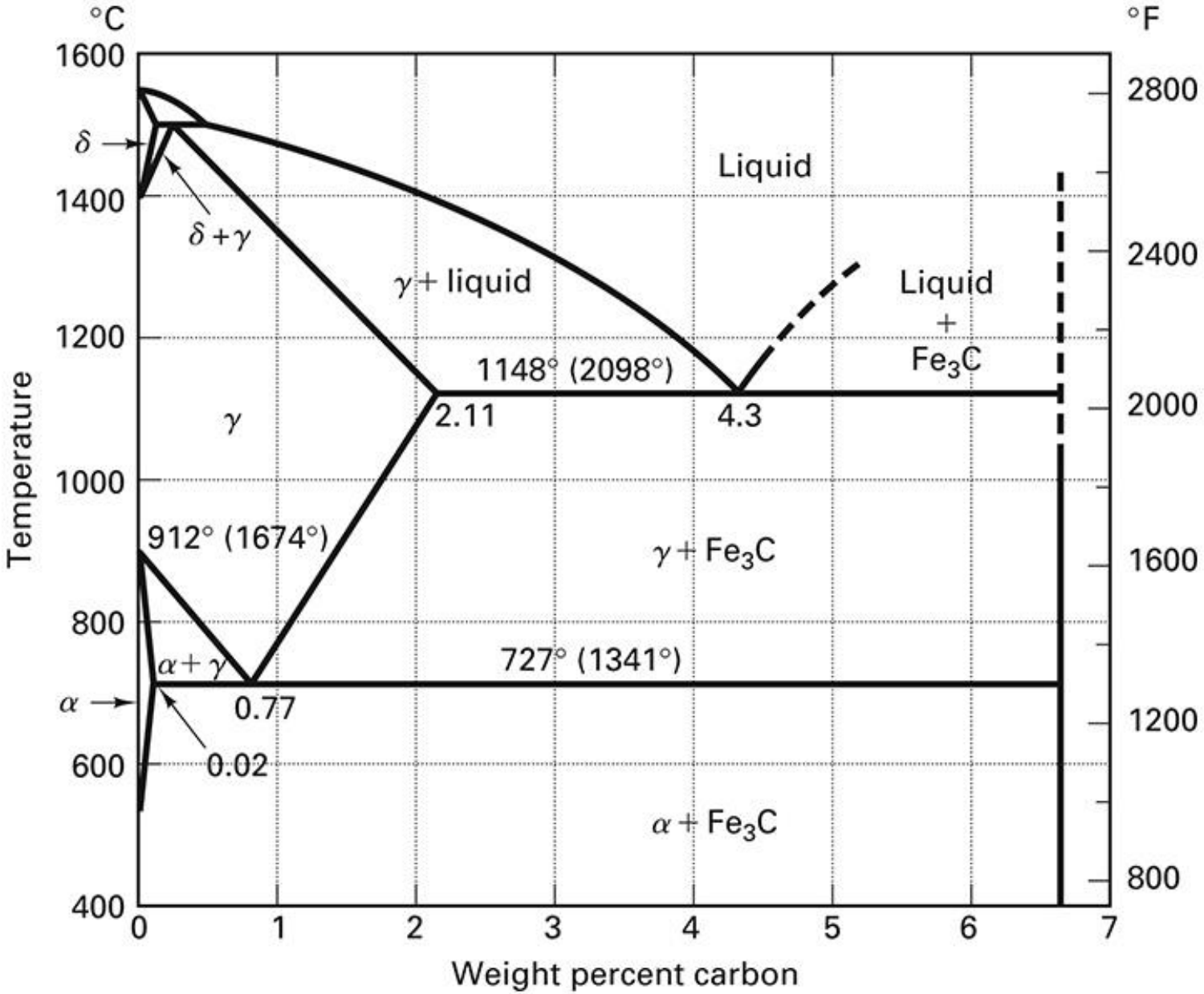
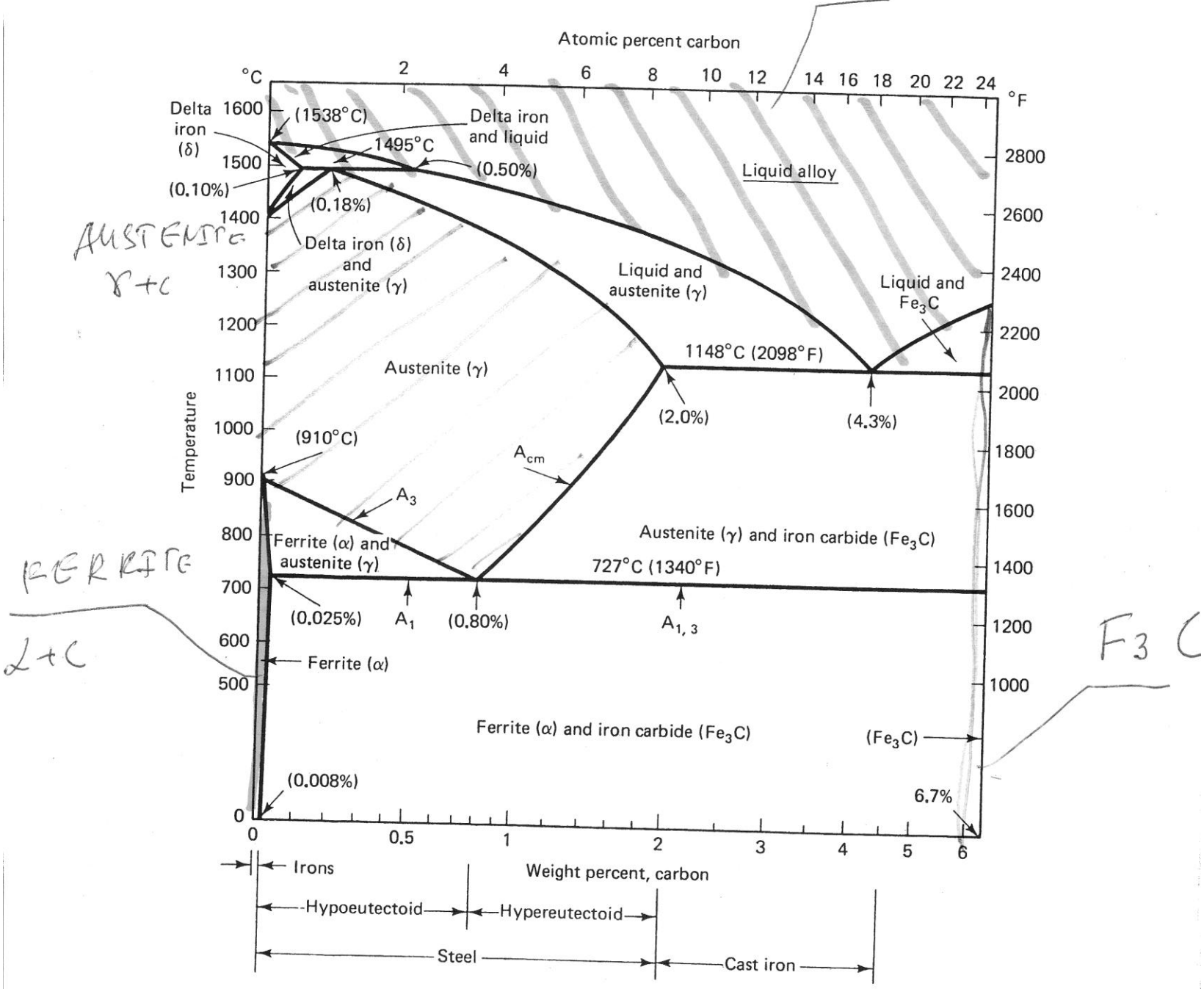
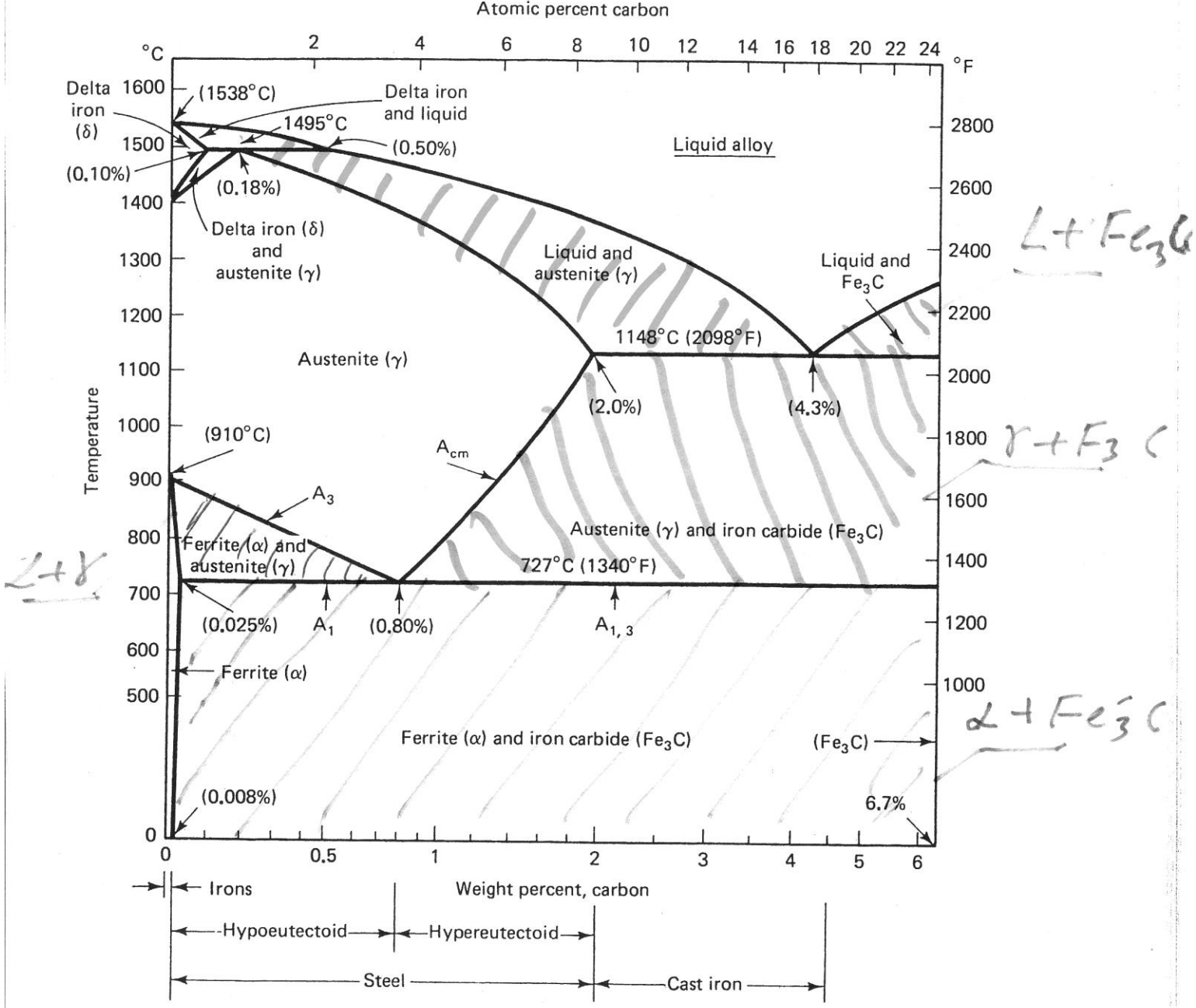
