Introduction to Iron Metallurgy

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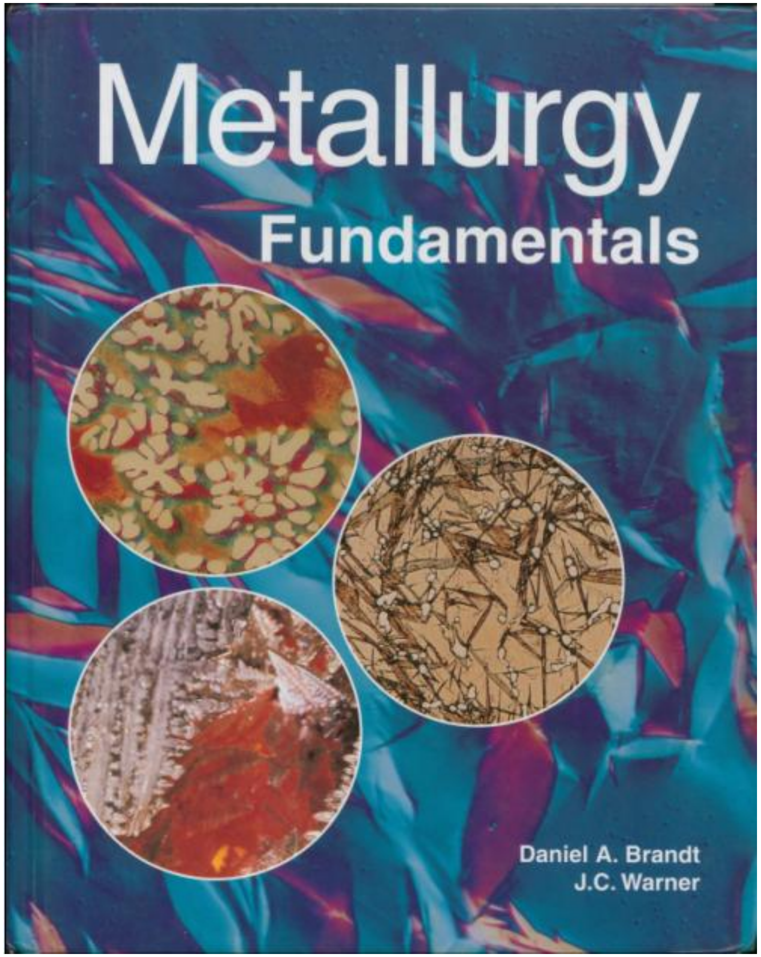
Houston Home Metal Shop Club
October 2010

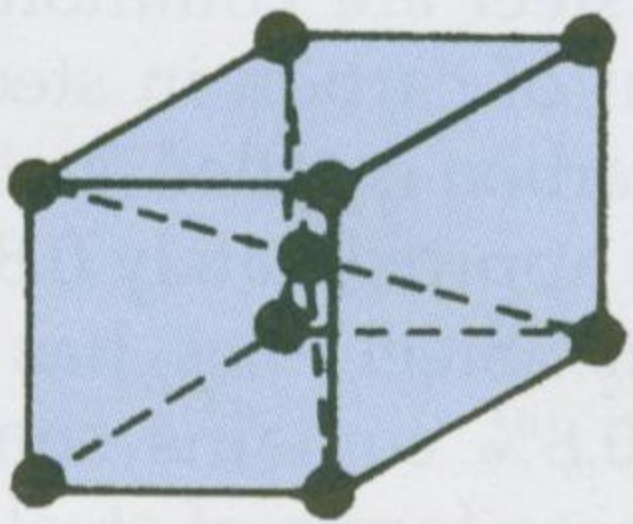
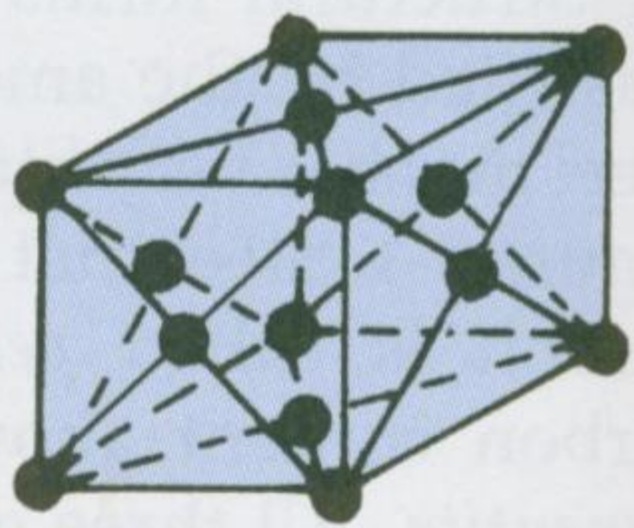
Book I stole the pictures from…



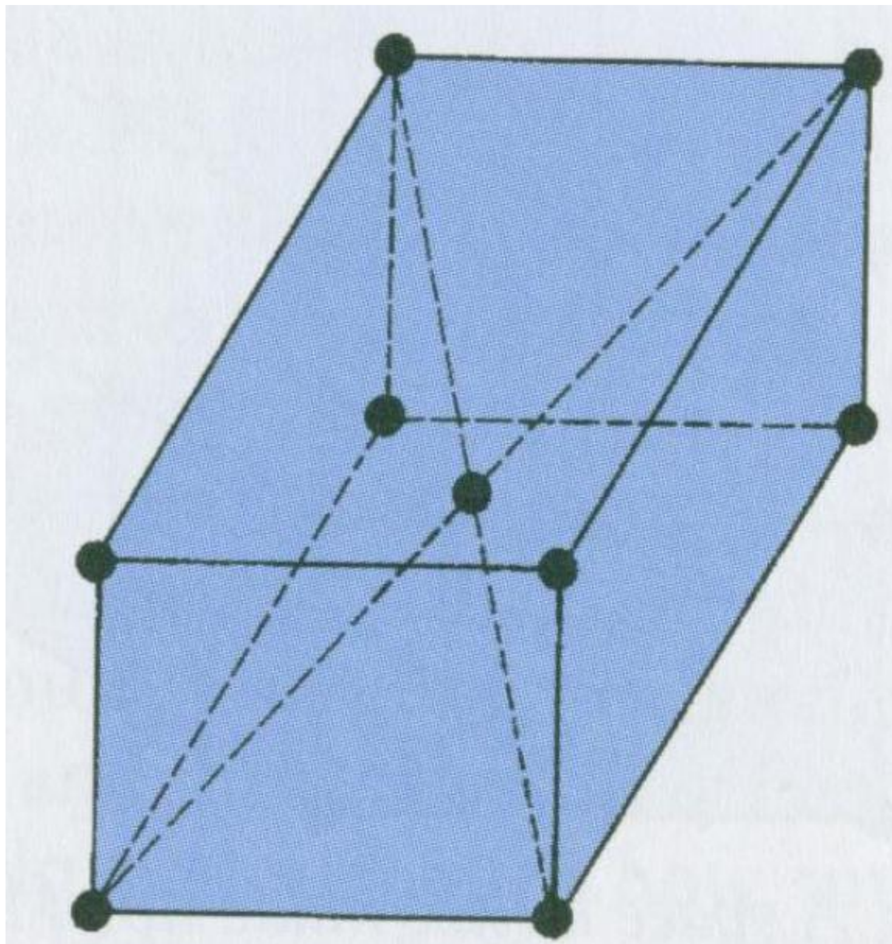
We will start with a brief overview!

Metals Are Crystals

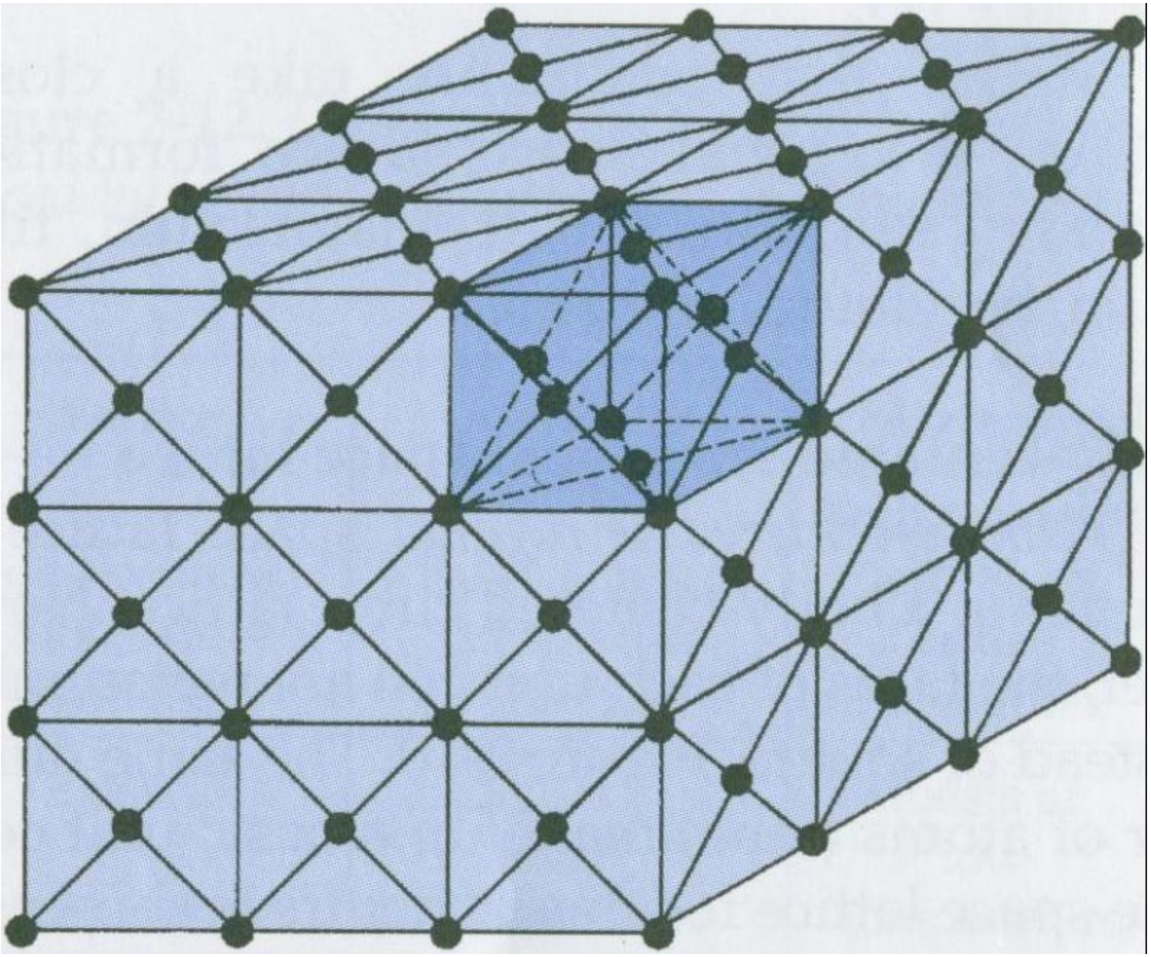
- Fundamental geometry of a crystal is the unit cell
  - Small box that is exactly repeated as you move across the crystal structure
- Iron has three crystalline structures:
  - Ferrite: Body Centered Cubic
  - Austenite: Face Centered Cubic
  - Martensite: Body Centered Tetragon

Ferrite	Austenite
• Low temperature • Body-centered cubic	• High temperature • Face-centered cubic
	

