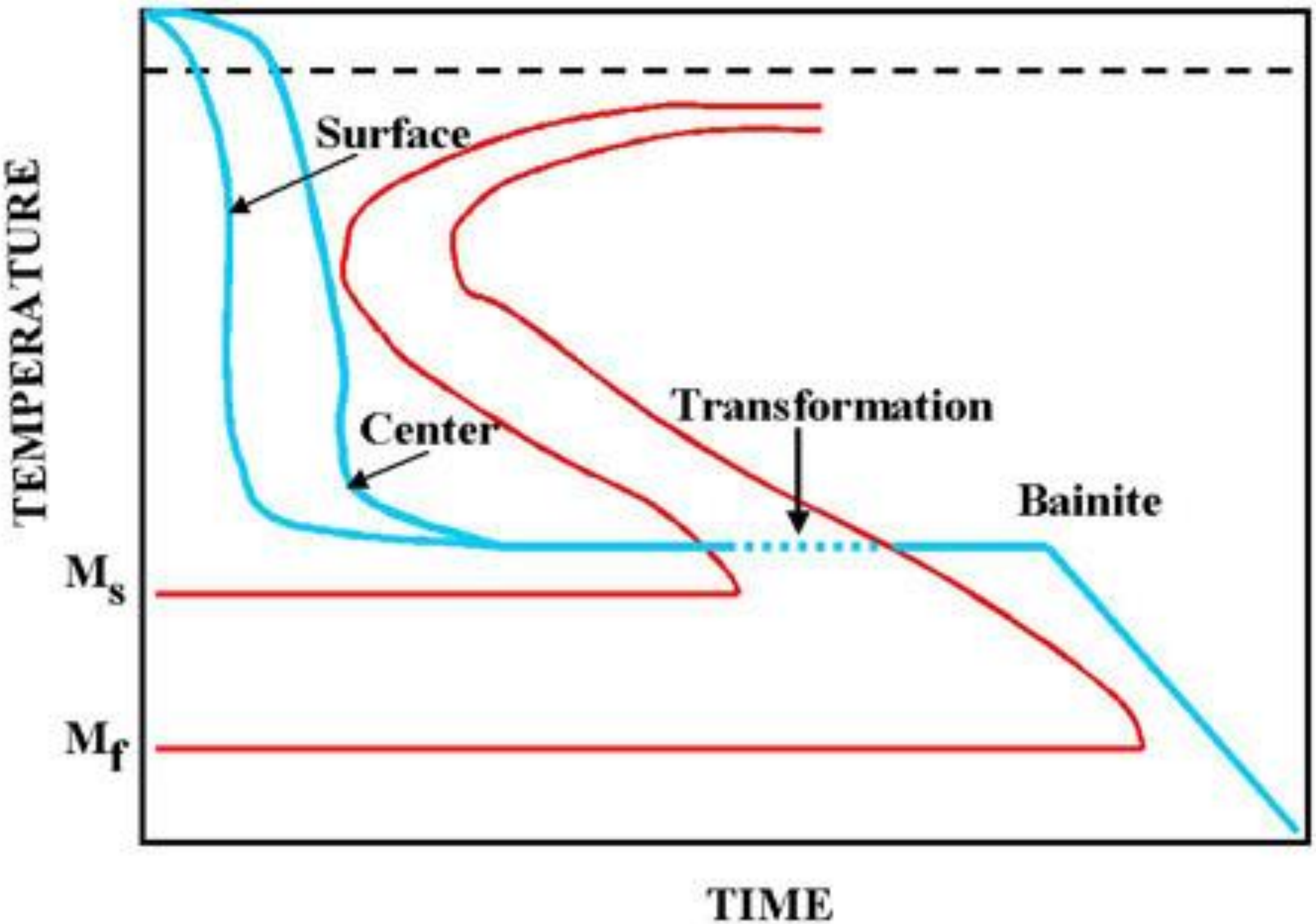
2. Austempering

- The austemper process offers benefits over the more conventional oil quench and temper method of heat treating springs and stampings that requires the uppermost in distortion control.

How to austemper?

- Quench the part from the proper austentizing temperature directly into a liquid salt bath at a temperature between 590 to 710 degrees Farenheit.
- Hold at this quench temperature for a recommended time to transform the Austenite into Bainite.
- Air cool to room temperature.

AUSTEMPERING



Advantages of Austempering:

- Less Distortion
- Greater Ductility
- Parts are plater friendly due to the clean surface from the salt quench
- Uniform and consistent Hardness
- Tougher and More Wear Resistant
- Higher Impact and Fatigue Strengths
- Resistance to Hydrogen Embrittlement

Limitations of Austempering:

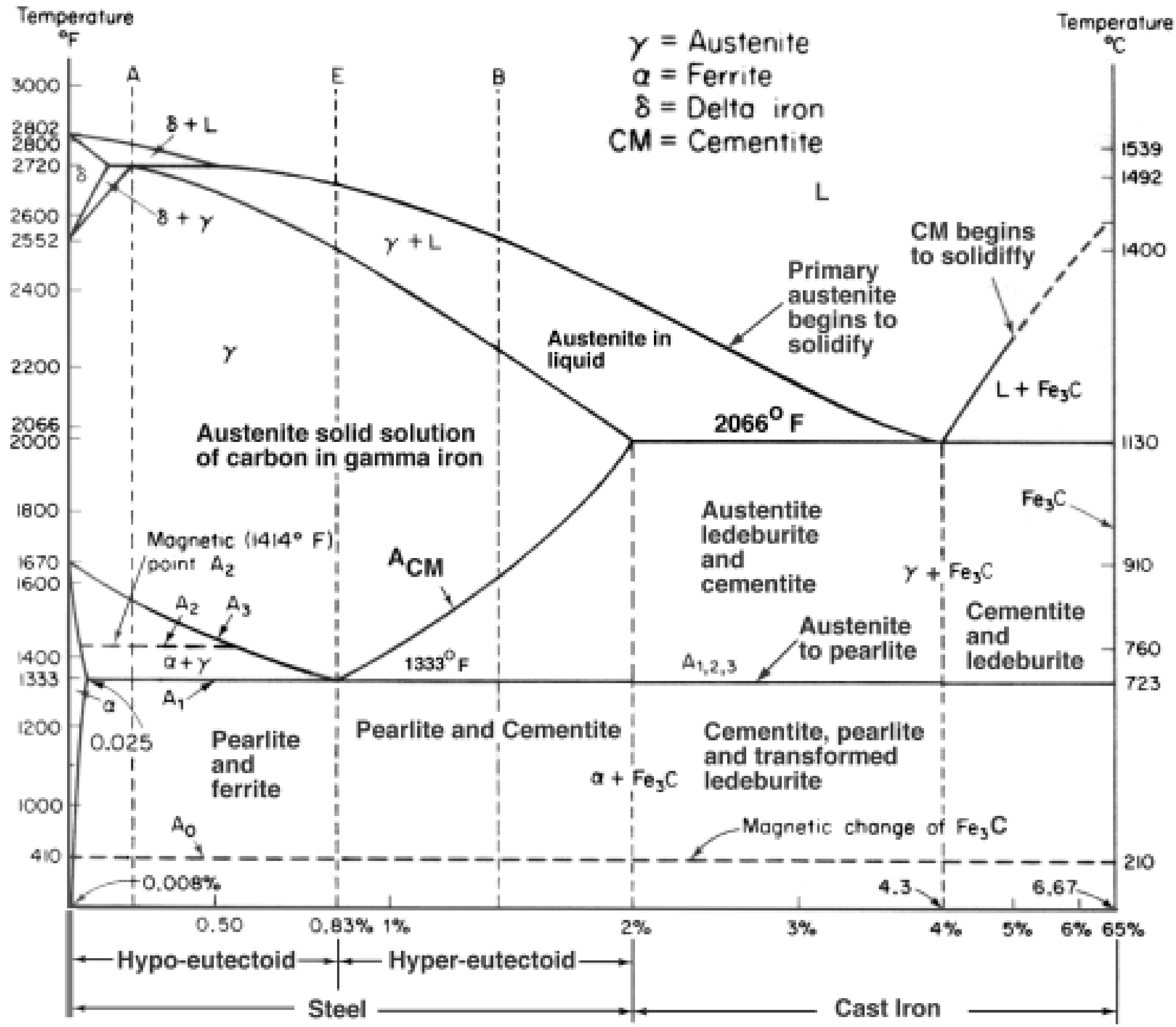
- Austempering can be applied to parts where the transformation to pearlite can be avoided.
- This means that the section must be cooled fast enough to avoid the formation of pearlite. Thin sections can be cooled faster than the bulky sections.