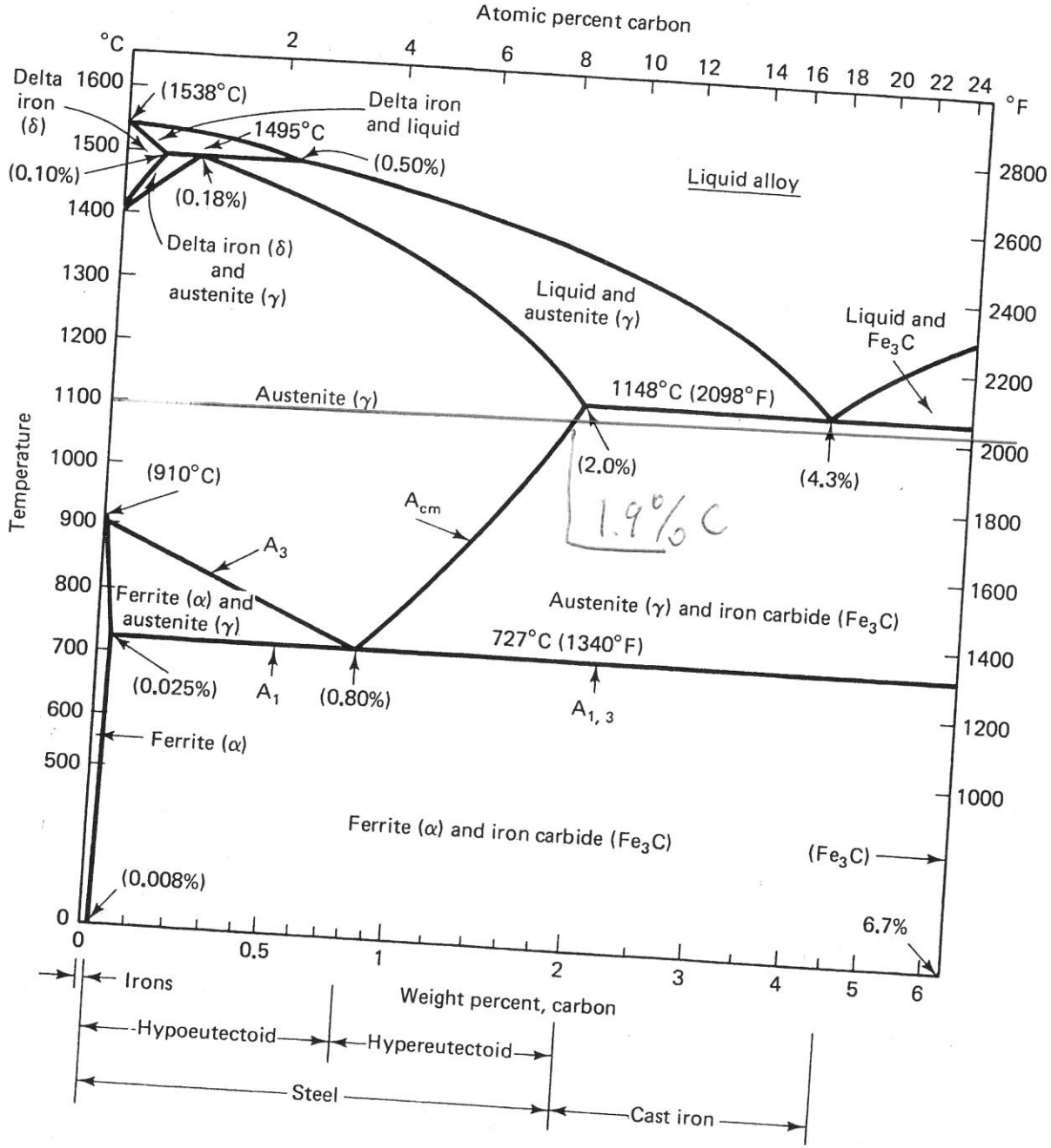
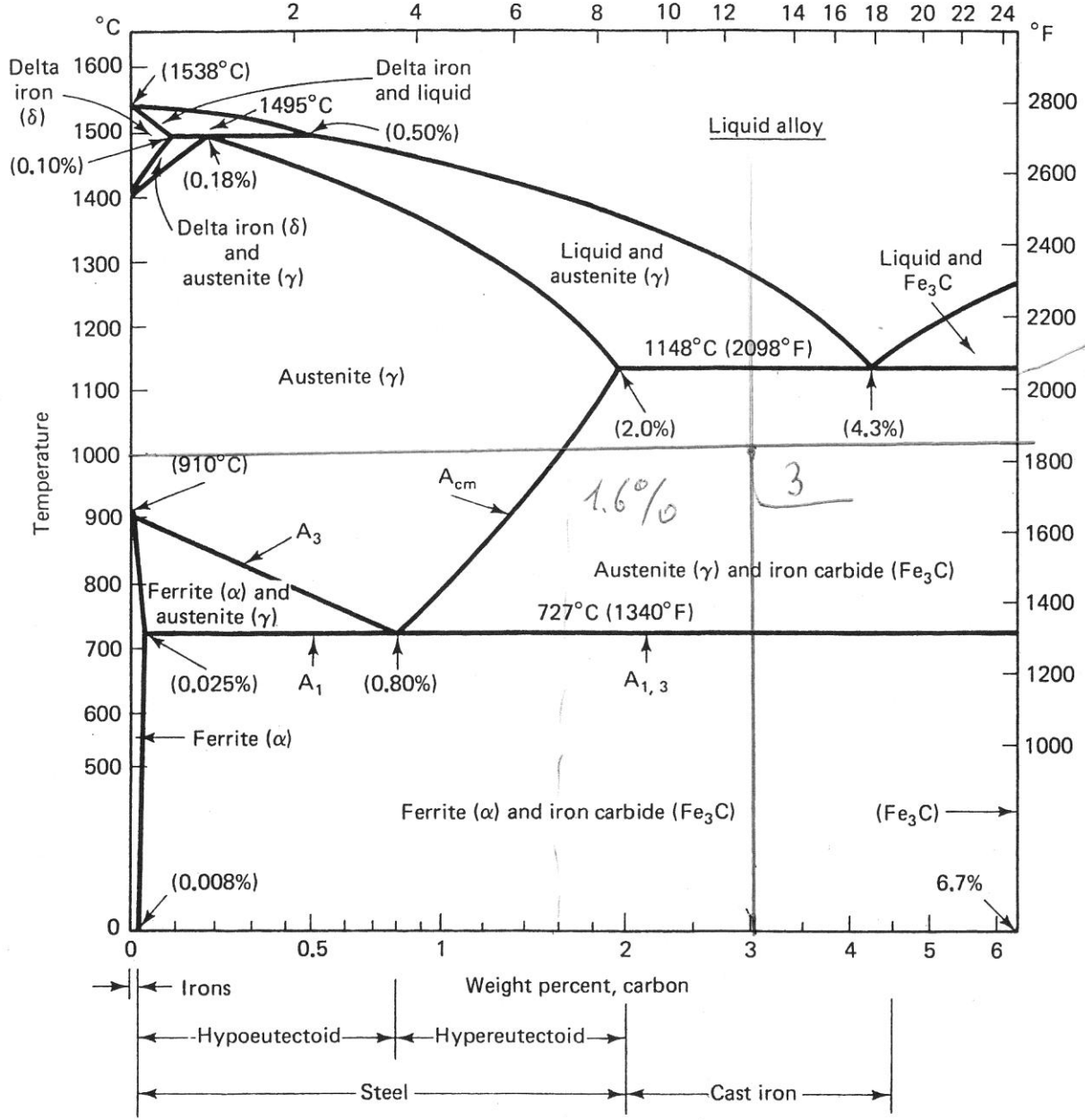
APPLICATIONS OF Fe-C PHASE DIAGRAM