Body Centered Tetragonal Unit Cell-Martensite



Unit Cells in a Lattice - Austenite



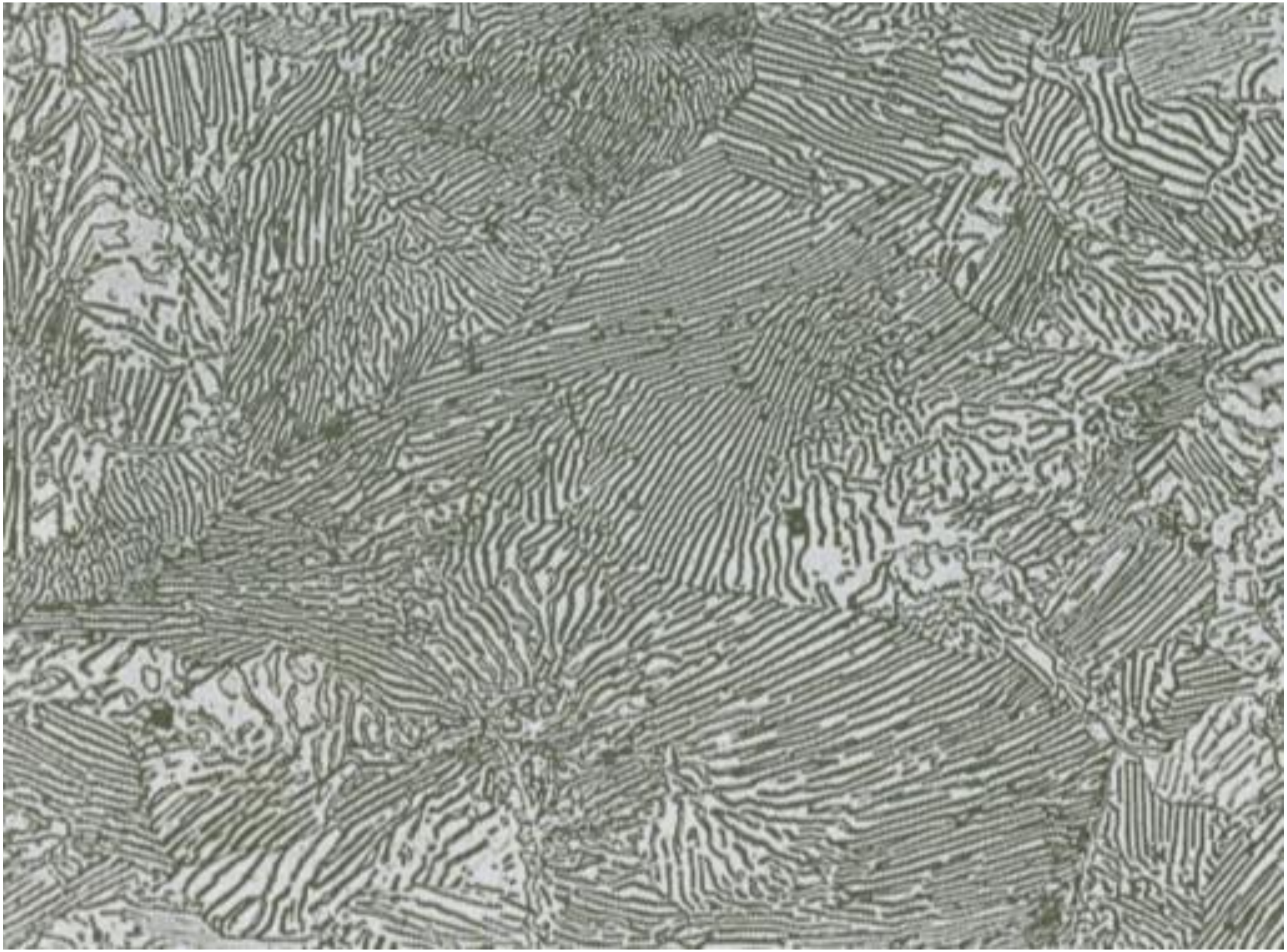
Now Add Carbon

- Solid solutions of carbon in iron are the foundational technology of our civilization
- Ferrite can absorb .025% carbon in its’ crystal lattice
- With more carbon you form Fe_3C, Iron Carbide
- Iron Carbide is Cementite
- Cementite is 6.67% carbon
- Pure Cementite is too brittle to be useful

If you have less than 6.67% Carbon, you get mixtures

- With .83% Carbon, you get Pearlite
  - Fine layers of cementite and ferrite
  - Looks like an aerial photo of plowed hills

Pearlite
1095



With less than .83% carbon, you get:

Regions of Pearlite and Regions of Ferrite

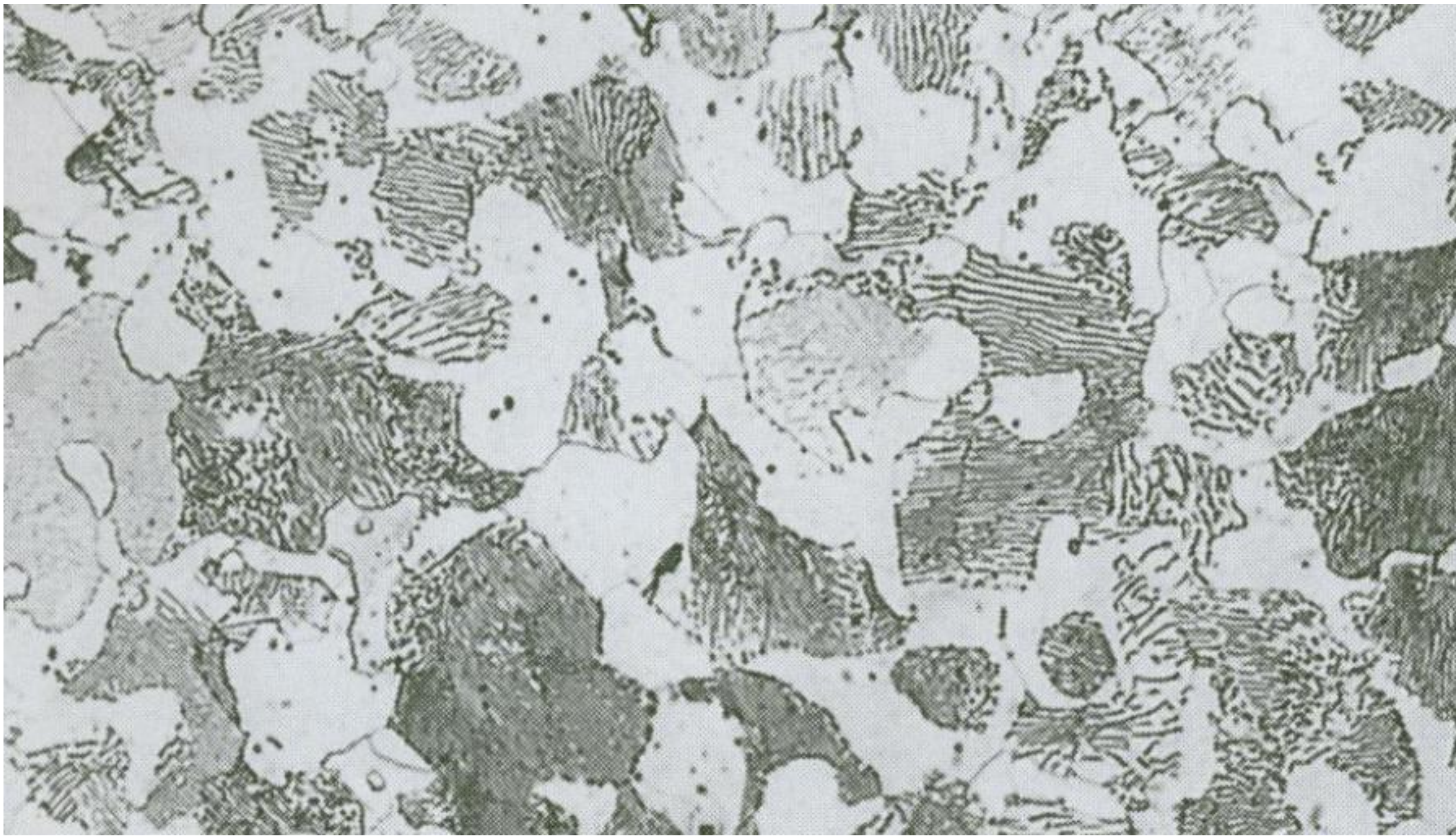
With more than .83% carbon, you get:

Regions of Pearlite and Regions of Cementite

Bottom Line:

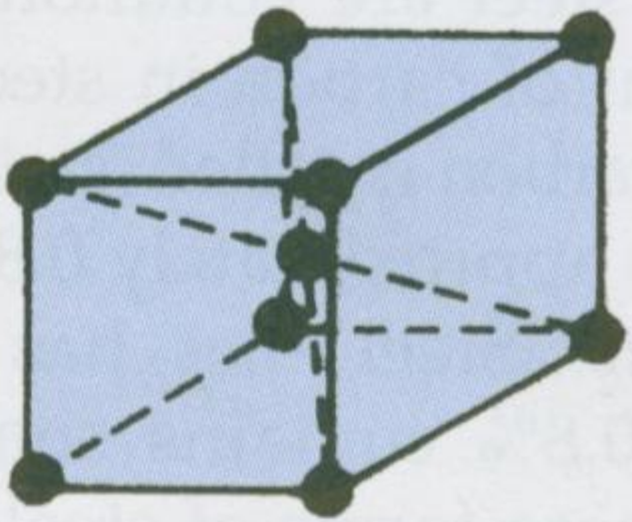
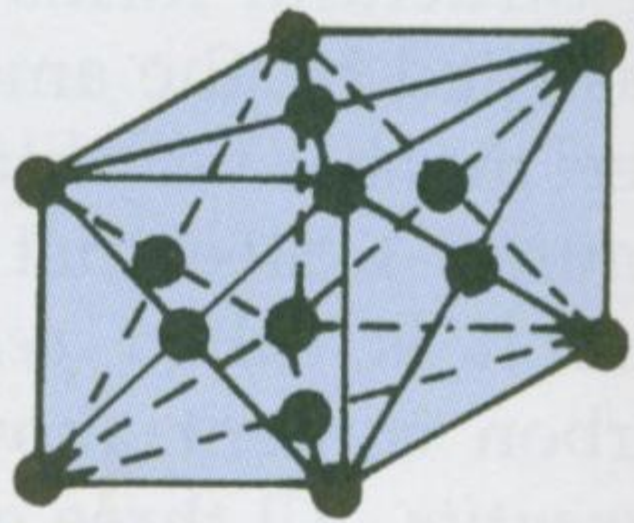
At room temperature and at equilibrium, iron-carbon alloys will be ferrite, cementite, pearlite, or mixtures of these.

Areas of Pearlite and Ferrite



Now Add Heat…

- With heating to 723°C or 1333°F:
  - Pearlite, Ferrite, Cementite are transformed to:
- Austenite
  - Can hold much more carbon – up to 2.06%
  - Only exists at high temperatures in Iron-Carbon alloys

Ferrite	Austenite
• Low temperature • Body-centered cubic	• High temperature • Face-centered cubic
	

From a home workshop perspective, 723^{o}C or 1333^{o}F is Cherry Red

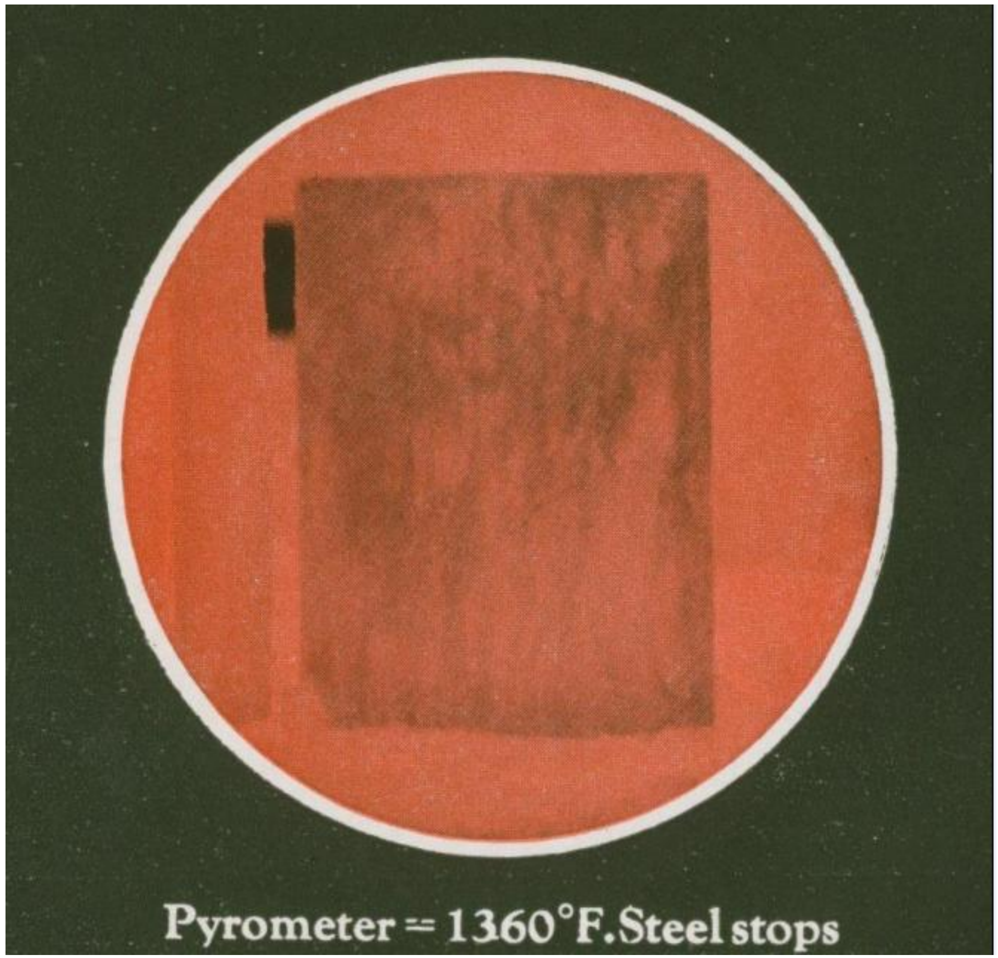
COLOR SCALE

	Fahr.	Cent.
WHITE	2200°	1200°
LIGHT YELLOW	1975°	1080°
LEMON	1830°	1000°
ORANGE	1725°	940°
DARK ORANGE	1680°	890°
SALMON	1550°	840°
BRIGHT CHERRY	1450°	790°
CHERRY	1375°	745°
MEDIUM CHERRY	1275°	690°
DARK CHERRY	1175°	635°
BLOOD RED	1075°	580°
FAINT RED	930°	500°