The Iron Carbon System

- Steels, ferrous alloys, cast irons, cast steels
  - Versatile and ductile
  - Cheap
- Irons (< 0.008% C)
- Steels (< 2.11% C)
- Cast irons (<6.67% [mostly <4.5%]C)

- The material properties are more than composition – they are dependent on how the material has been treated.

The Phase Diagram



Fe - C

- Iron melts at 1538°C
  - As it cools, it forms in sequence
    - Delta ferrite
    - Austenite
    - Alpha ferrite
- Alpha ferrite
  - Solid solution of BCC iron
  - Maximum C solubility of 0.022% at 727°C
  - Soft and ductile
  - Magnetic up to the Curie temperature of 768°C

Fe - C

- Delta ferrite
  - exists only at high temperatures and is of little engineering consequence.
- Note that little carbon can be actually interstitially dissolved in BCC iron
- Significant amounts of Chromium (Cr), Manganese (Mn), Nickel (Ni), Molybdenum (Mb), Tungsten (W), and Silicon (Si) can be contained in iron in solid solution.

Fe - C

- Austenite (gamma γ iron)
  - Between 1394 and 912°C iron transforms from the BCC to the FCC crystal structure.
  - It can accept carbon in its interstices up to 2.11%
  - Denser than ferrite, and the FCC phase is much more formable at high temperatures.
  - Large amounts of Ni and Mn can be dissolved into this phase
  - The phase is non-magnetic.

Fe - C

- Cementite
  - 100% iron carbide Fe_3C
  - Very hard
  - Very brittle
- Pearlite
  - Mixture of ferrite and cementite
  - Formed in thin parallel plates
- Bainite
  - Alternate mixture of the same phases
  - Needle like cementite regions
  - Formed by quick cooling

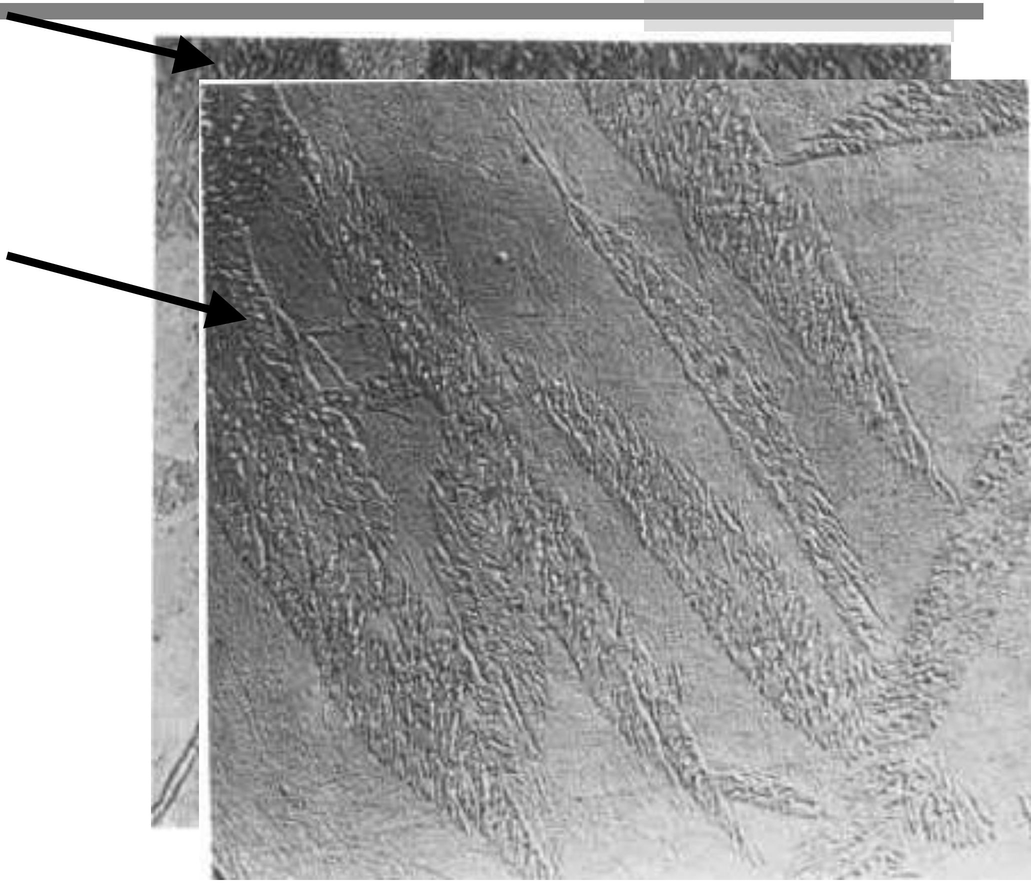
Microconstituents vs. Cooling Rate

In creasing Cooling Rate

- **Spheroidite:** Spherical “globs” of Fe3C in Ferrite
- **Pearlite**: Layers of α ferrite and Fe3C
  - Course Pearlite
  - Fine Pearlite
- **Bainite**: 200 – 500 °C Transformation
- **Martensite**: Rapid Cooling

Bainite

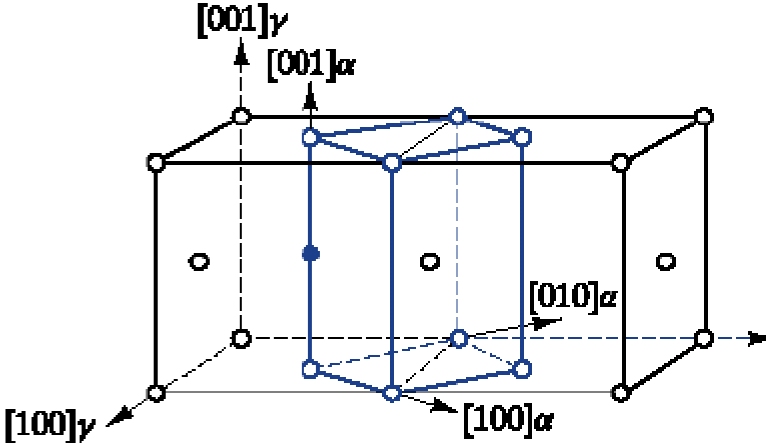
- Upper (550-350°C)
  - Rods of Fe_3C
- Lower (350-250°C)
  - Fe_3C Precipitates in Plates of Ferrite
- It is still Ferrite and Cementite! It’s just acicular.