°C
°F
1600
1400
1200
1000
800
600
400
2800
2400
2000
1600
1200
800
Temperature
δ
δ + γ
Liquid
γ + liquid
Liquid
+
Fe3C
1148° (2098°)
2.11
4.3
γ
912° (1674°)
γ + Fe3C
α + γ
727° (1341°)
α
0.77
0.02
α + Fe3C
0
1
2
3
4
5
6
7
Weight percent carbon


Atomic percent carbon
2
4
6
8
10
12
14
16
18
20
22
24
°C
°F
Delta iron (δ)
(1538°C)
Delta iron and liquid
1495°C
(0.50%)
(0.10%)
(0.18%)
Liquid alloy
Delta iron (δ) and austenite (γ)
Liquid and austenite (γ)
Liquid and Fe_3C
1148°C (2098°F)
Austenite (γ)
(2.0%)
(4.3%)
(910°C)
A_{cm}
A_3
Ferrite (α) and austenite (γ)
Austenite (γ) and iron carbide (Fe_3C)
727°C (1340°F)
(0.025%)
A_1
(0.80%)
$A_{1,3}$
Ferrite (α)
Ferrite (α) and iron carbide (Fe_3C)
(Fe_3C)
(0.008%)
6.7%
Temperature
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
0
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
0
0.5
1
2
3
4
5
6
Weight percent, carbon
Irons
Hypoeutectoid
Hypereutectoid
Steel
Cast iron
AUSTENITE
γ+C
FERRITE
α+C
F3 C


Atomic percent carbon
2 4 6 8 10 12 14 16 18 20 22 24
°C
°F
Delta iron (δ)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
0
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
(1538°C)
Delta iron and liquid
1495°C
(0.50%)
Liquid alloy
(0.10%)
(0.18%)
Delta iron (δ) and austenite (γ)
Liquid and austenite (γ)
Liquid and Fe3C
1148°C (2098°F)
Austenite (γ)
(2.0%)
(4.3%)
Temperature
(910°C)
Acm
A3
Ferrite (α) and austenite (γ)
Austenite (γ) and iron carbide (Fe3C)
727°C (1340°F)
(0.025%)
A1
(0.80%)
A1, 3
Ferrite (α)
Ferrite (α) and iron carbide (Fe3C)
(Fe3C)
(0.008%)
6.7%
0 0.5 1 2 3 4 5 6
Weight percent, carbon
Irons
Hypoeutectoid
Hypereutectoid
Steel
Cast iron
L+Fe3C
γ+Fe3C
L+γ
α+Fe3C