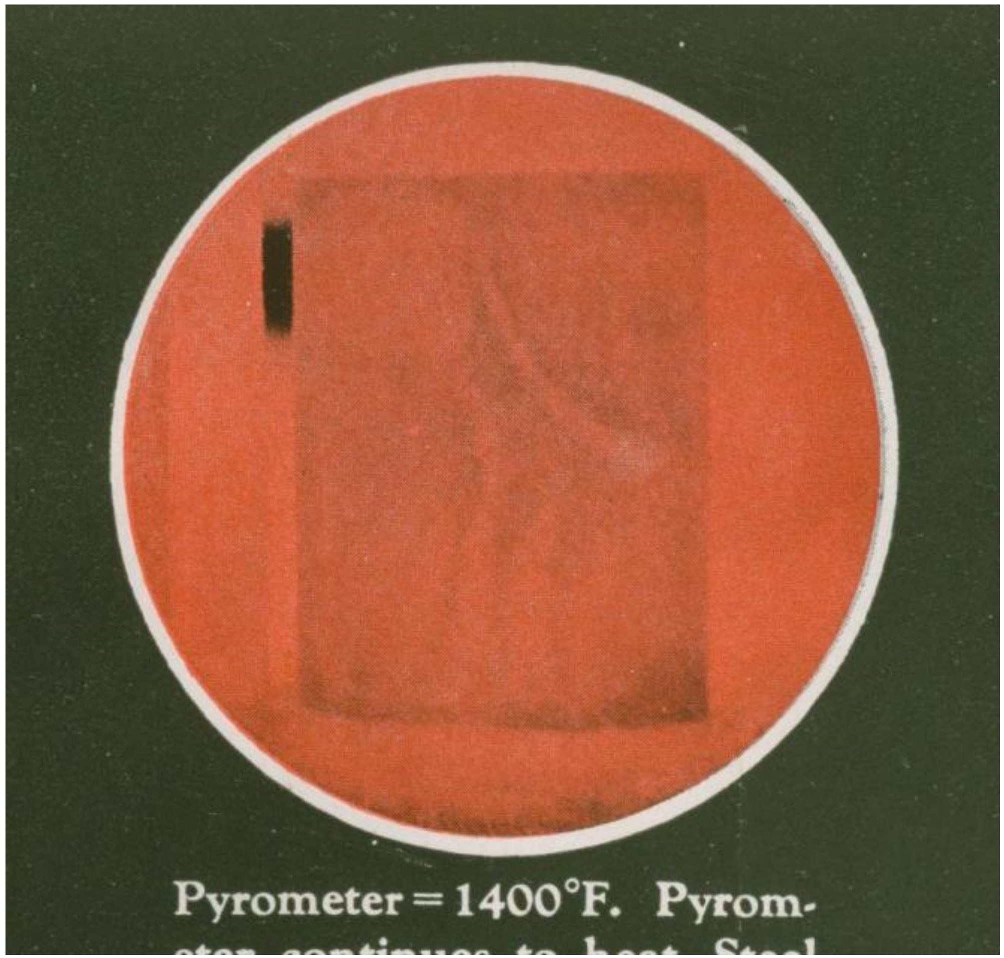
- Just like the phase transformation of melting ice to water holds the temperature of a glass of warming water, the phase transformation of pearlite to austenite will hold the temperature of a block of warming steel.

Heating Steel – 1300 Deg F

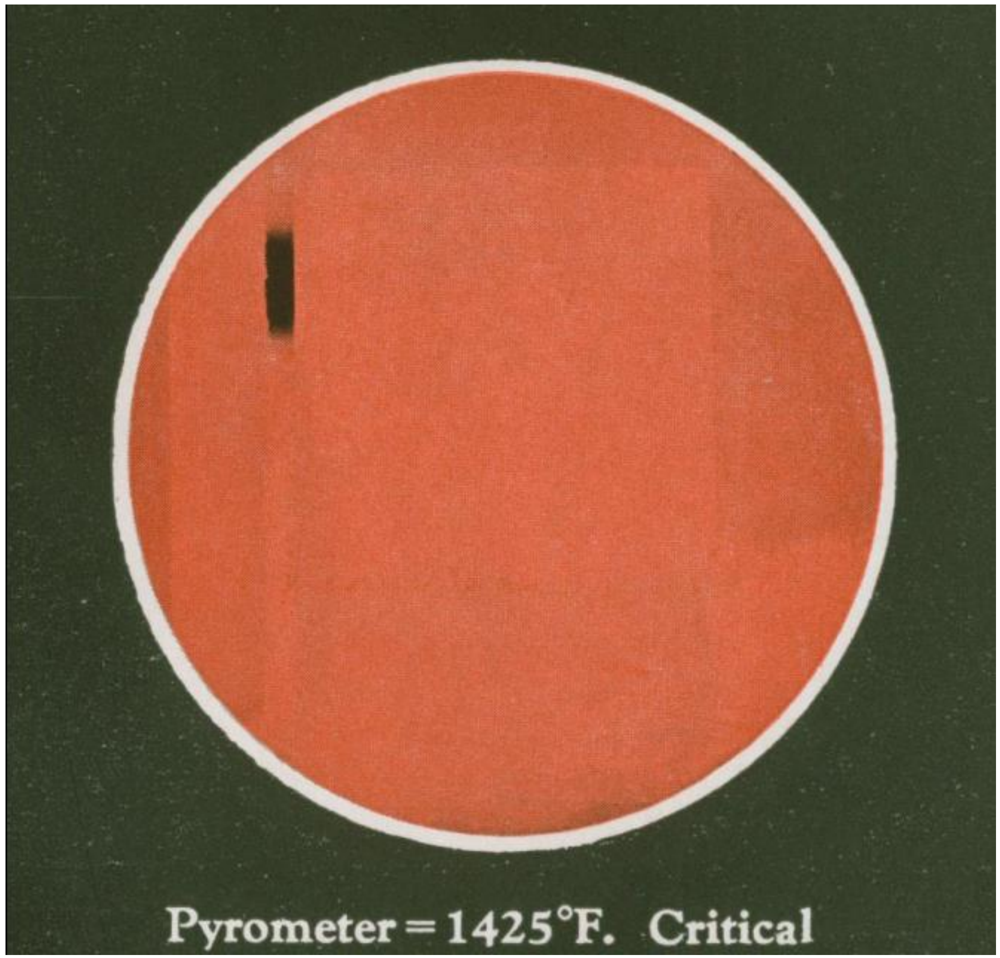
Heating Steel – 1360 Deg F



Heating Steel – 1400 Deg F

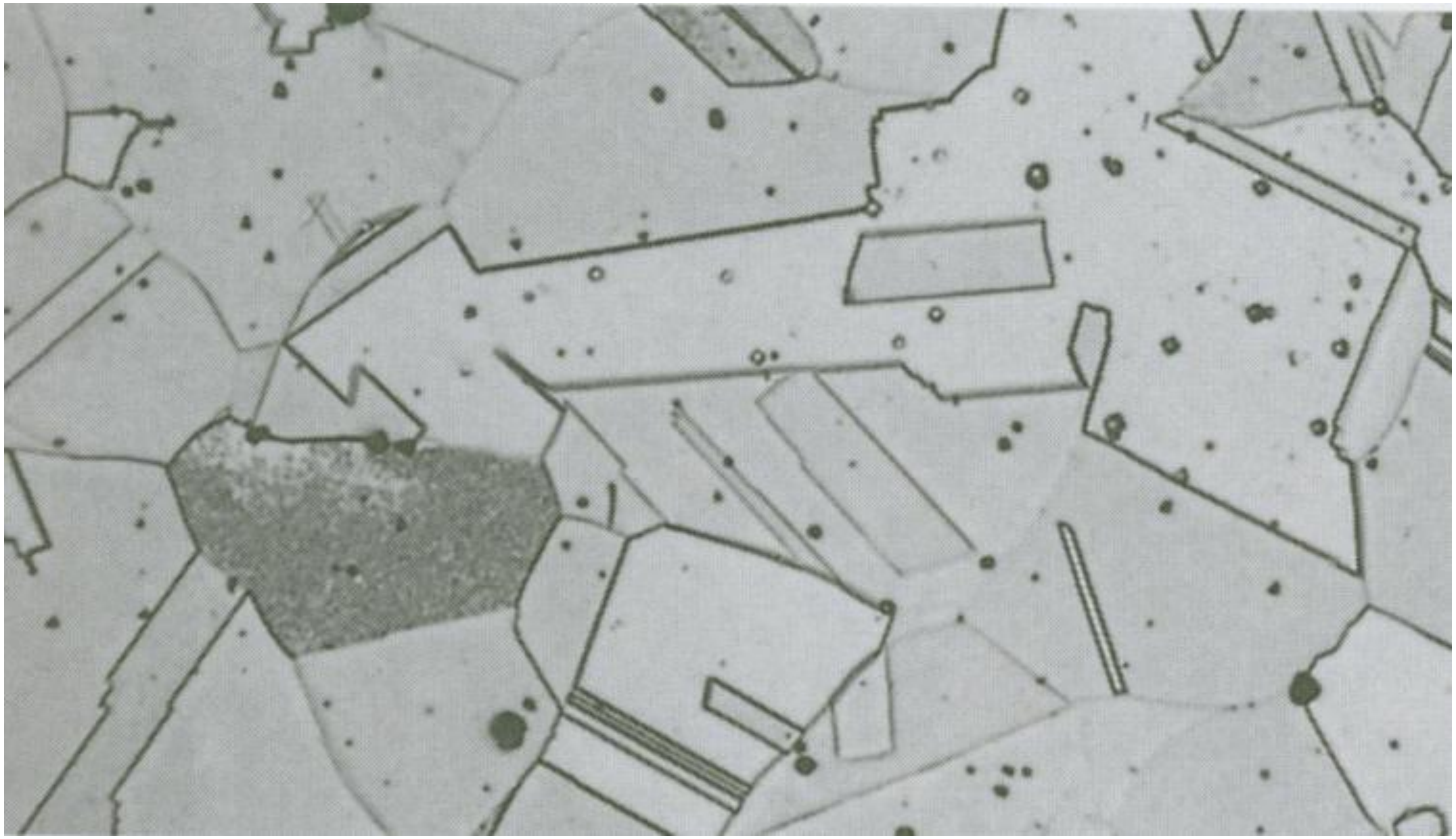


Heating Steel – 1425 Deg F



Certain alloys with other elements besides carbon and iron will maintain the austenite structure at room temperature so we can see it under the microscope.