Martensite

- <u>Diffusionless transformation</u>

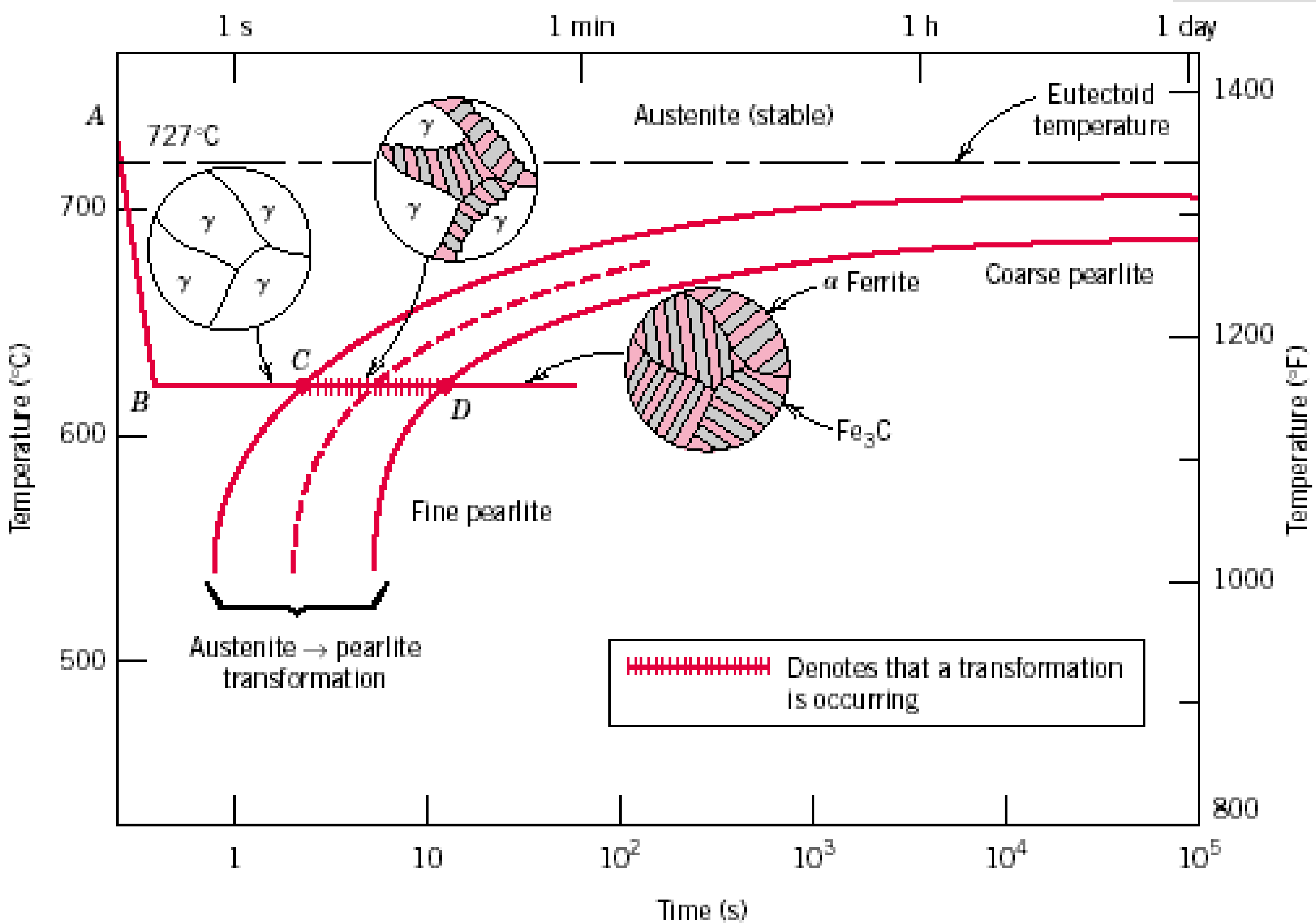
  of FCC to BCT (more volume!)
- Lenticular structure
- Very hard & very brittle.



Time-Temperature-Transformation (TTT) Diagram

- T (Time) T(Temperature) T(Transformation) diagram is a plot of temperature versus the logarithm of time for a steel alloy of definite composition. It is used to determine when transformations begin and end for an isothermal (constant temperature) heat treatment of a previously austenitized alloy. When austenite is cooled slowly to a temperature below LCT (Lower Critical Temperature), the structure that is formed is Pearlite. As the cooling rate increases, the pearlite transformation temperature gets lower. The microstructure of the material is significantly altered as the cooling rate increases. By heating and cooling a series of samples, the history of the austenite transformation may be recorded. TTT diagram indicates when a specific transformation starts and ends and it also shows what percentage of transformation of austenite at a particular temperature is achieved.
- Cooling rates in the order of increasing severity are achieved by quenching from elevated temperatures as follows: furnace cooling, air cooling, oil quenching, liquid salts, water quenching, and brine. If these cooling curves are superimposed on the TTT diagram, the end product structure and the time required to complete the transformation may be found.

TTT Diagrams



Full TTT Diagram

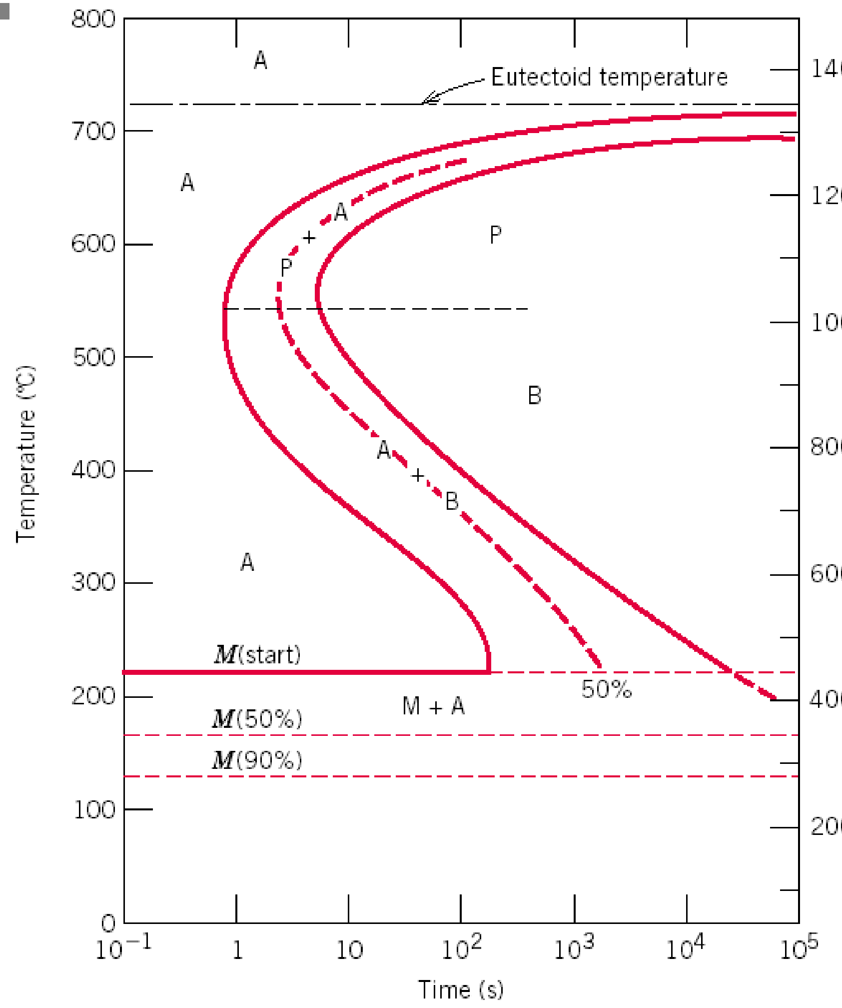
The complete TTT diagram for an iron-carbon alloy of eutectoid composition.