Atomic percent carbon
°C
°F
Temperature
Delta iron (δ)
(1538°C)
Delta iron and liquid
1495°C
(0.50%)
(0.10%)
(0.18%)
Liquid alloy
Delta iron (δ) and austenite (γ)
Liquid and austenite (γ)
Liquid and Fe3C
Austenite (γ)
1148°C (2098°F)
(2.0%)
(4.3%)
1.9% C
(910°C)
Acm
A3
Ferrite (α) and austenite (γ)
Austenite (γ) and iron carbide (Fe3C)
727°C (1340°F)
(0.025%)
A1
(0.80%)
A1, 3
Ferrite (α)
Ferrite (α) and iron carbide (Fe3C)
(Fe3C)
(0.008%)
6.7%
Weight percent, carbon
Irons
Hypoeutectoid
Hypereutectoid
Steel
Cast iron



6.67

1.6%

3

$$\% \text{ AUSTENITE} = \frac{6.67-3}{6.67-1.6} = 66\%$$

KEY POINTS OF Fe-C Diagram

Phases:

- Liquid Fe-Tmin=1148C @ 4.3%C
- 1394 C<δ-Fe-<1538C
- α-Ferrite (Ferrite)<912C; <0.02%C
- Magnetic-nonmagnetic-770C
- Cementite F_3C=6.67weight %C
- Austenite-727 C<T<1495 C; 0<%C<2.11

PHASE TRANSFORMATION

Liquid to Austenite

- Eutectic transformation-1148C,
- C-2.11%-4.3%
- Eutectic transformation-4.3% C, 1148C
- Eutectic transformation L-γ+F_3C (fast)
- Eutectic trans L-γ+C (graphite) (slow)

EUTECTOID TRANSFORMATION

- $\gamma \rightarrow$pearlite (ferrite+F_3C)
- 727 C, 077 % C eutectic point

Cast Irons

- Iron-carbon alloys with more than 2.11% carbon are known as cast irons
- Relatively inexpensive with good fluidity and low liquidis temperatures make them ideal for casting
- Contain significant amounts of silicon, manganese, and sulfur
- High silicon content enhances oxidation and corrosion resistance of cast irons

White cast irons

- White cast irons
  - Excess carbon is in the form of iron carbide
  - White surface appears when the material is fractured
  - Very hard and brittle

Gray Iron

- Gray iron was the original "cast iron", and is an iron alloy characterized by its relatively high carbon content (usually 2% to 4%).
- When molten cast iron solidifies some of the carbon precipitates as graphite, forming tiny, irregular flakes within the crystal structure of the metal.
- While the graphite enhances the desirable properties of cast iron (improved casting & machining properties and better thermal conductivity), the flakes disrupt the crystal structure and provide a nucleation point for cracks, leading to cast iron's characteristic brittleness.

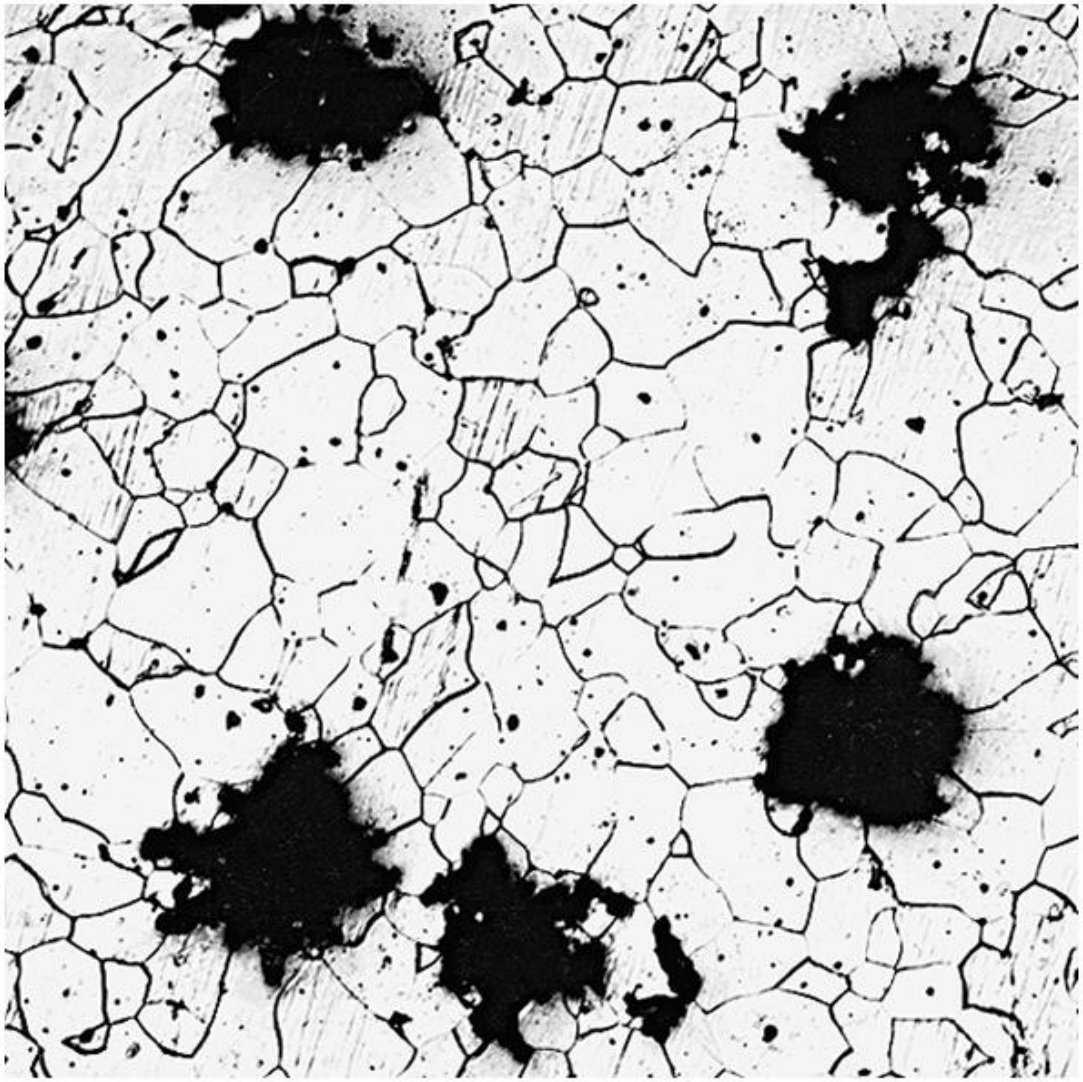
MALLEABLE IRON

- **Malleable iron** is cast as White iron,
- The structure being a metastable carbide in a perlitic matrix.
- Through an annealing heat treatment the brittle as cast structure is transformed.
- Carbon agglomerates into small roughly spherical aggregates of graphite leaving a matrix of ferrite or pearlite according to the exact heat treat used.