303



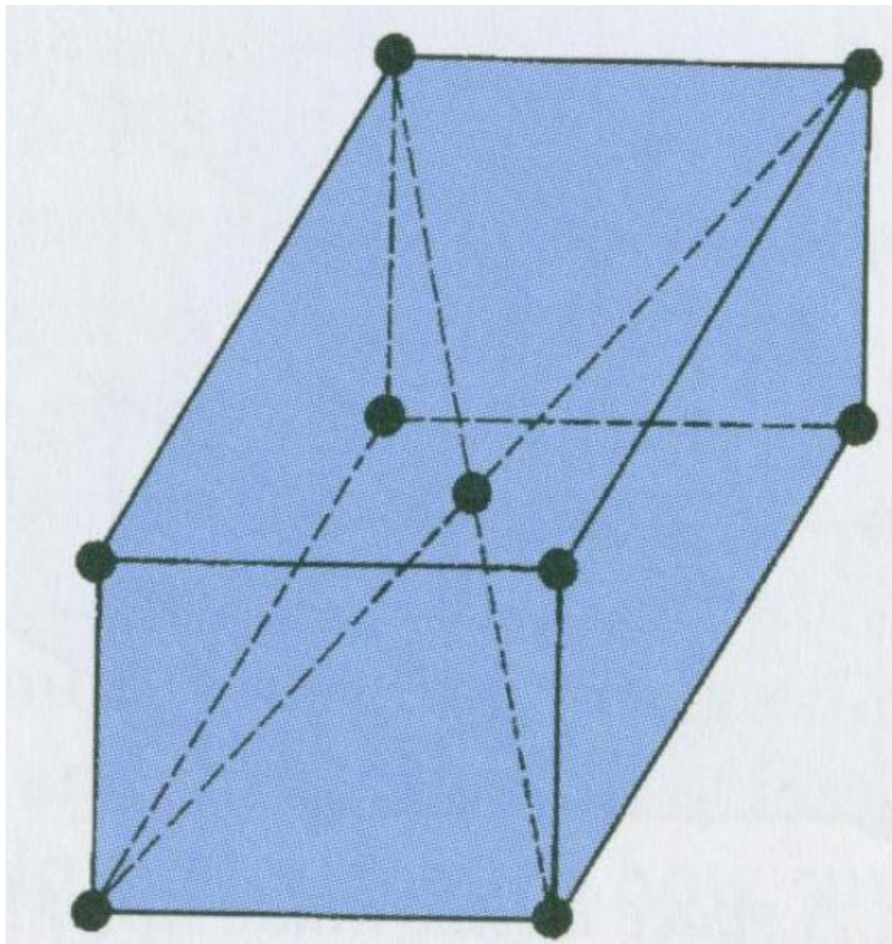
Remove Heat Slowly:

- Austenite reverts to
  - Pearlite
  - Ferrite
  - And/or Cementite
- Slow heat removal means the phases or states can come into equilibrium

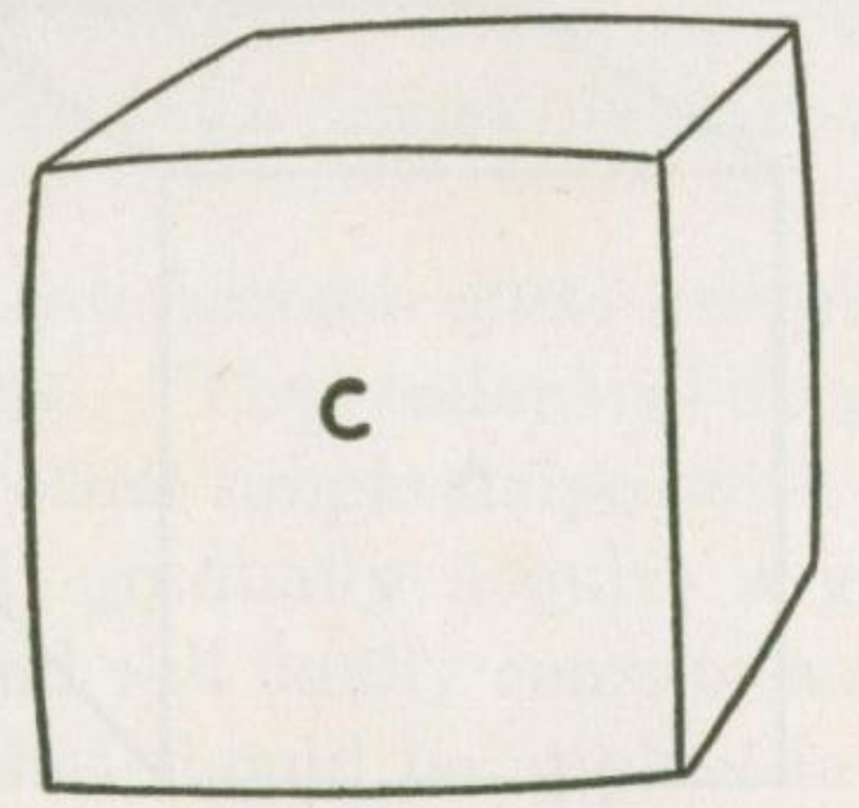
Remove Heat quickly:

- Austenite transforms to
  - Martensite
    - Very strained
    - Very Brittle
    - Very Hard

Body Centered Tetragonal Unit Cell- Martensite

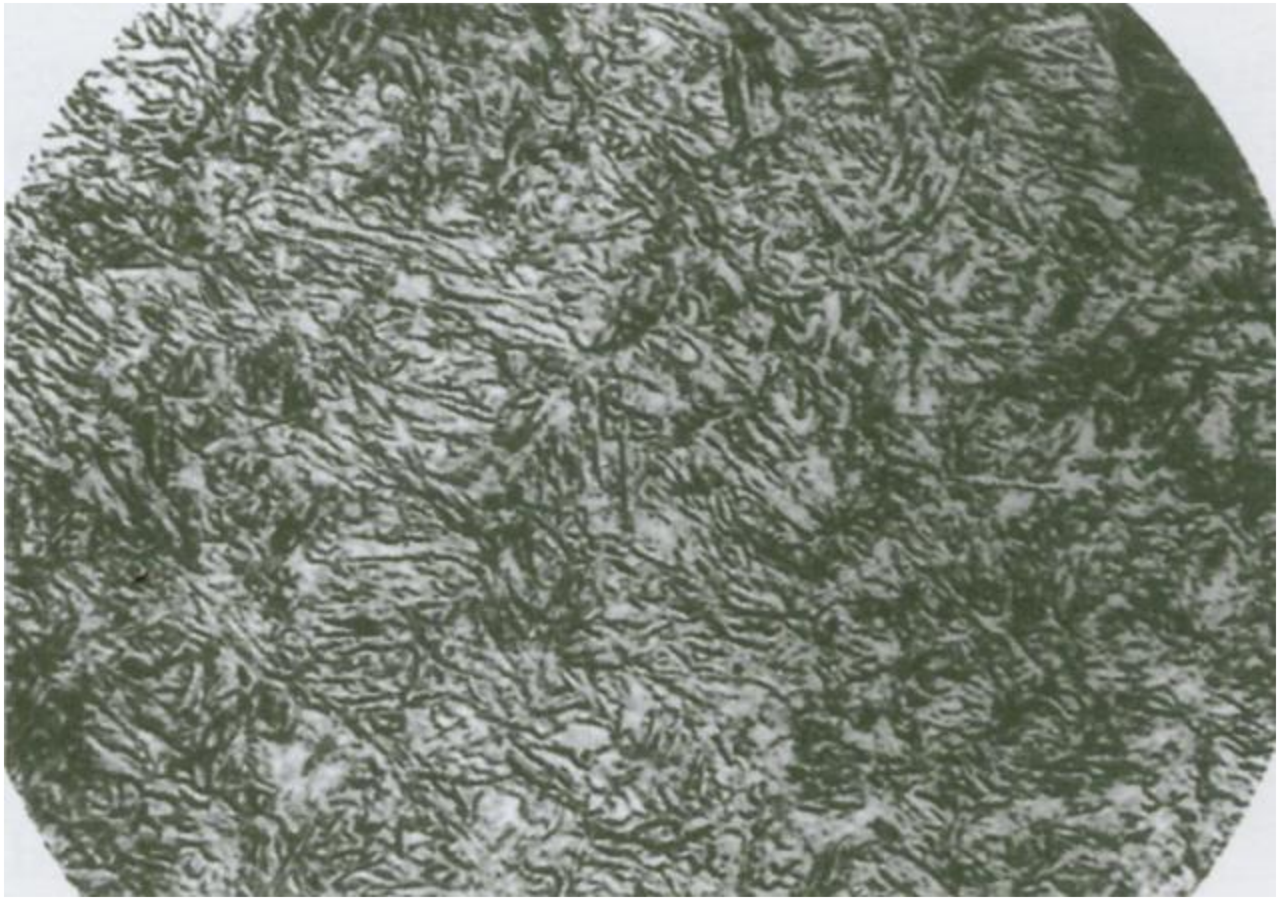


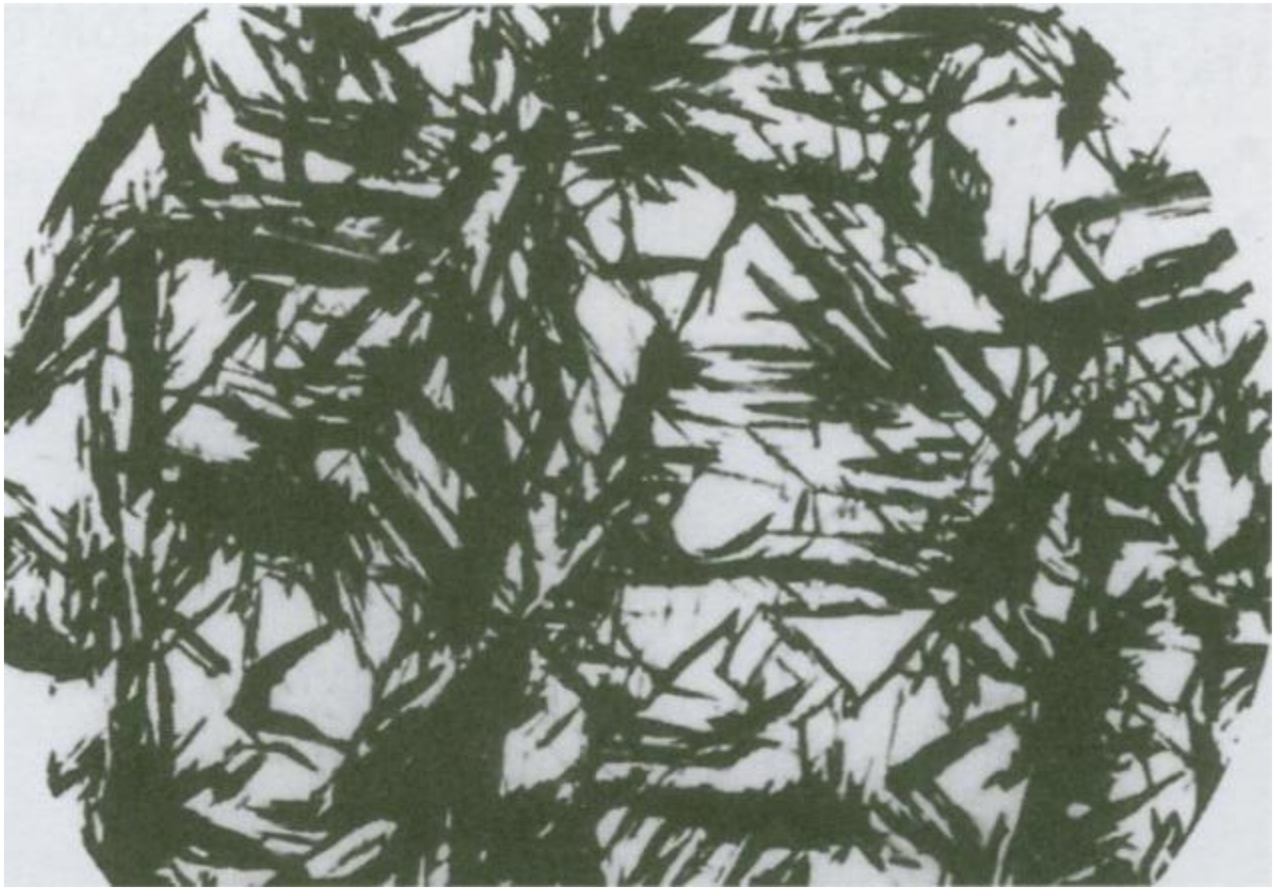
Mechanical Distortion from Quenching



After quench-
Bulge of approx. 004"