A: austenite

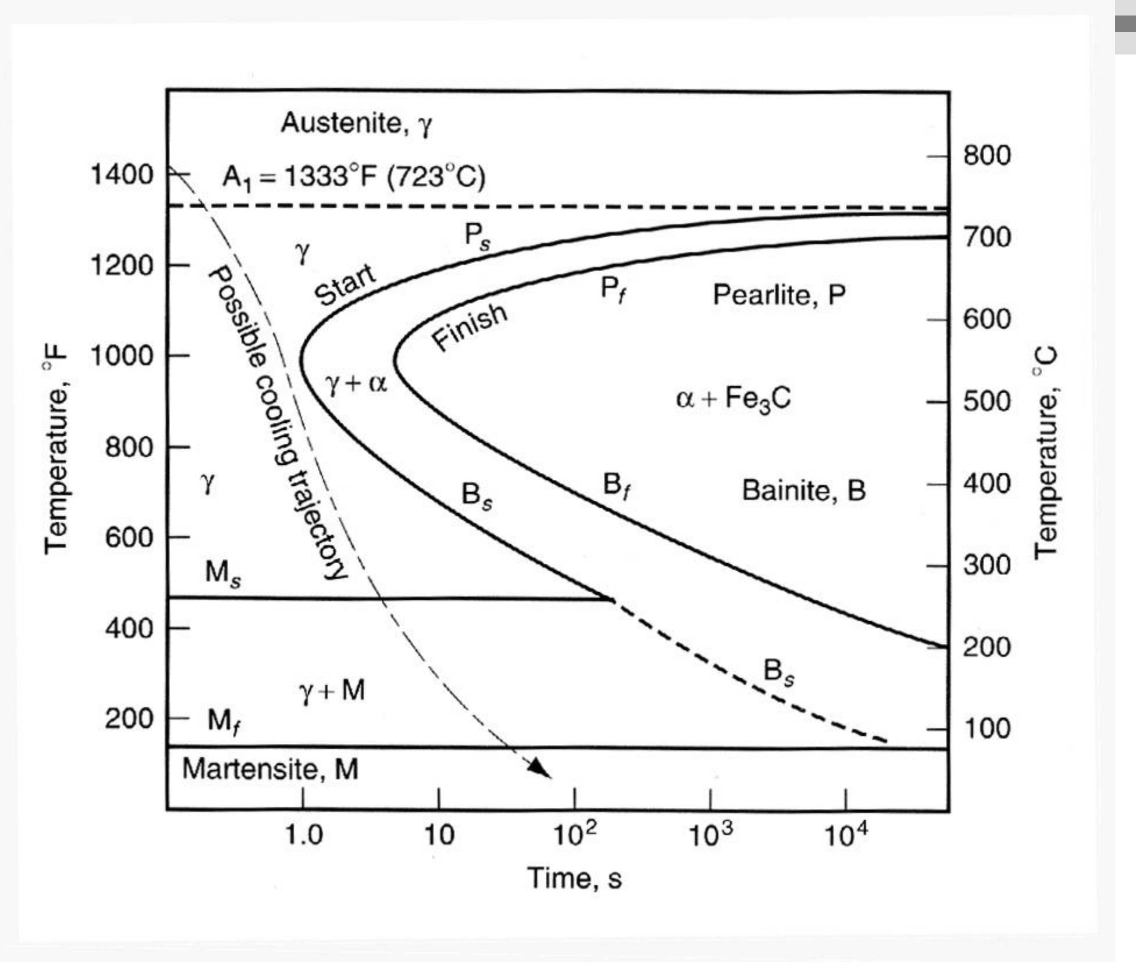
B: bainite

M: martensite

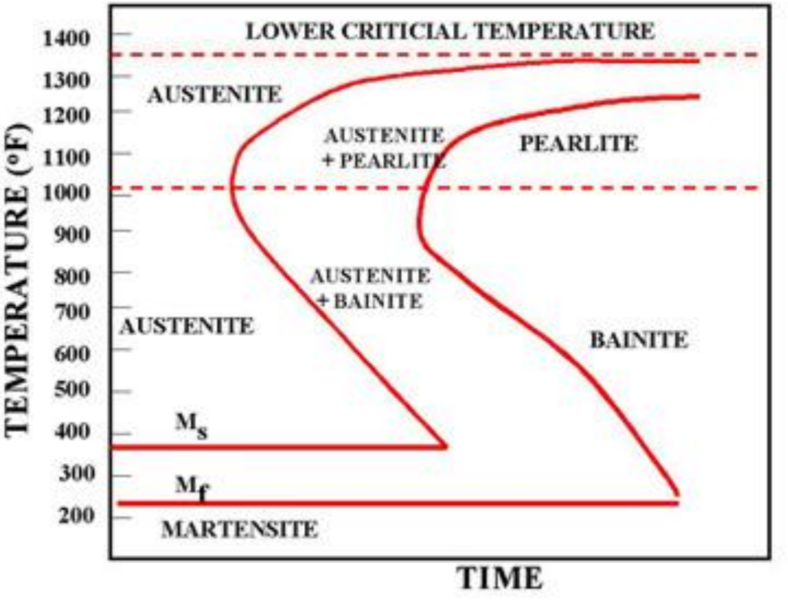
P: pearlite



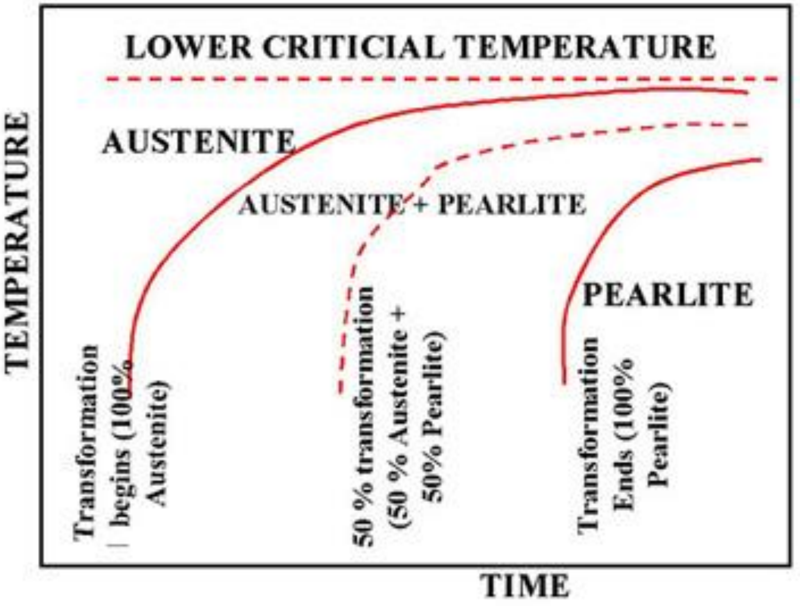
The Time – Temperature – Transformation Curve (TTT)