Malleable cast iron

- Malleable cast iron
  - Greater ductility than gray cast iron
  - Favorable graphite shape removes the internal notches
- Several types of malleable iron are recognized within the casting industry,

MALLEABLE IRON



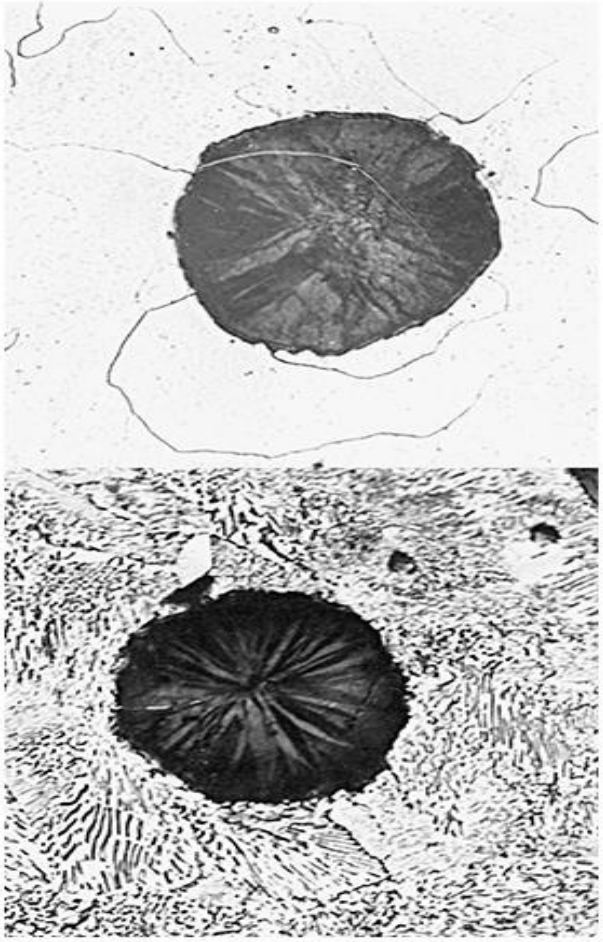
DUCTILE CAST IRON

- In ductile iron the graphite is in the form of spherical *nodules* rather than flakes, thus inhibiting the creation of cracks and providing the enhanced ductility that gives the alloy its name.
- The formation of nodules is achieved by addition of "nodulizers" (for example, magnesium or cerium) into the melt.

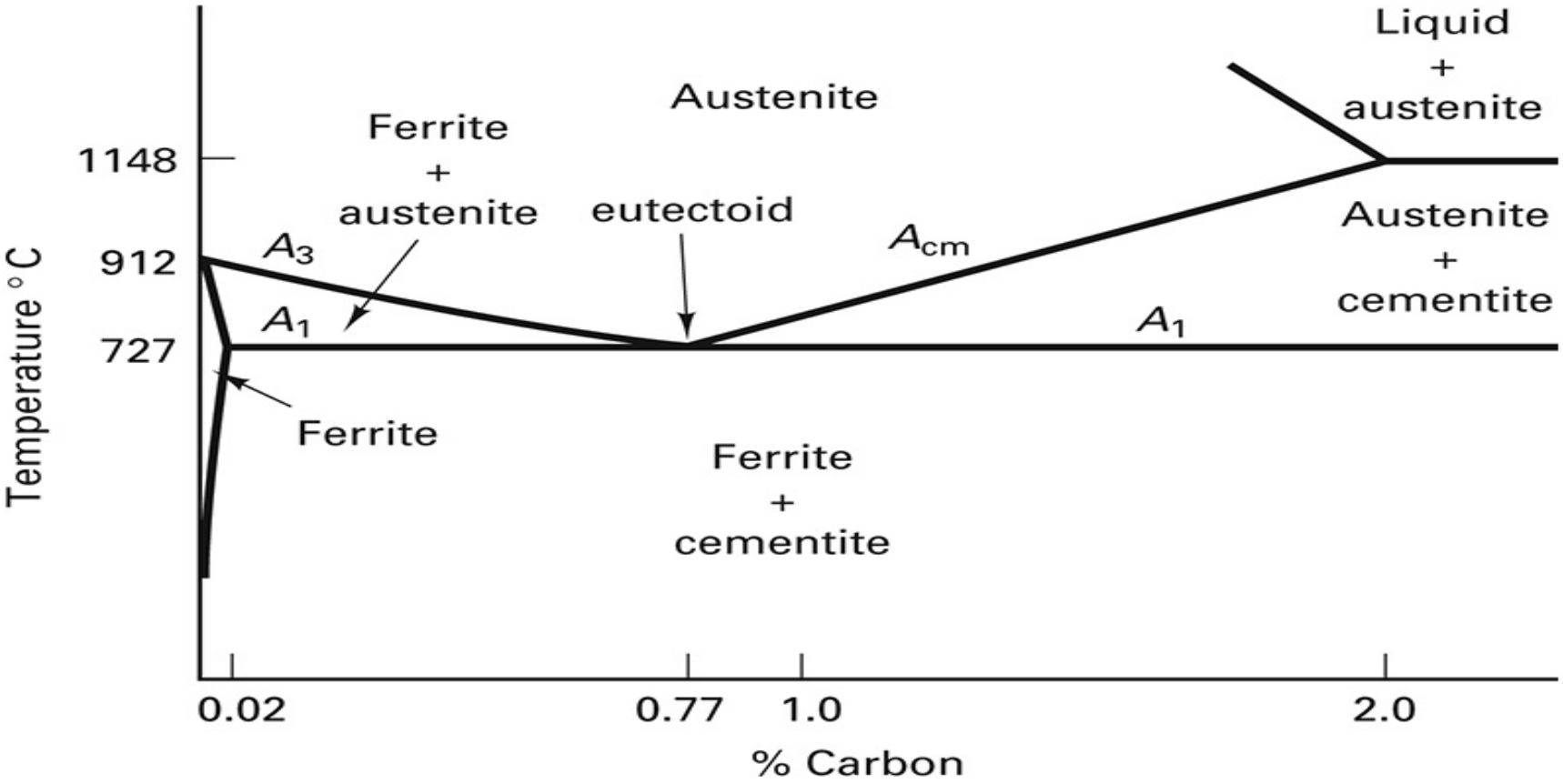
DUCTILE IRON

- **Ductile iron**, also called **ductile cast iron**, **spheroidal graphite iron**, or **nodular cast iron**, is a type of cast iron.[1]
- While most varieties of cast iron are brittle, ductile iron is much more flexible and elastic, due to its nodular graphite inclusions.