MartinsiteNeedles

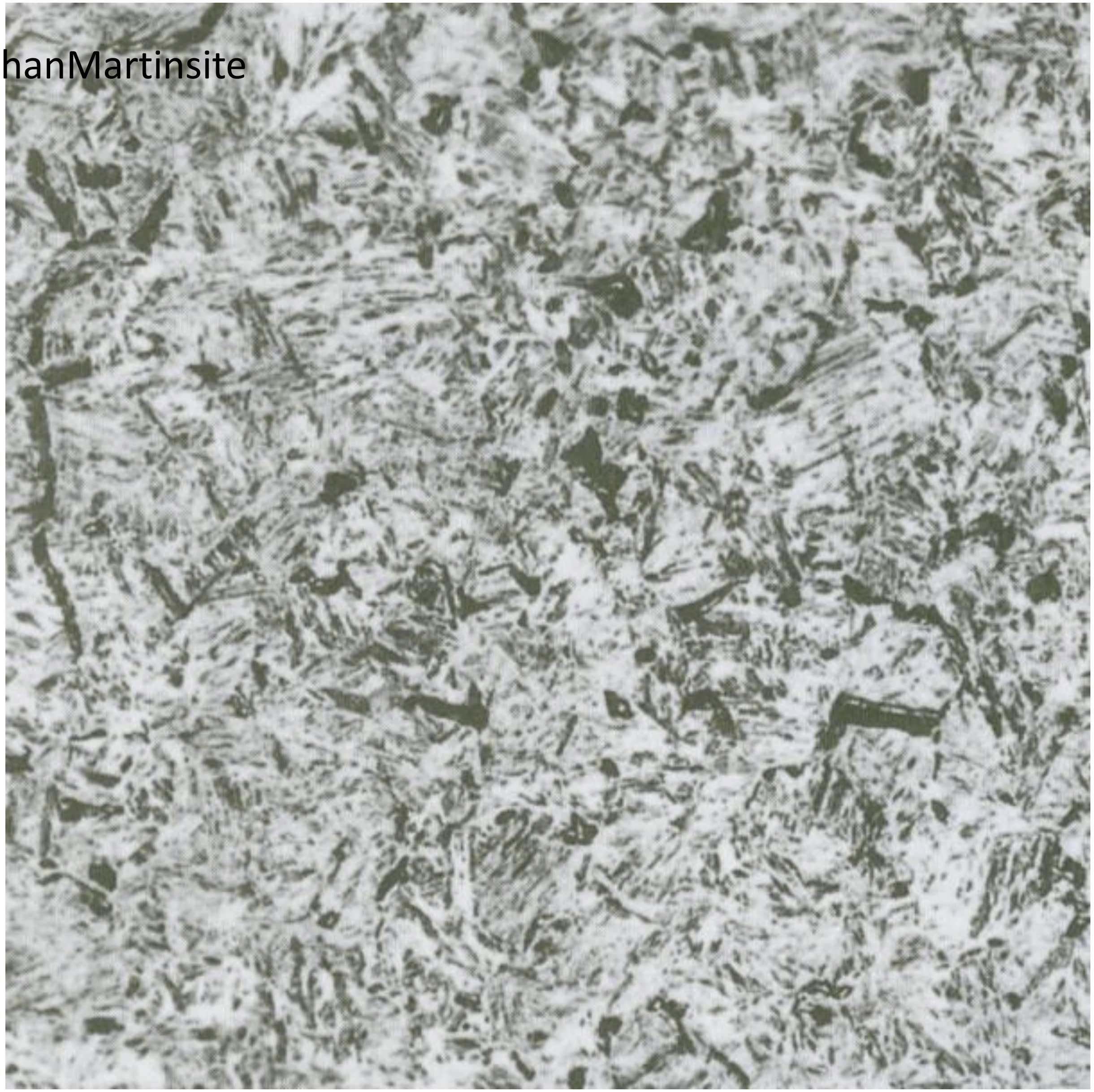




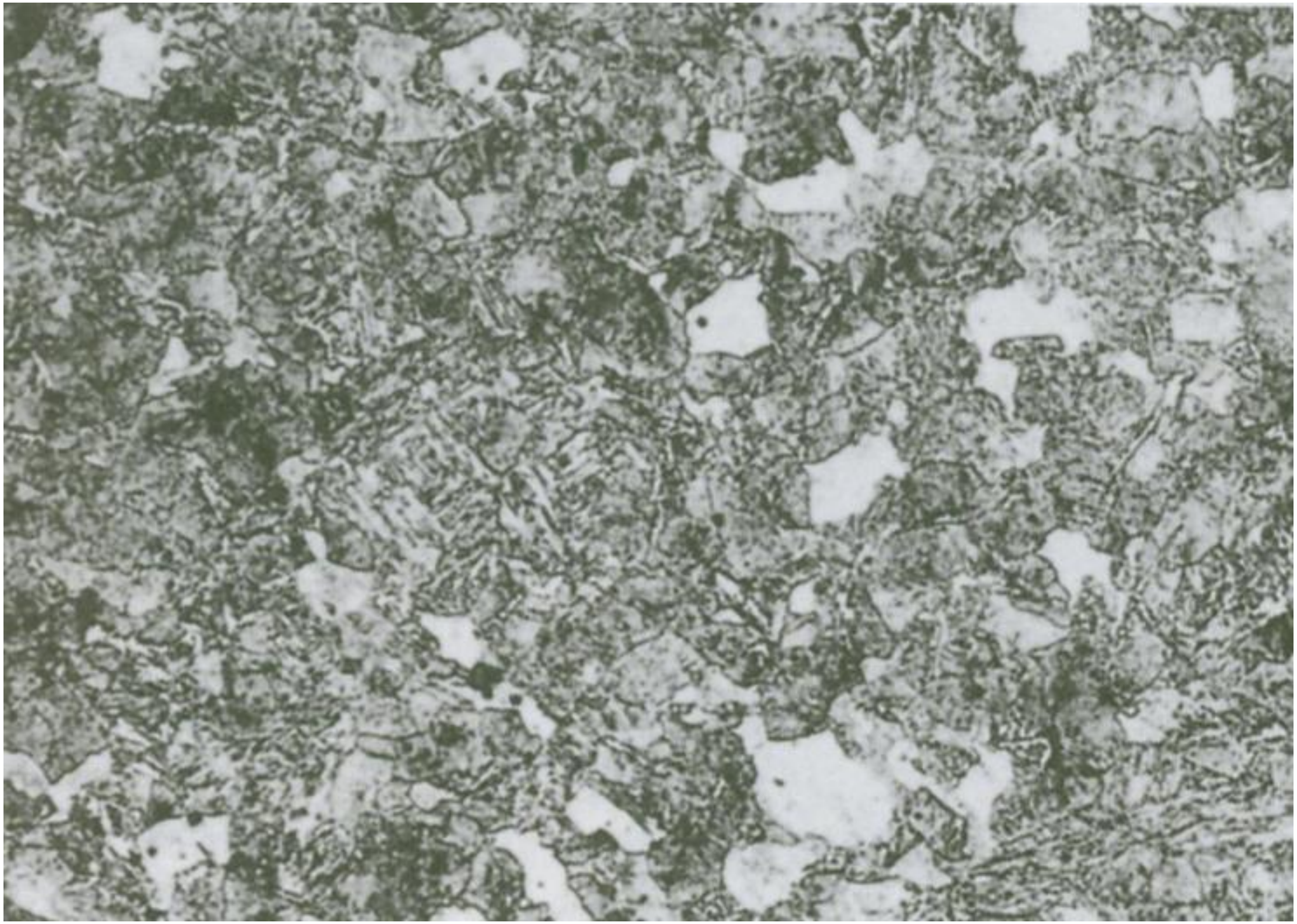
Reheat less and cool in a controlled way:

- The Martensite (or some of it) gets converted to:
  – Pearlite
  – Cementite
  – And/or Ferrite
- The resulting mixture is Bainite

BainiteDarkerthanMartinsite



1045 MartinsiteFerrite with bainite pearlite



One more concept: Grain Size

- If the grains are larger, the metal is more ductile. More heat results in more equilibration and more chances for grains to grow.
- If the grains are smaller, the metal is stronger. Cracks have a harder time propagating across grain boundaries. Less heating and more rapid cooling keeps grain sizes smaller.

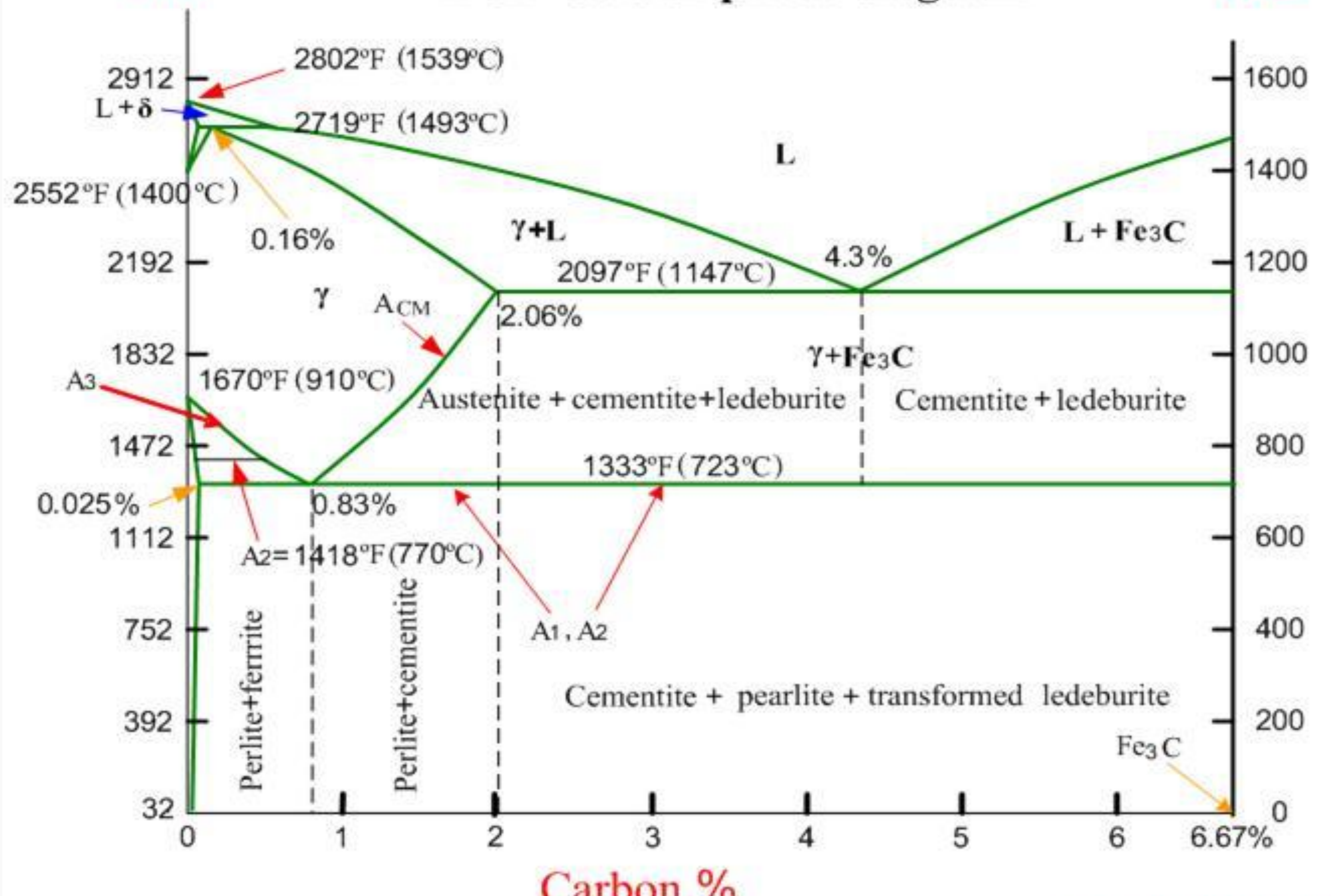
Now that we have had the big picture overview, we are ready to review two key diagrams:

- Iron-Carbon Equilibrium Phase Diagram
- Isothermal Transformation Diagram

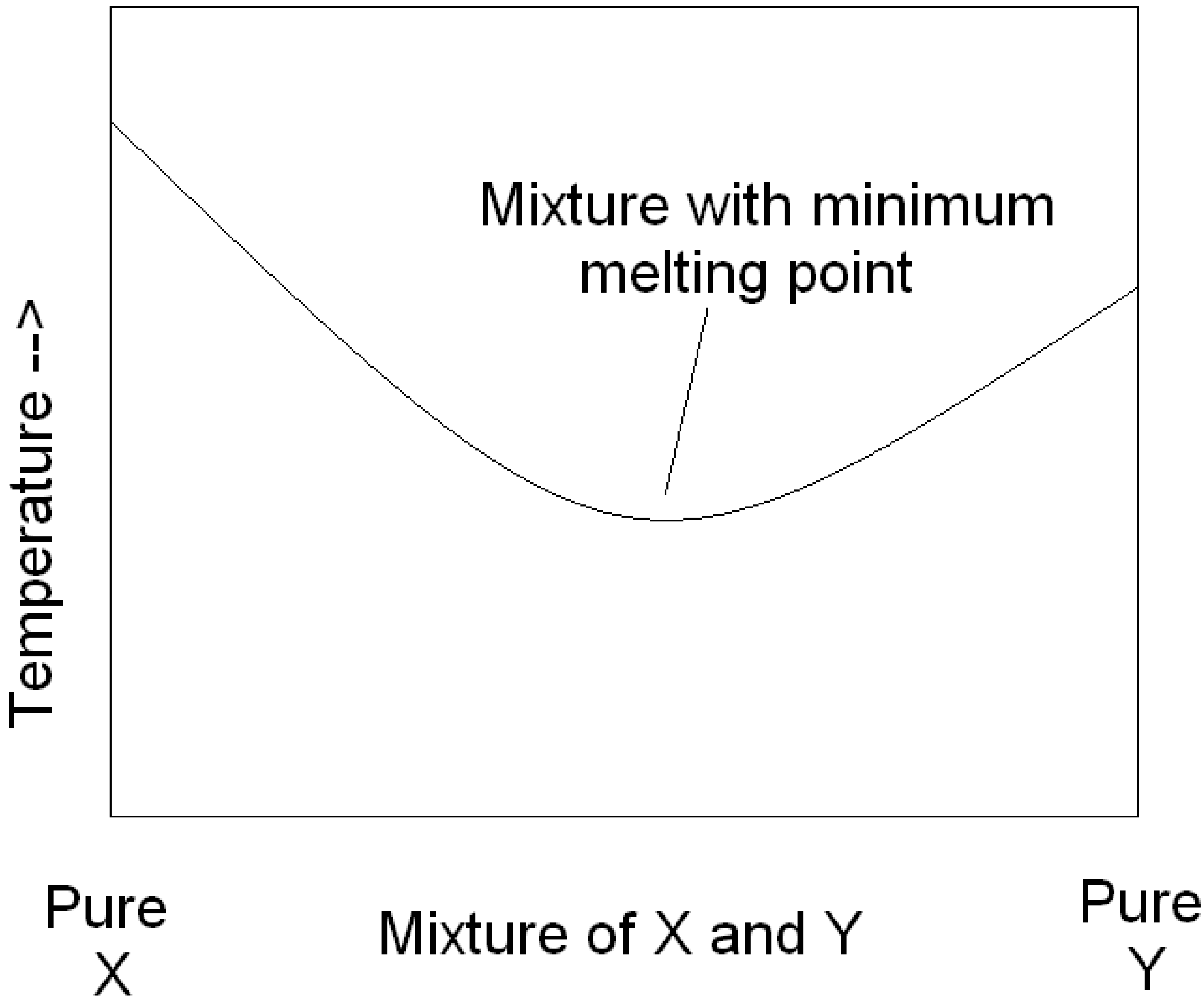
Start with the Iron-Carbon Phase Diagram

- Equilibrium states – shows results from very slow cooling
- Plots percent carbon along horizontal axis and temperature along vertical
- Any point on the horizontal axis represents metal with a fixed composition.
- With a given piece of metal, all you can do is move vertically by heating or cooling it.