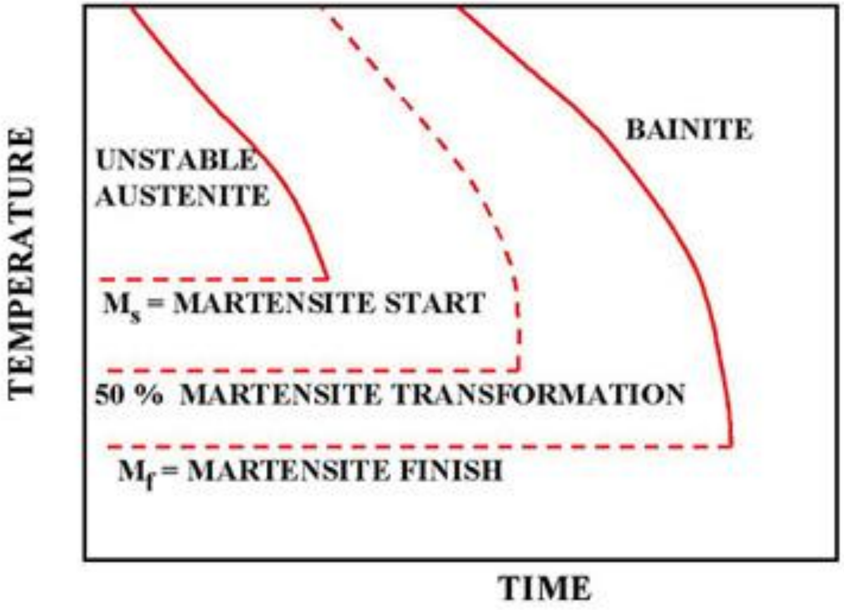
- In Figure 1 the area on the left of the transformation curve represents the austenite region. Austenite is stable at temperatures above LCT but unstable below LCT. Left curve indicates the start of a transformation and right curve represents the finish of a transformation. The area between the two curves indicates the transformation of austenite to different types of crystal structures. (Austenite to pearlite, austenite to martensite, austenite to bainite transformation.)



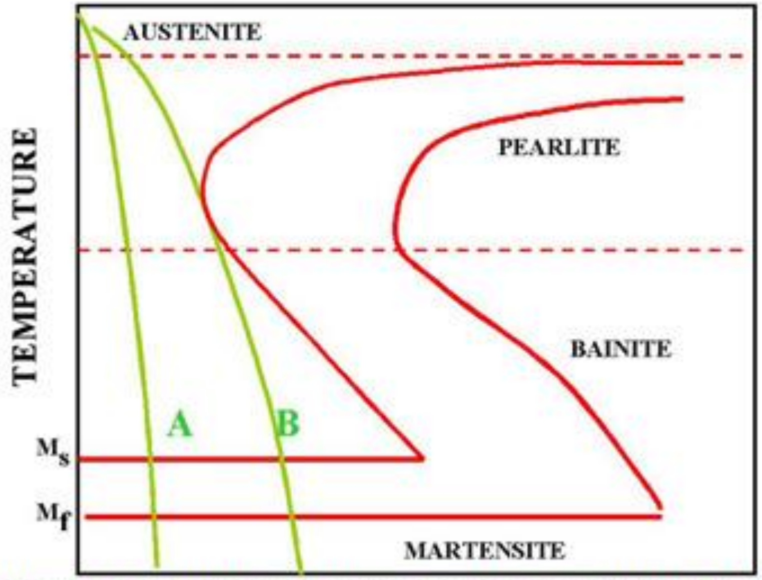
- Figure 2 represents the upper half of the TTT diagram. As indicated in Figure 2, when austenite is cooled to temperatures below LCT, it transforms to other crystal structures due to its unstable nature. A specific cooling rate may be chosen so that the transformation of austenite can be 50 %, 100 % etc. If the cooling rate is very slow such as annealing process, the cooling curve passes through the entire transformation area and the end product of this the cooling process becomes 100% Pearlite. In other words, when slow cooling is applied, all the Austenite will transform to Pearlite. If the cooling curve passes through the middle of the transformation area, the end product is 50 % Austenite and 50 % Pearlite, which means that at certain cooling rates we can retain part of the Austenite, without transforming it into Pearlite.



- **Figure 3 indicates the types of transformation that can be found at higher cooling rates. If a cooling rate is very high, the cooling curve will remain on the left hand side of the Transformation Start curve. In this case all Austenite will transform to Martensite. If there is no interruption in cooling the end product will be martensite.**

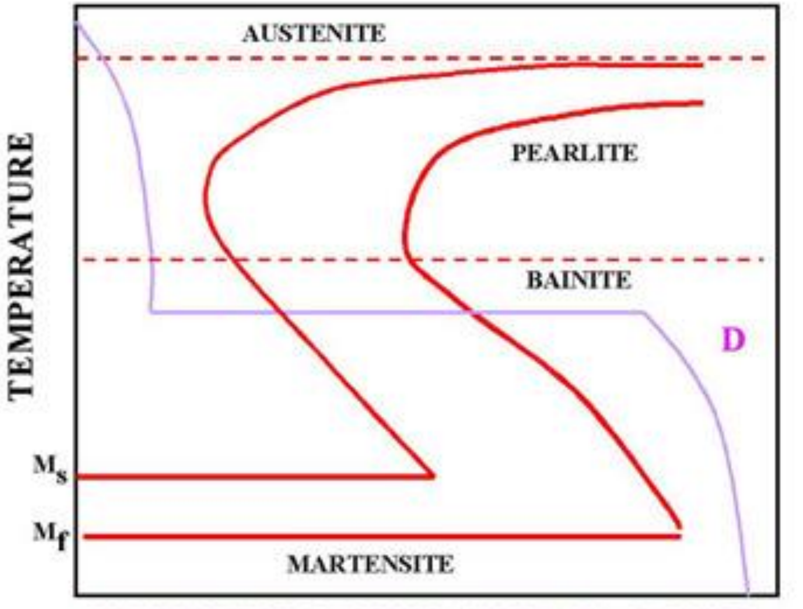


- In Figure 4 the cooling rates A and B indicate two rapid cooling processes. In this case curve A will cause a higher distortion and a higher internal stresses than the cooling rate B. The end product of both cooling rates will be martensite. Cooling rate B is also known as the Critical Cooling Rate, which is represented by a cooling curve that is tangent to the nose of the TTT diagram. Critical Cooling Rate is defined as the lowest cooling rate which produces 100% Martensite while minimizing the internal stresses and distortions.