DUCTILE CAST IRON



EUTECTOID TRANSFORMATION IN STEEL



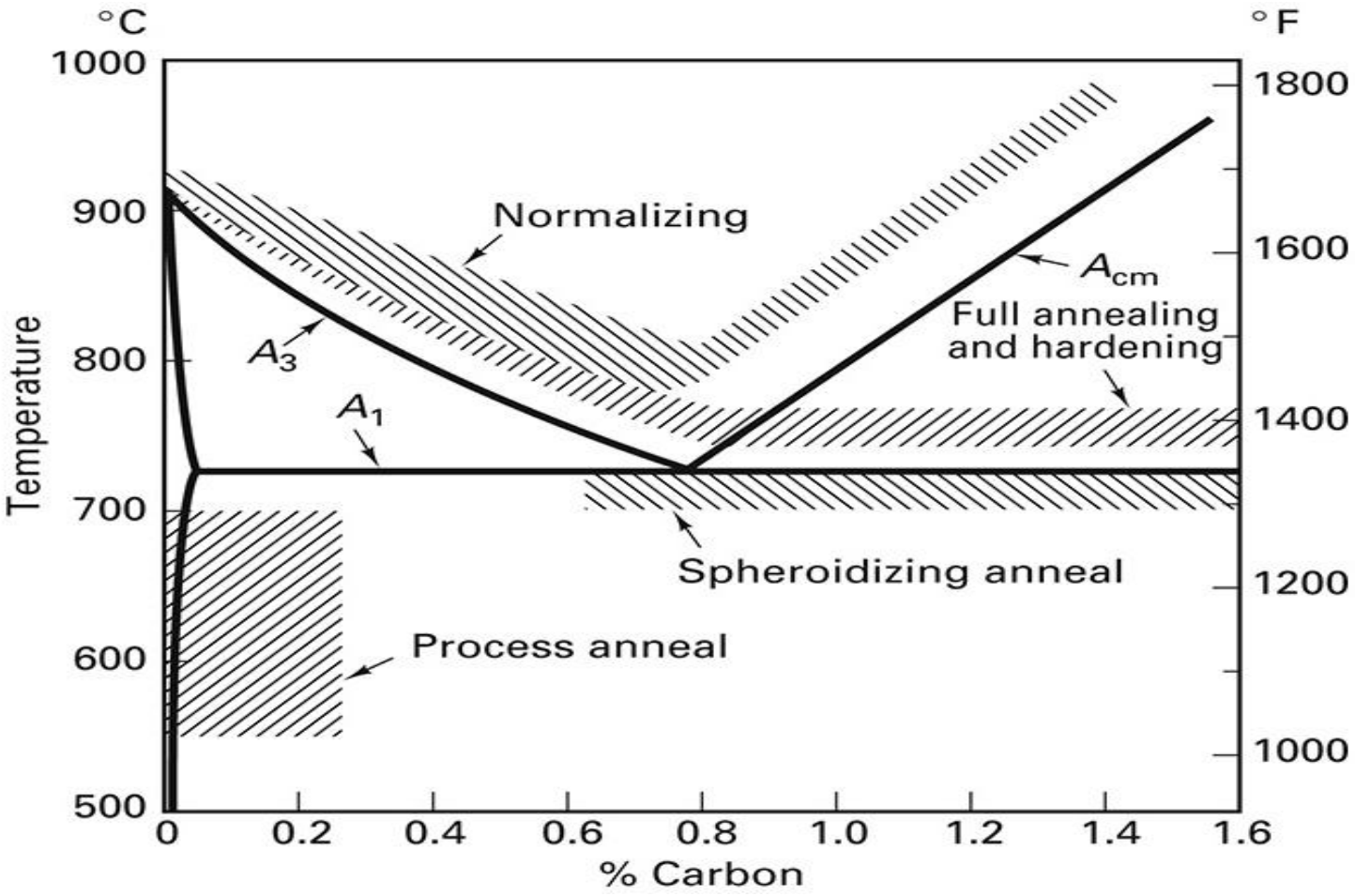
PEARLITE

- **Pearlite** is a two-phased, lamellar (or layered) structure composed of alternating layers of alpha-ferrite (88 wt%) and cementite (12%) that occurs in some steels and cast irons.
- It forms by a eutectoid reaction as austenite is slowly cooled below 727 C.
- The eutectoid composition of Austenite is approximately 0.8% carbon [1];.

PEARLITE

- Steel with less carbon content will contain a corresponding proportion of relatively pure ferrite crystallites that do not participate in the eutectoid reaction and cannot transform into pearlite.
- Steel with more carbon content will contain a corresponding proportion of relatively pure cementite crystallites that do not participate in the eutectoid reaction and cannot transform into pearlite
- Hypo- vs Hypereutectoid steels

KINDS OF THERMAL TREATMENT



Annealing

- Full annealing
  - Hypoeutectoid steels are heated to convert the grain structure to homogenous single-phase austenite, then control cooled
    - The cooling results in coarse pearlite with excess ferrite
    - Results in soft and ductile steel
  - Hypereutectoid steels undergo a similar process but the structure will be coarse pearlite with excess cementite
  - Full anneals are time and energy consuming processes

SPHEROIDIZING ANNEAL

- Applied to high-carbon (.0.6% C) steel
- Heated below A1
- Cementite form globules throughout a ferrite matrix

PROCESS ANNEAL

- Steel is heated to a temperature slightly below A1
- Held long enough to attain recristallization with no phase change
- Recrystallization is induced after a material has been cold worked to reduce strain

Stress-relief anneal

- Reduces residual stresses in casting, welded assemblies, and cold-formed products
- Materials are heated and then slow cooled

NORMALIZING

- Carbon steel is heated to approximately 55 C above Ac3 or Acm for 1 hour;
- The steel completely transforms to austenite
- The steel is then air-cooled, which is a cooling rate of approximately 38 C (100 F) per minute
- This results in a fine pearlitic uniform structure, and a more- structure.
- Normalized steel has a higher strength than annealed steel;
- It has a relatively high strength and ductility.[

Normalizing

- Normalizing vs. annealing
  - In normalizing, cooling will be different in different locations
  - Properties will vary between the surface and interior in normalized steel
  - Lower cost of normalizing is justified if uniform properties are needed

Tempering

- This is the most common heat treatment
- Involves reheating quenched steel to a temperature below the eutectoid temperature then cooling.
- The elevated temperature allows very small amounts of spheroidite to form
- This restores ductility, but reduces hardness.