Iron - carbon phase diagram



A Eutectic is a:

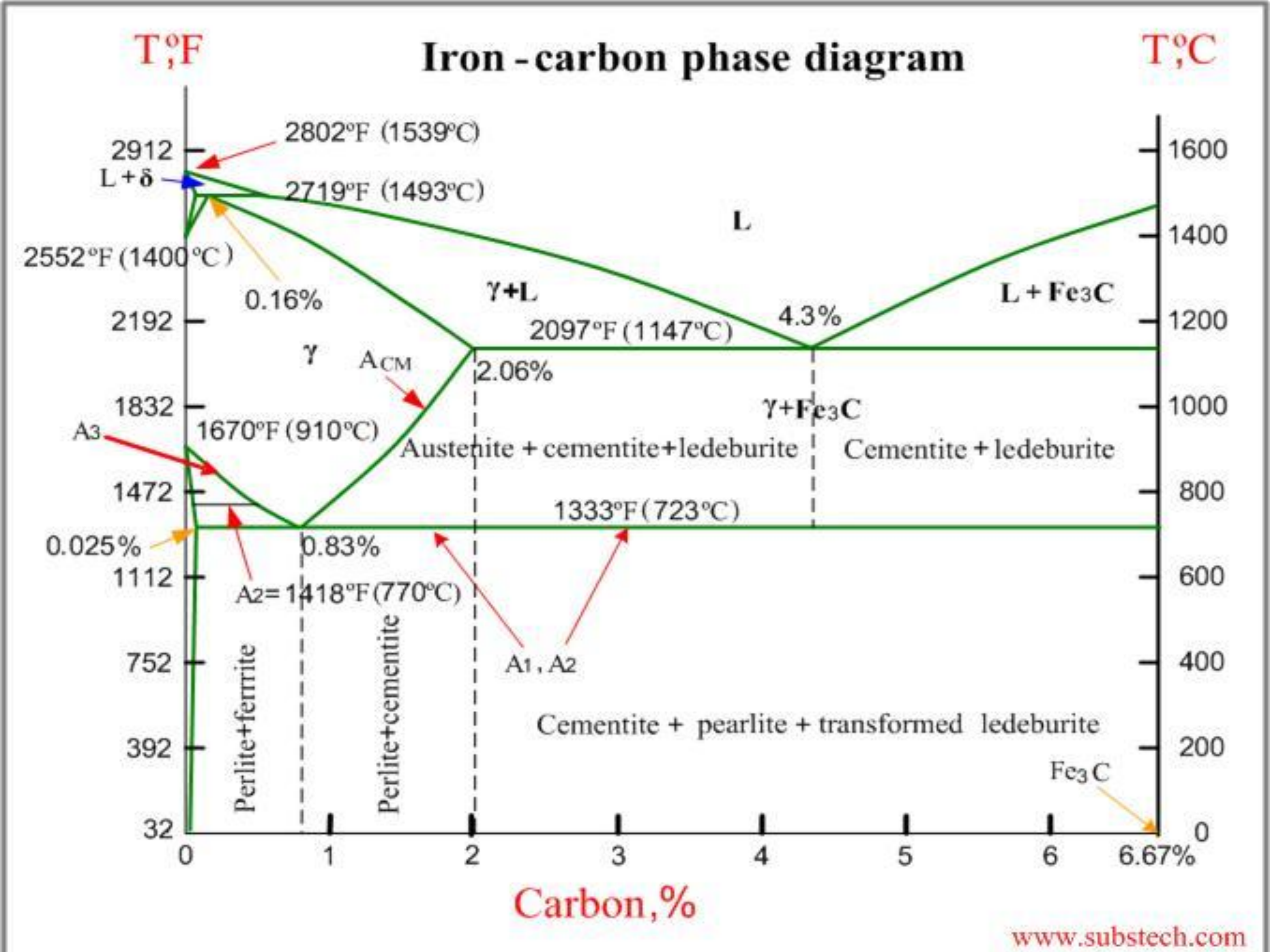


Key Concept about Eutectics:

- If you freeze a solution with the eutectic proportion, pure eutectic will freeze out.
- If you freeze a solution with more Y than the eutectic, you will get a mixture of eutectic plus Y
- If you freeze a solution with more X than the eutectic, you will get a mixture of eutectic plus X

Eutectics refer to freezing liquids

- But similar things happen in solid solutions (like carbon atoms in a lattice of iron)
- For solid solutions the term is “Eutectoid” instead of Eutectic
- Concepts are the same



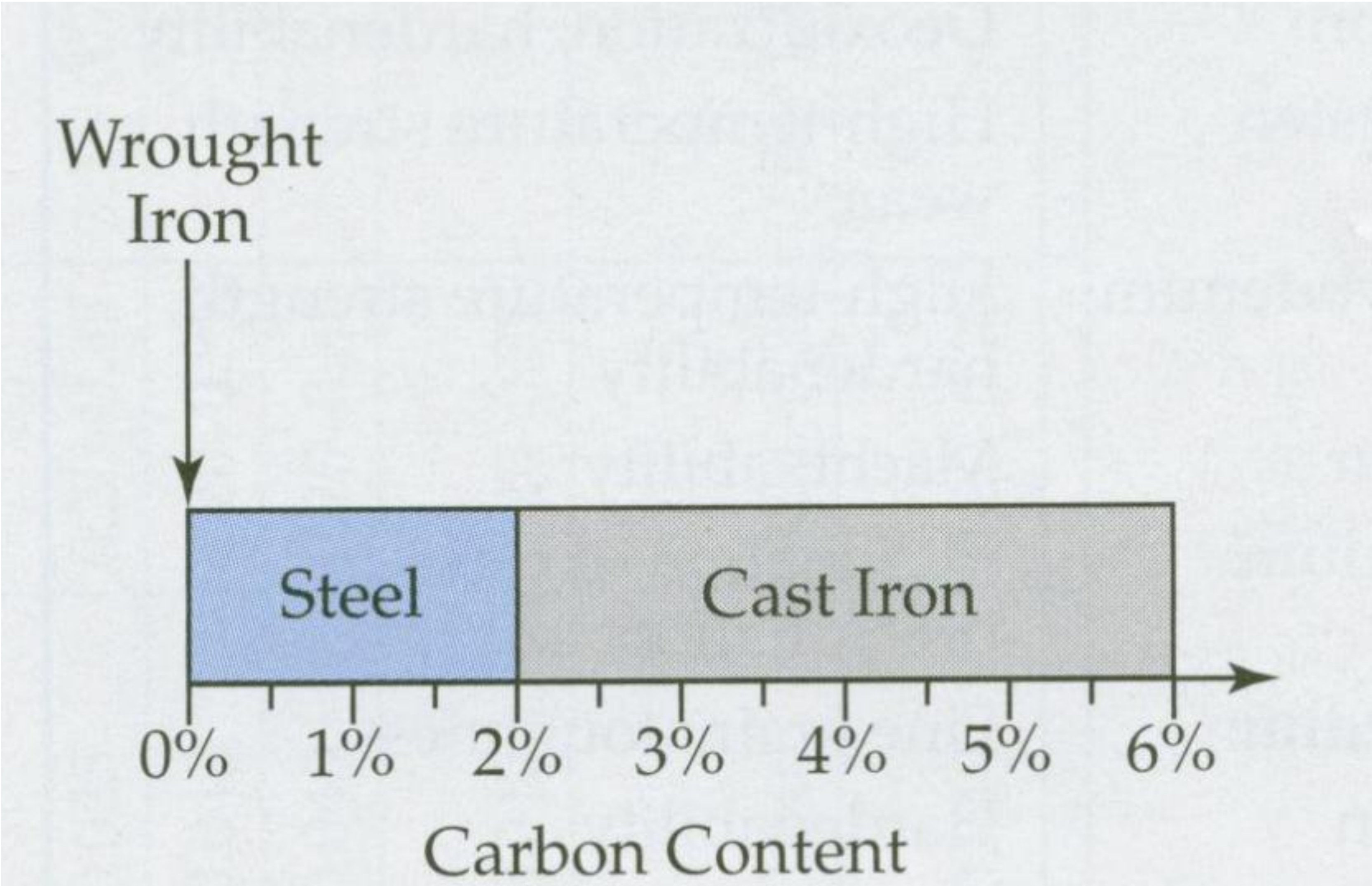
Iron - carbon phase diagram
T,ºF
T,ºC
2802ºF (1539ºC)
L + δ
2719ºF (1493ºC)
2552ºF (1400ºC)
0.16%
L
γ+L
L + Fe3C
4.3%
2097ºF (1147ºC)
γ
ACM
2.06%
γ+Fe3C
A3
1670ºF (910ºC)
Austenite + cementite+ledeburite
Cementite + ledeburite
1333ºF (723ºC)
0.025%
0.83%
A2= 1418ºF (770ºC)
A1 , A2
Perlite+ferrite
Perlite+cementite
Cementite + pearlite + transformed ledeburite
Fe3 C
2912
2192
1832
1472
1112
752
392
32
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
6.67%
Carbon,%
www.substech.com

Where is the Eutectic?

- We see there is a Eutectic on the Iron Carbon Diagram at 4.3% carbon. This eutectic is called ledeburite.

How much carbon can iron hold max?

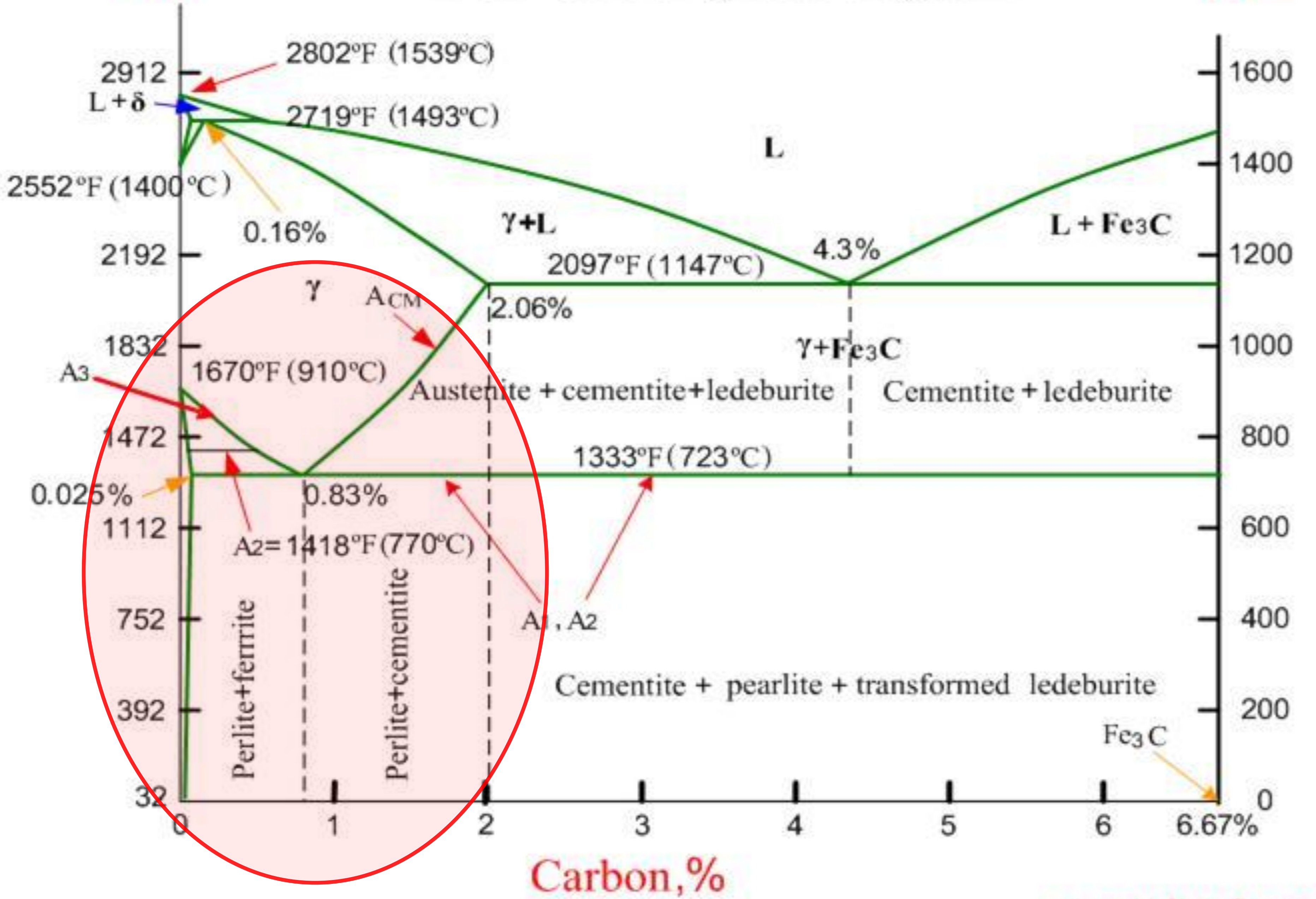
- We see the maximum amount of carbon that can be dissolved without forming Iron Carbide is 2.06% at 2097 degrees F.
- Iron alloys below 2.06% carbon are called steels.
- Above 2.06% are called cast irons.