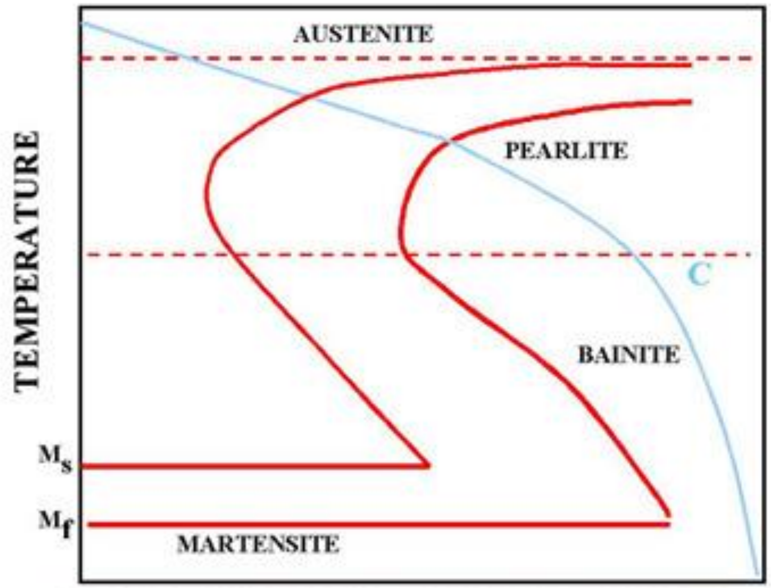
PRODUCT OF COOLING CURVES (A) AND (B) : MARTENSITE

- In Figure 5, a rapid quenching process is interrupted (horizontal line represents the interruption) by immersing the material in a molten salt bath and soaking at a constant temperature followed by another cooling process that passes through Bainite region of TTT diagram. The end product is Bainite, which is not as hard as Martensite. As a result of cooling rate D; more dimensional stability, less distortion and less internal stresses are created.



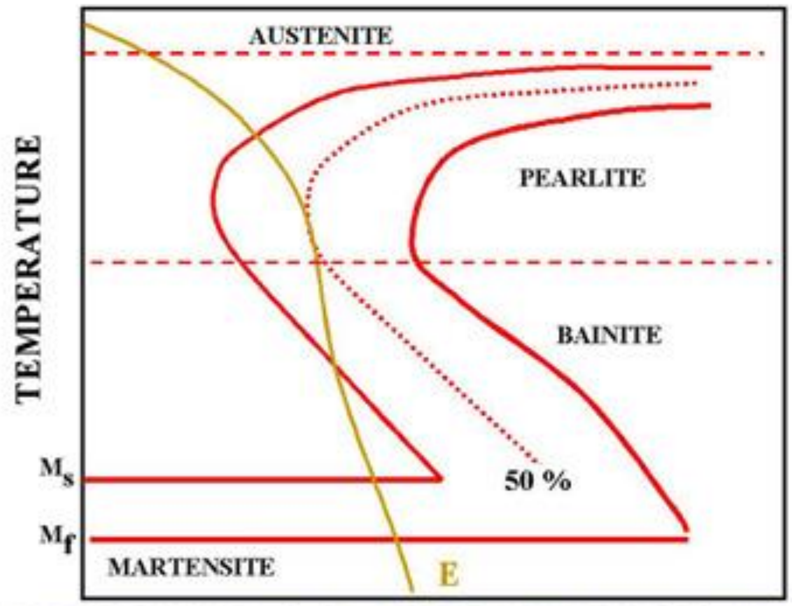
PRODUCT OF COOLING CURVE (D) : BAINITE

- **In Figure 6 cooling curve C represents a slow cooling process, such as furnace cooling. An example for this type of cooling is annealing process where all the Austenite is allowed to transform to Pearlite as a result of slow cooling.**