T-T-T

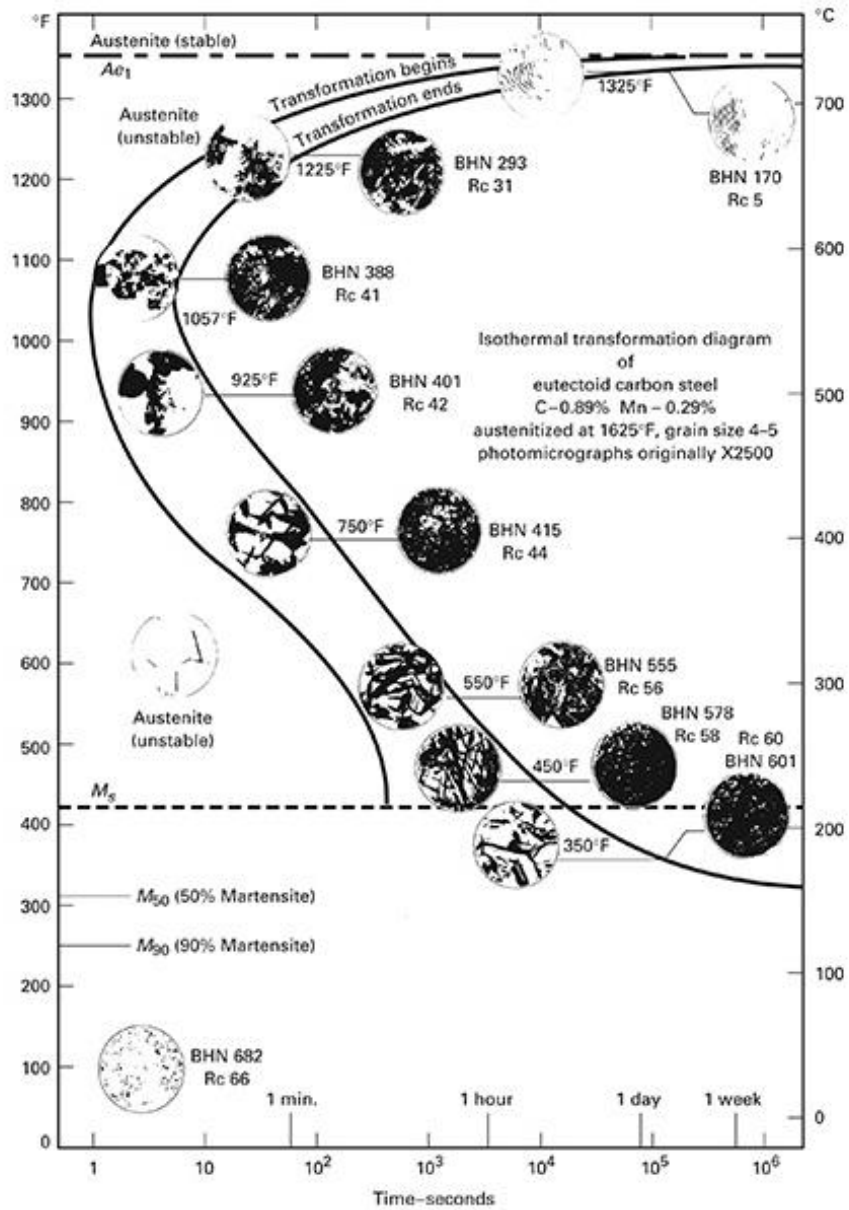
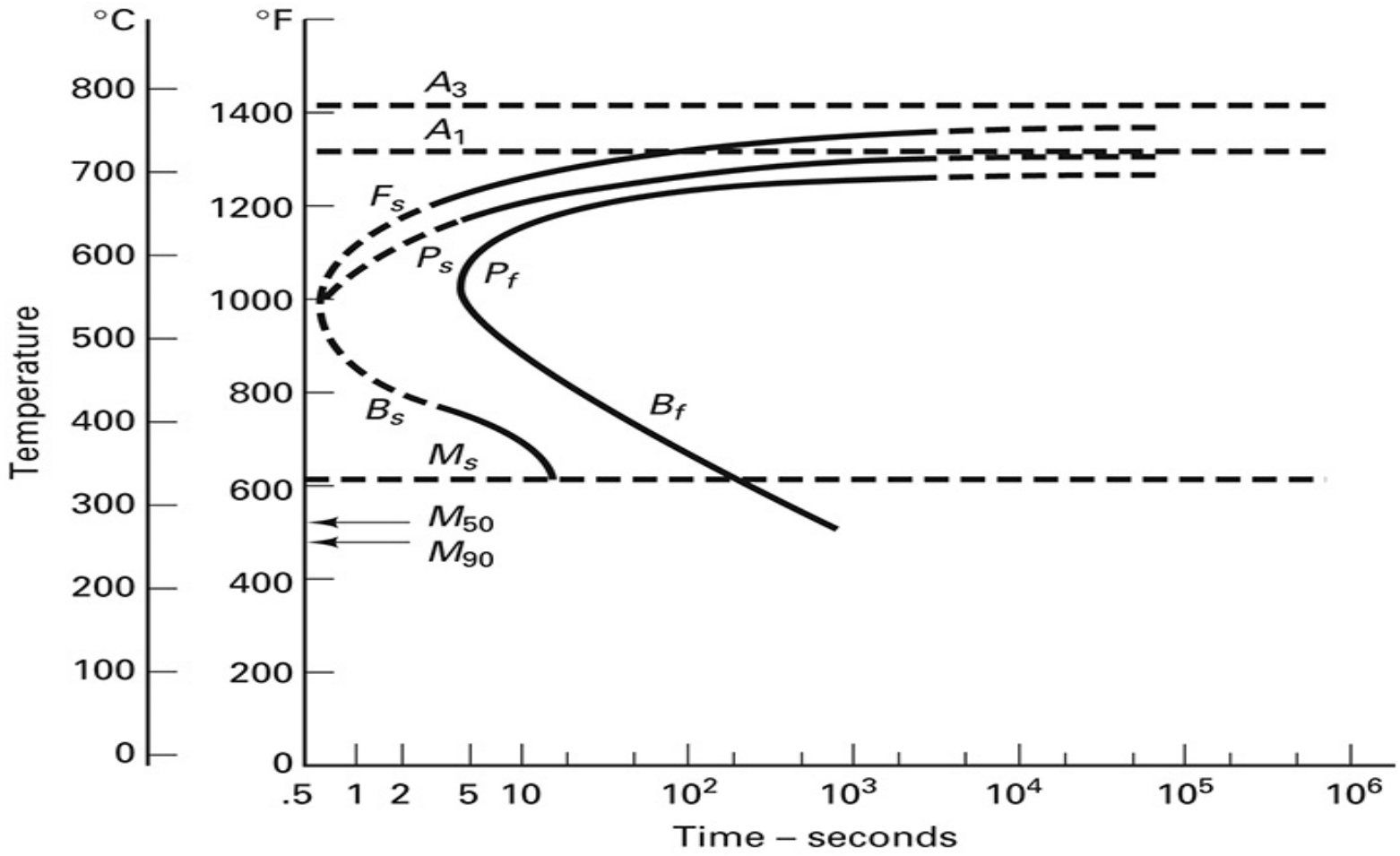


Figure 5-7 Isothermal transformation diagram (T-T-T diagram) for eutectoid composition steel. Structures resulting from transformation at various temperatures are shown as insets. (Courtesy of United States Steel Corp., Pittsburgh, PA.)

CCT OF STEEL


°C
°F
Temperature
800
700
600
500
400
300
200
100
0
1400
1200
1000
800
600
400
200
0
A_3
A_1
F_s
P_s
P_f
B_s
B_f
M_s
M_{50}
M_{90}
.5
1
2
5
10
10^2
10^3
10^4
10^5
10^6
Time – seconds

MARTENSITE TRANSFORMATION

- Carbon steel with at least 0.4 wt% C is heated to normalizing temperatures and then rapidly cooled (quenched) in water, brine, or oil to the critical temperature.
- The critical temperature is dependent on the carbon content, but as a general rule is lower as the carbon content increases.
- The steel possesses a super-saturated carbon content.
- The steel is extremely hard but brittle, usually too brittle for practical purposes.
- The internal stresses cause stress cracks on the surface.

Tempering of Martensite

- Initially after it has been quenched, martensite lacks the toughness and ductility for engineering applications.
- Tempering is a subsequent heating to give the steel necessary ductility and fracture toughness

Maraging steels

- **Maraging steels** (a portmanteau of martensitic and aging) are iron alloys which are known for possessing superior strength and toughness without losing malleability.
- A special class of low carbon ultra-high strength steels which derive their strength not from carbon, but from precipitation of inter-metallic compounds.
- The principal alloying element is 15 to 25% nickel.[1]
- Secondary alloying elements are added to produce intermetallic precipitates, which include cobalt, molybdenum, and titanium.[1]
- Original development was carried out on 20 and 25% Ni steels to which small additions of Al, Ti, and Nb were made.