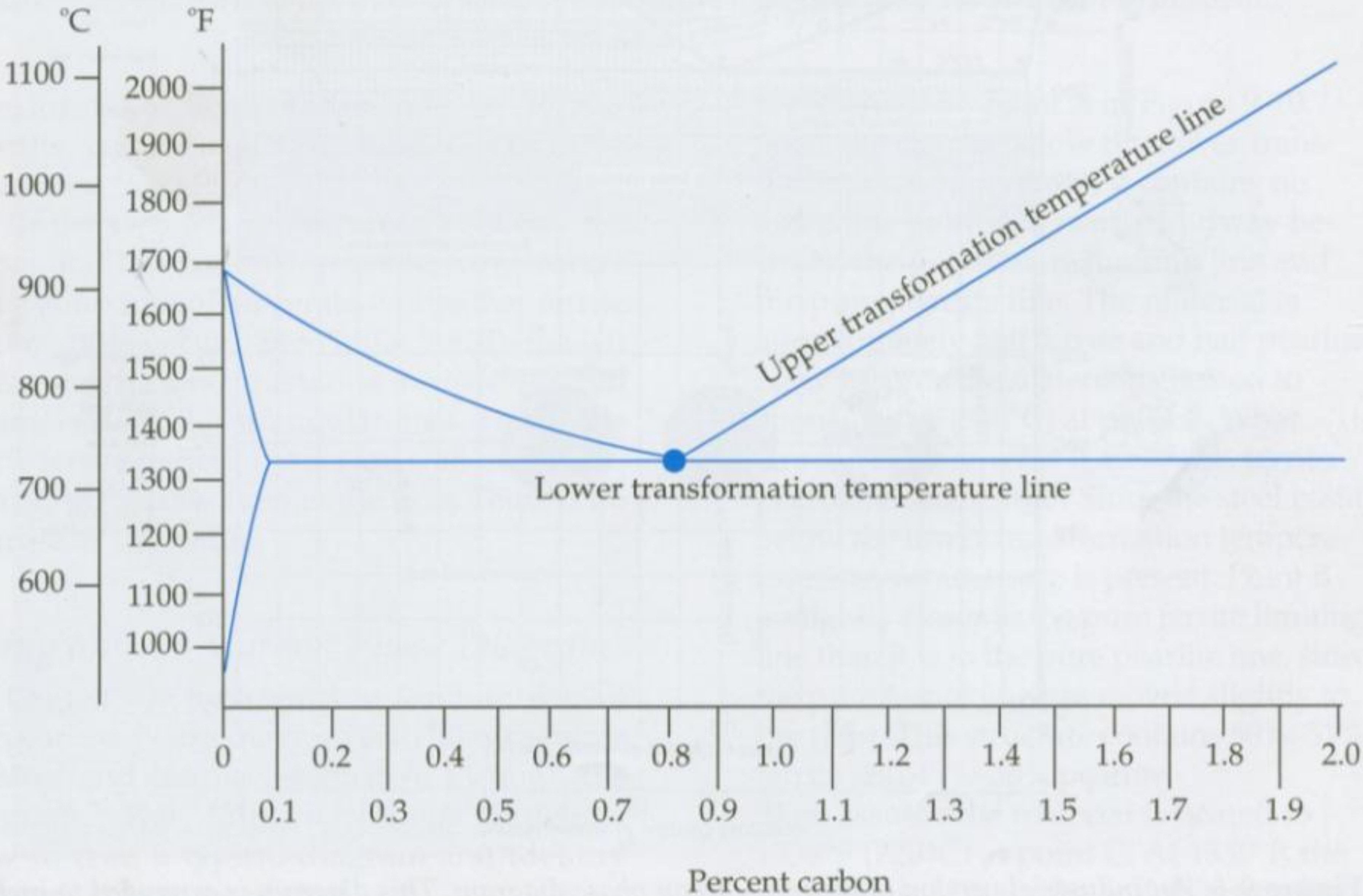


Wrought Iron
Steel
Cast Iron
0%
1%
2%
3%
4%
5%
6%
Carbon Content

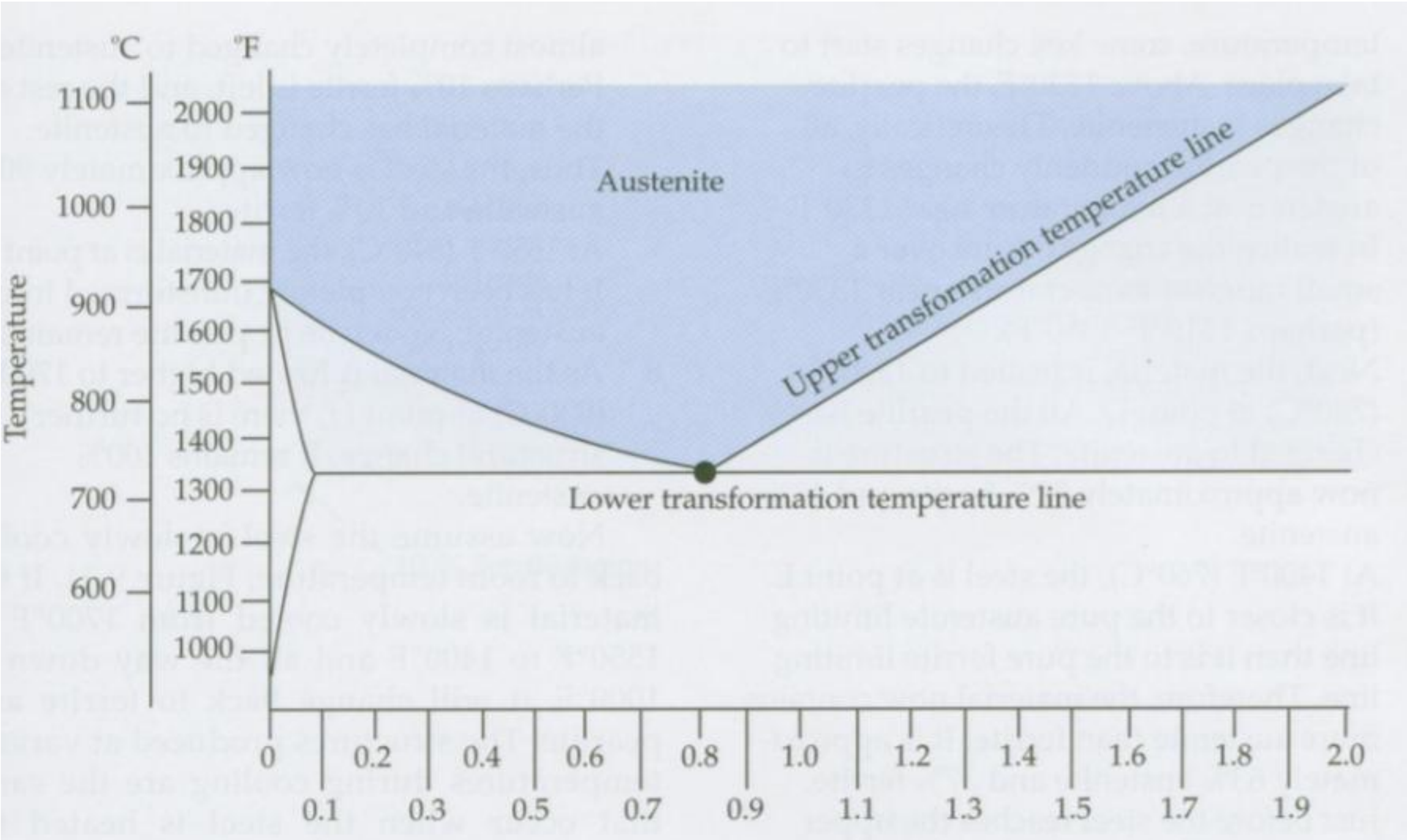
- Since we are not interested in working with molten steel or cast iron for purposes of this talk, we will limit our attention to the lower left portion of the phase diagram.