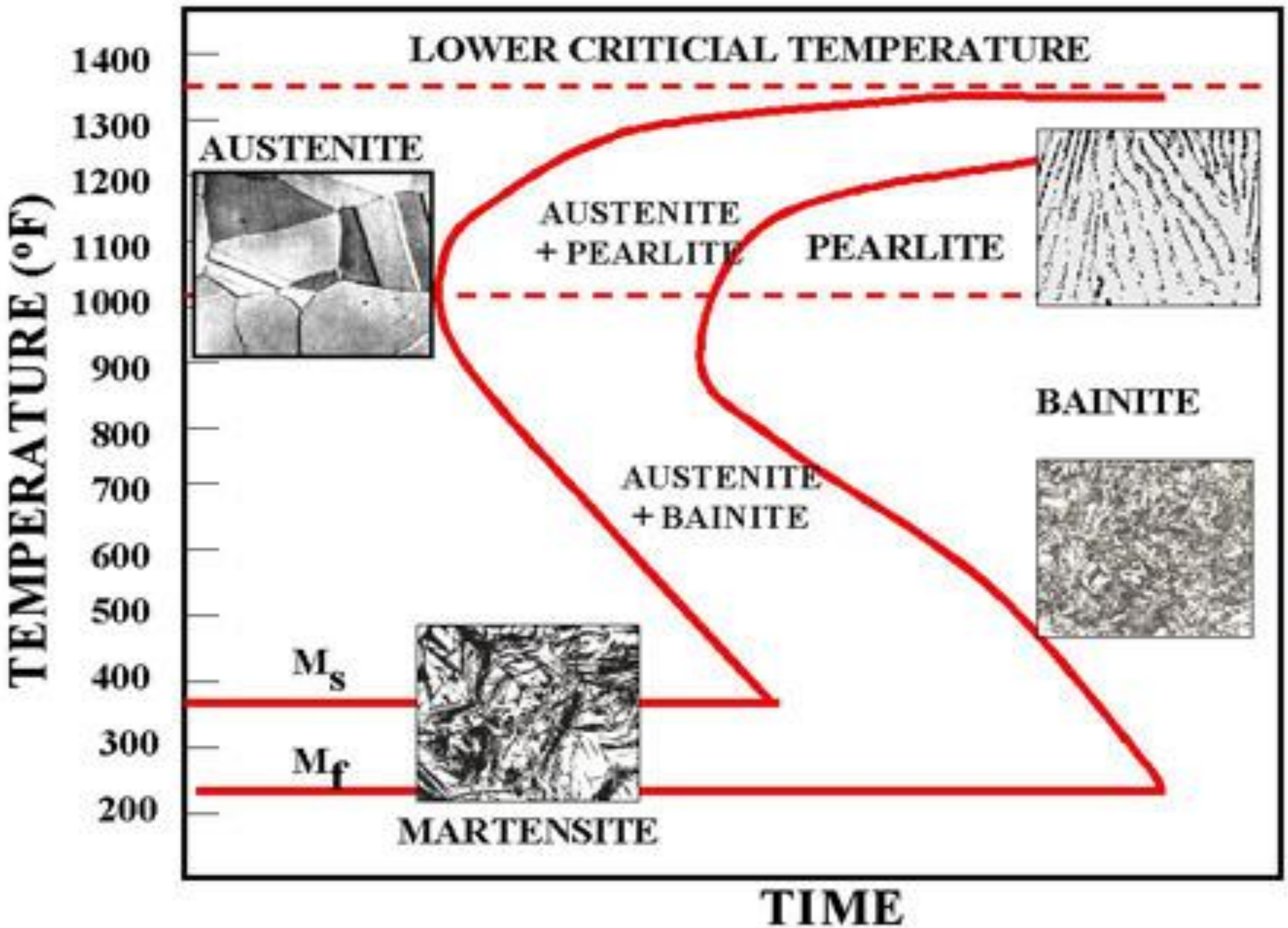


PRODUCT OF COOLING CURVE (C) : PEARLITE

- Sometimes the cooling curve may pass through the middle of the Austenite-Pearlite transformation zone. In Figure 7, cooling curve E indicates a cooling rate which is not high enough to produce 100% martensite. This can be observed easily by looking at the TTT diagram. Since the cooling curve E is not tangent to the nose of the transformation diagram, austenite is transformed to 50% Pearlite (curve E is tangent to 50% curve). Since curve E leaves the transformation diagram at the Martensite zone, the remaining 50 % of the Austenite will be transformed to Martensite.

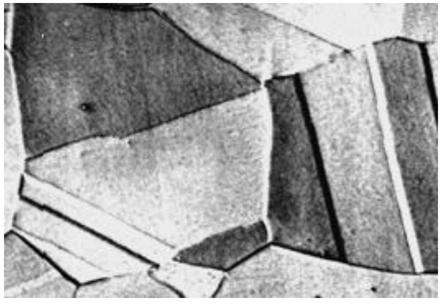


PRODUCT OF COOLING CURVE (E) : 50 % PEARLITE, 50 % MARTENSITE

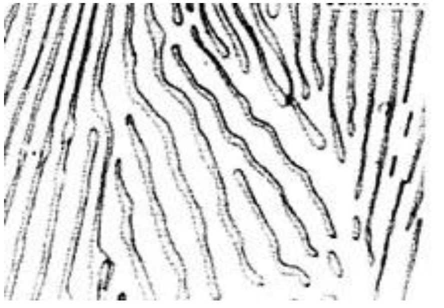


LOWER CRITICIAL TEMPERATURE
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE (°F)
AUSTENITE
AUSTENITE
+ PEARLITE
PEARLITE
BAINITE
AUSTENITE
+ BAINITE
M_s
M_f
MARTENSITE
TIME

Micro Sturcture



Austenite

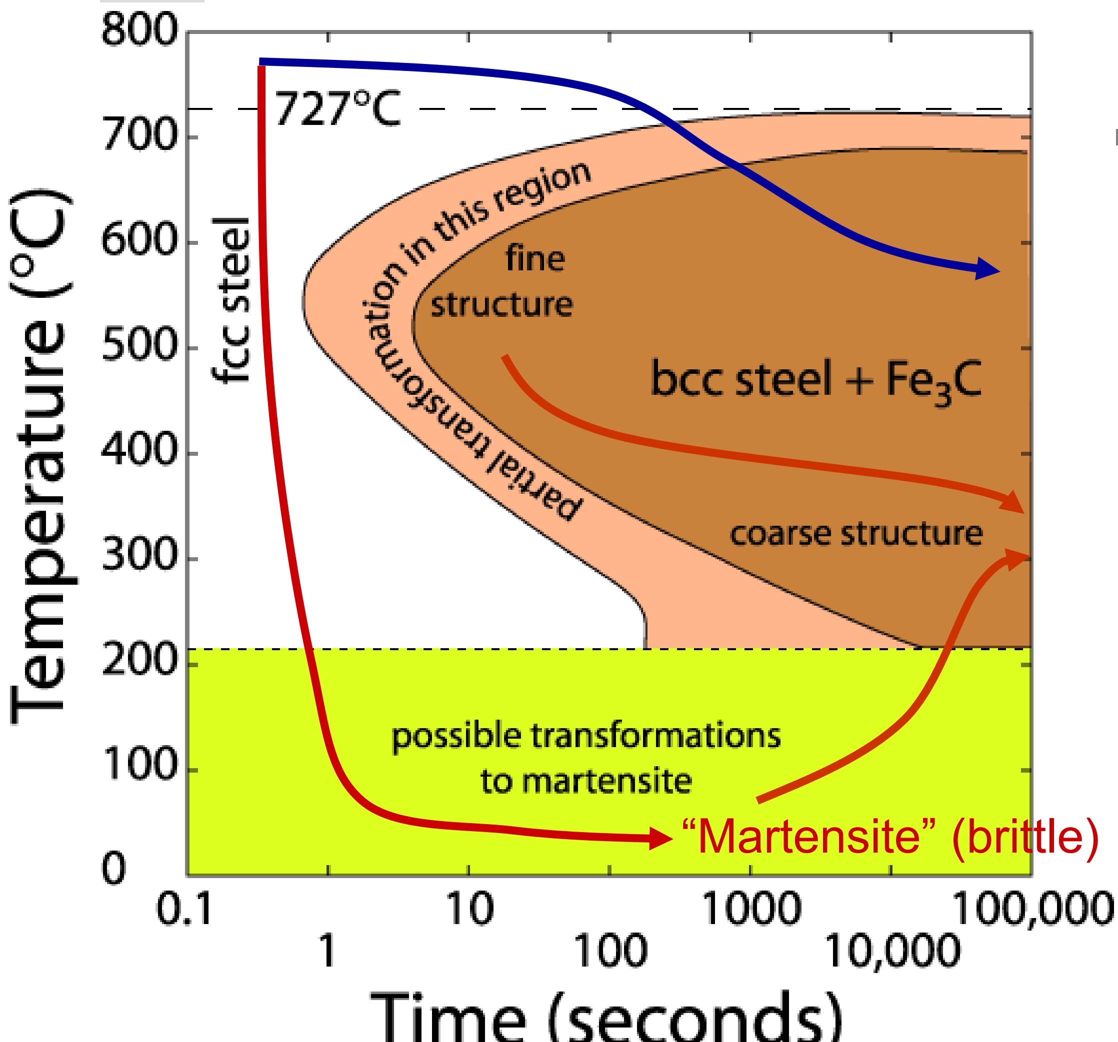


Pearlite

Martensite

Bainite

The Heat Treatment Process



"Pearlite" (ductile)

BCC + Fe_3C with different microstructures

How you heat treat makes all the difference to the steel you get

Strengthening heat treatments for steel

- **Isothermal transformation diagram (I-T)**
- **Time-Temperature-Transformation**
  (T-T-T Diagram)