Quench Media

- Quenchants are the medium in which a material is quenched
  - Selected to provide necessary cooling rates
- Stages of quenching
  - Formation of the vapor jacket
    - Vapor jacket is the thin gaseous layer between the metal and the liquid during cooling
  - Nucleate boiling phase
    - Produces rapid rates of cooling down to the boiling point of the quenchant
  - Conduction and convection
    - Slower cooling from the boiling point to room temperature

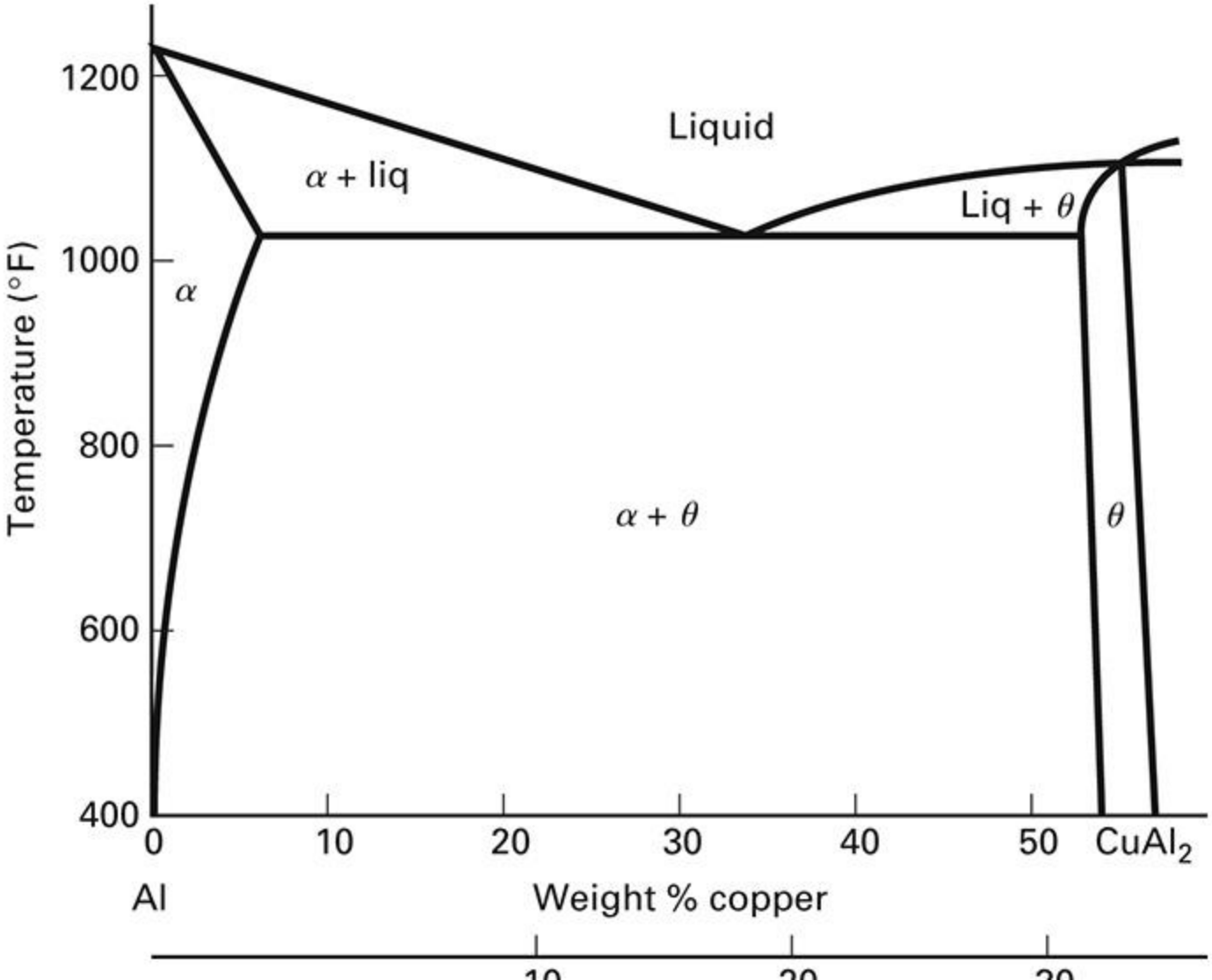
Quenching Considerations

- Water is an effective quenching medium because of its high heat of vaporization and relatively high boiling point
  - The quenchant should be agitated due to the tendency of bubbles to form soft spots on the metal
  - A negative consequence is that it may oxidize the material
- Brine is similar to water as a quenchant medium
  - Rapid cooling occurs because the salt nucleates bubbles
  - Corrosion problems may exist

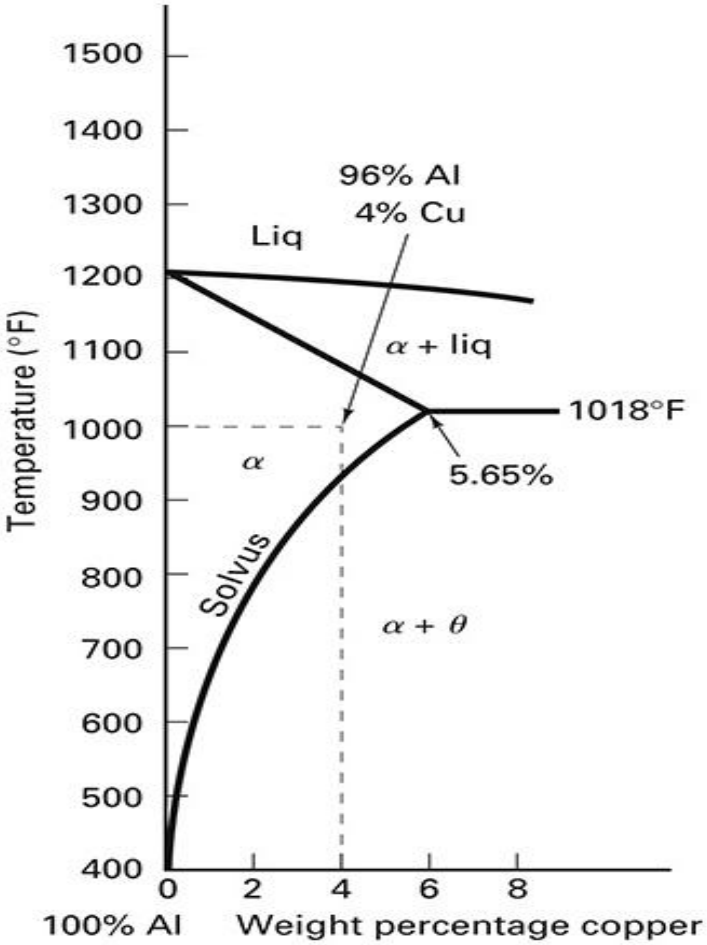
Quenching Considerations

- Oil is utilized if slower quenching rates are desired
  - Oil may cause water contamination, smoke, fumes, etc.
  - More expensive than water or brine quenchants
- Water based polymer quenchants have properties between oil and water and brine
- Molten salt baths may be used for even slower cooling rates
- High pressure quenching uses a stream of flowing gas to extract heat

Cu-Al Phase Diagram



THERMAL TREATMENT OF Cu-Al ALLOY AT $% of Al



5.7 Furnaces

- Furnace types
  - Parts remain stationary in batch furnaces
  - Continuous furnaces move the components through heat treating processes that are compatible with other manufacturing processes
    - Box furnaces are horizontal batch furnaces
    - Car-bottom-box furnaces are used for large and long workpieces
  - Bell furnaces place a “bell” over the workpiece to control heating and cooling
    - Elevator furnaces
  - Vertical pit furnaces prevent horizontal sagging or warping

Furnace Atmospheres

- Artificial gas atmospheres
  - Prevents scaling or tarnishing
- Fluidized-bed
  - Inert particles are heated and suspended in a stream of gas
- Salt bath furnaces
  - Salt is heated by passing a current between two electrodes placed in the batch
  - Lead pot is a bath where lead is used instead of salt
- Electrical induction heating