Nose of T-T-T diagram

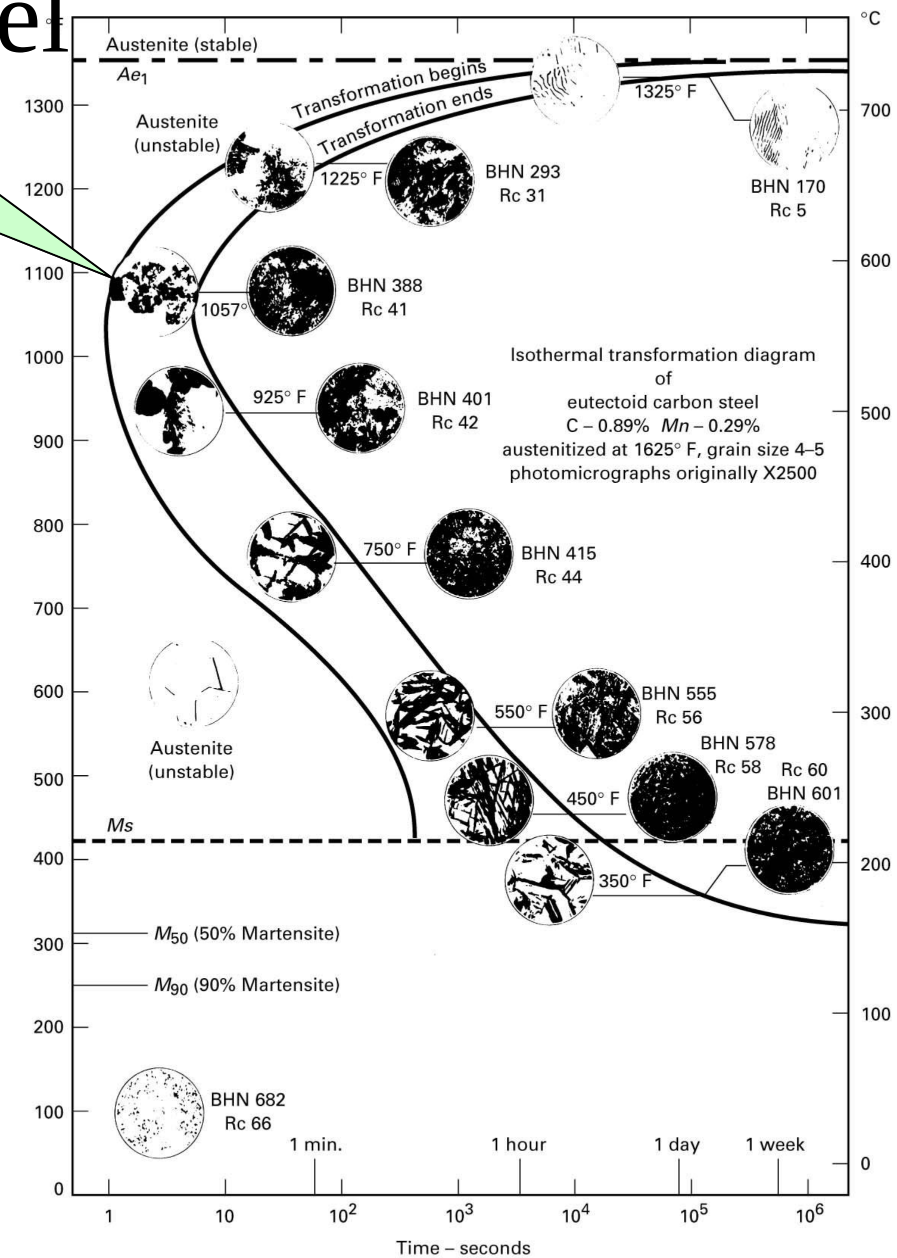
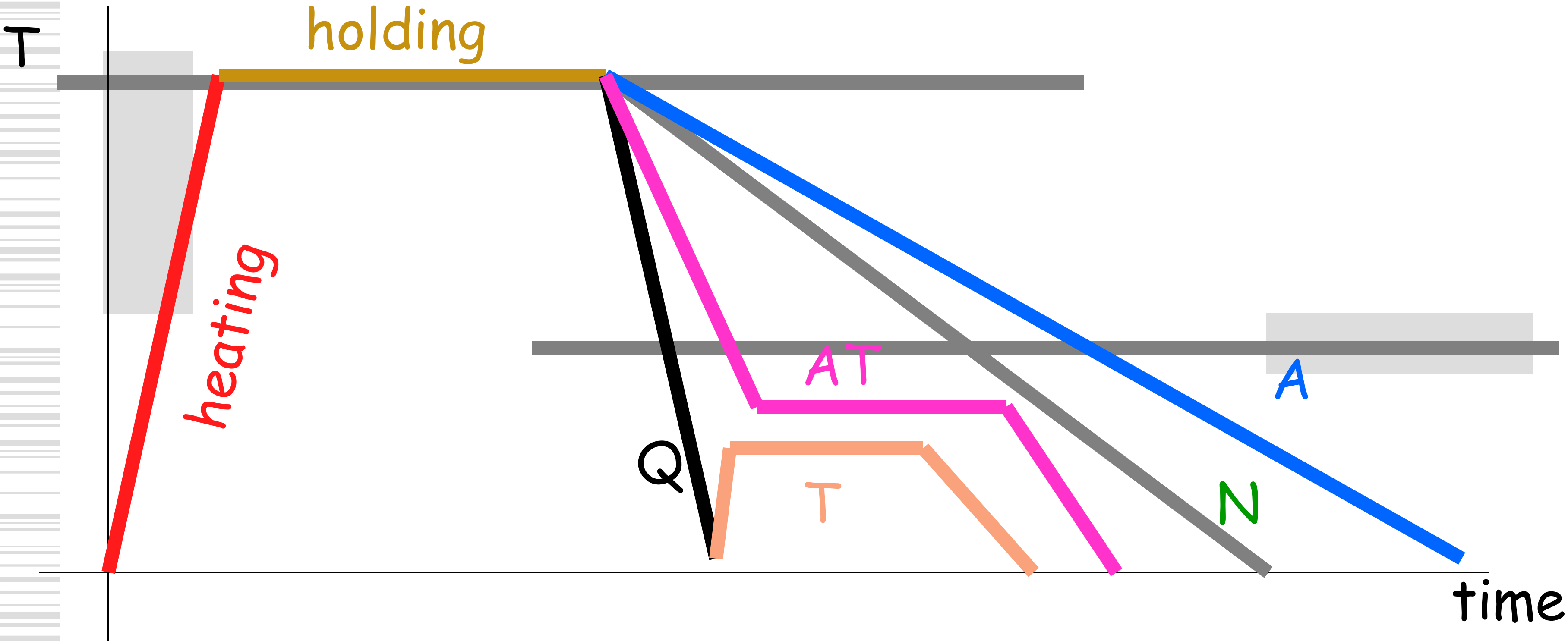


FIGURE 5-6 Isothermal transformation diagram (T-T-T diagram) for eutectoid composition steel. Structures resulting from transformation at various temperatures are shown as insets. *(Courtesy of USX Corporation.)*



Annealing	Furnace cooling	RC 15
Normalizing	Air cooling	RC 30
Quenching	Water cooling	RC 65
Tempering	Heating after quench	RC 55
Austempering	Quench to an inter-mediate temp and hold	RC 45

Hardenability

Ability or ease of hardening a steel by formation of martensite using as slow quenching as possible

Alloying elements in steels shift the C-curve to the right

Alloy steels have higher hardenability than plain C steels.

Hardnenability	Hardness
Ability or ease of hardening a steel	Resistance to plastic deformation as measured by indentation
Only applicable to steels	Applicable to all materials

Alloying additions increase the hardenability of steels but not the hardness.

C increases both hardenability and hardness of steels.