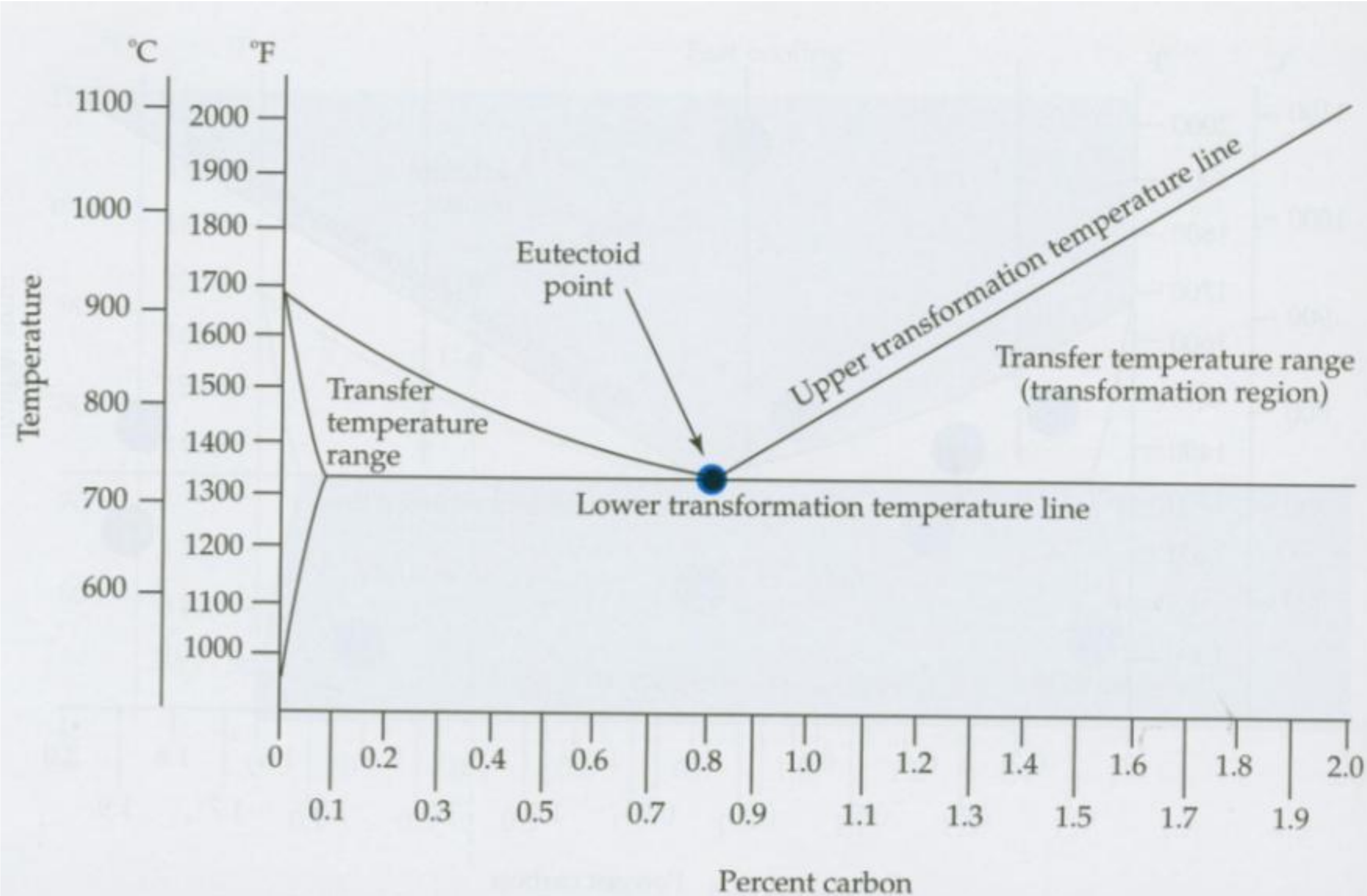
Iron - carbon phase diagram

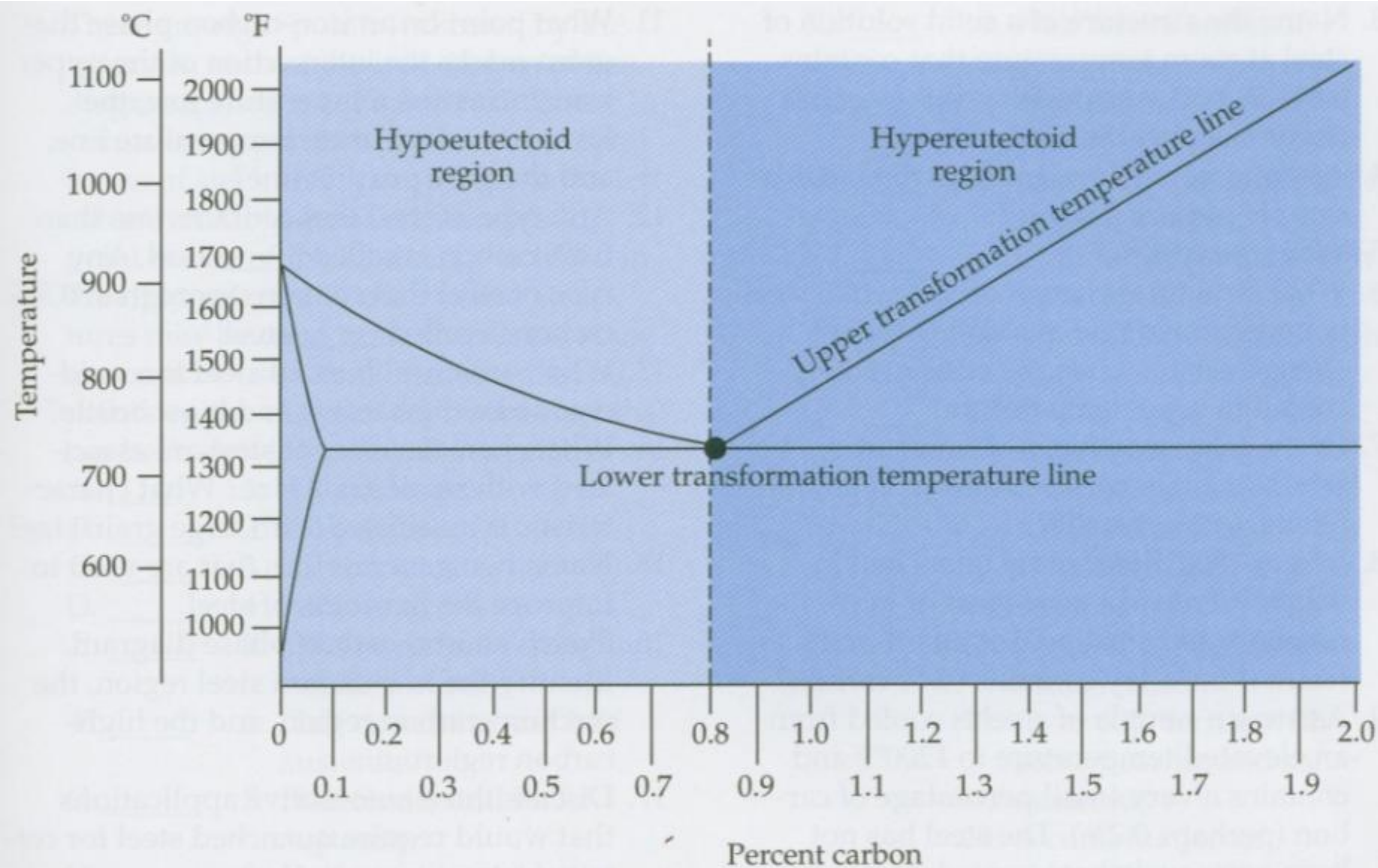




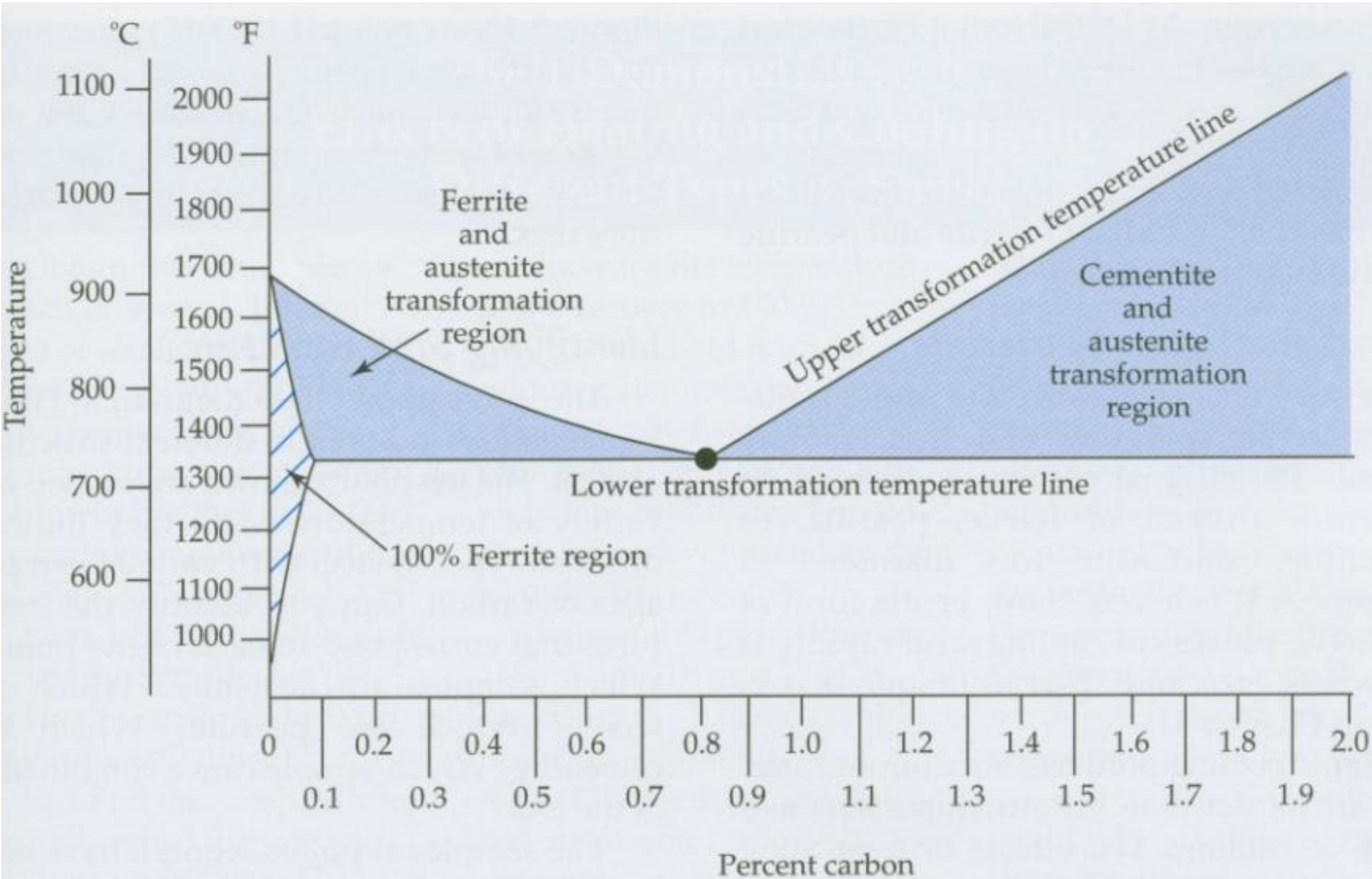
°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Upper transformation temperature line
Lower transformation temperature line
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon


°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Temperature
Austenite
Upper transformation temperature line
Lower transformation temperature line
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9

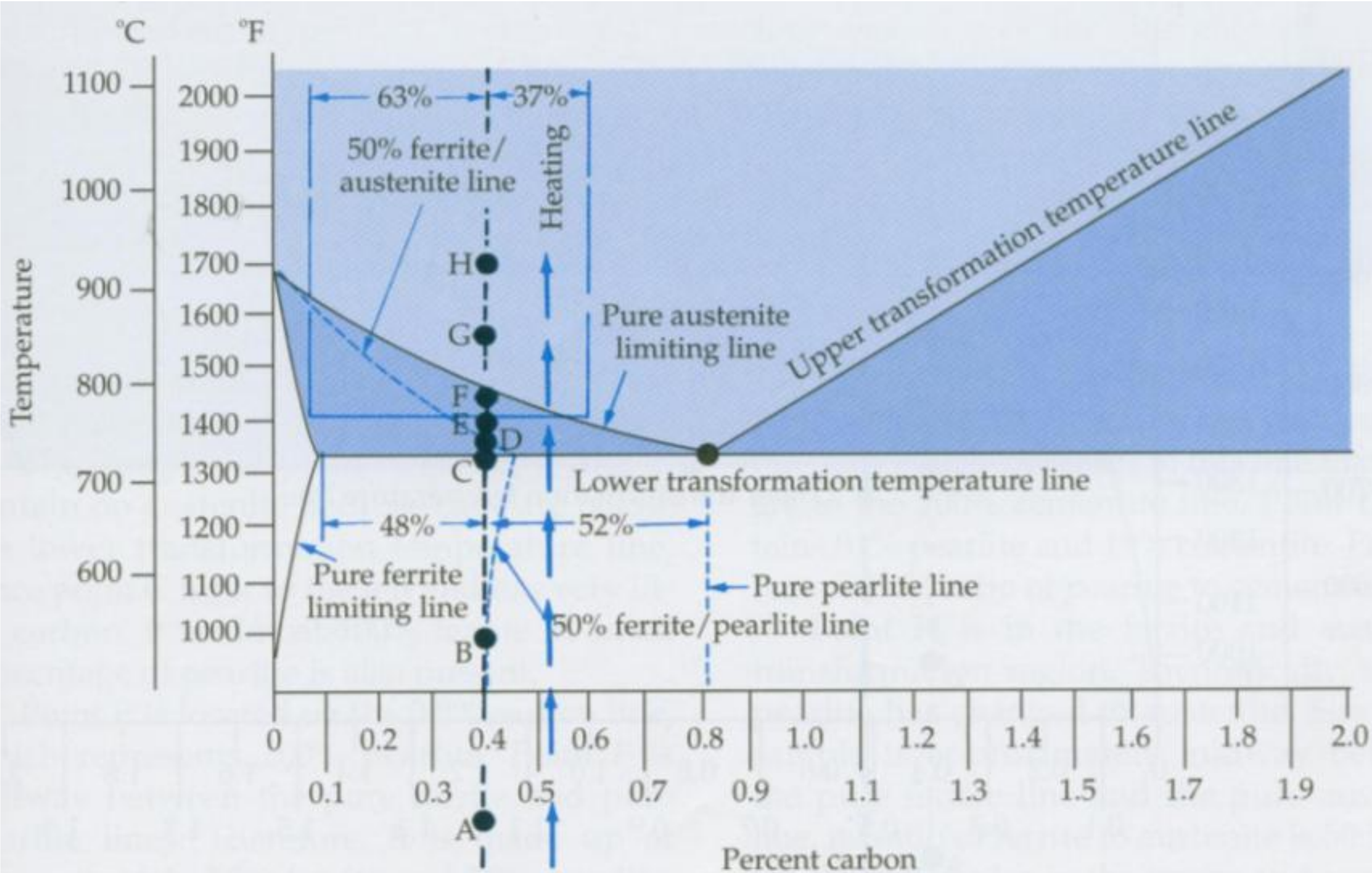

°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Temperature
Eutectoid
point
Upper transformation temperature line
Transfer temperature range
(transformation region)
Transfer
temperature
range
Lower transformation temperature line
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Percent carbon



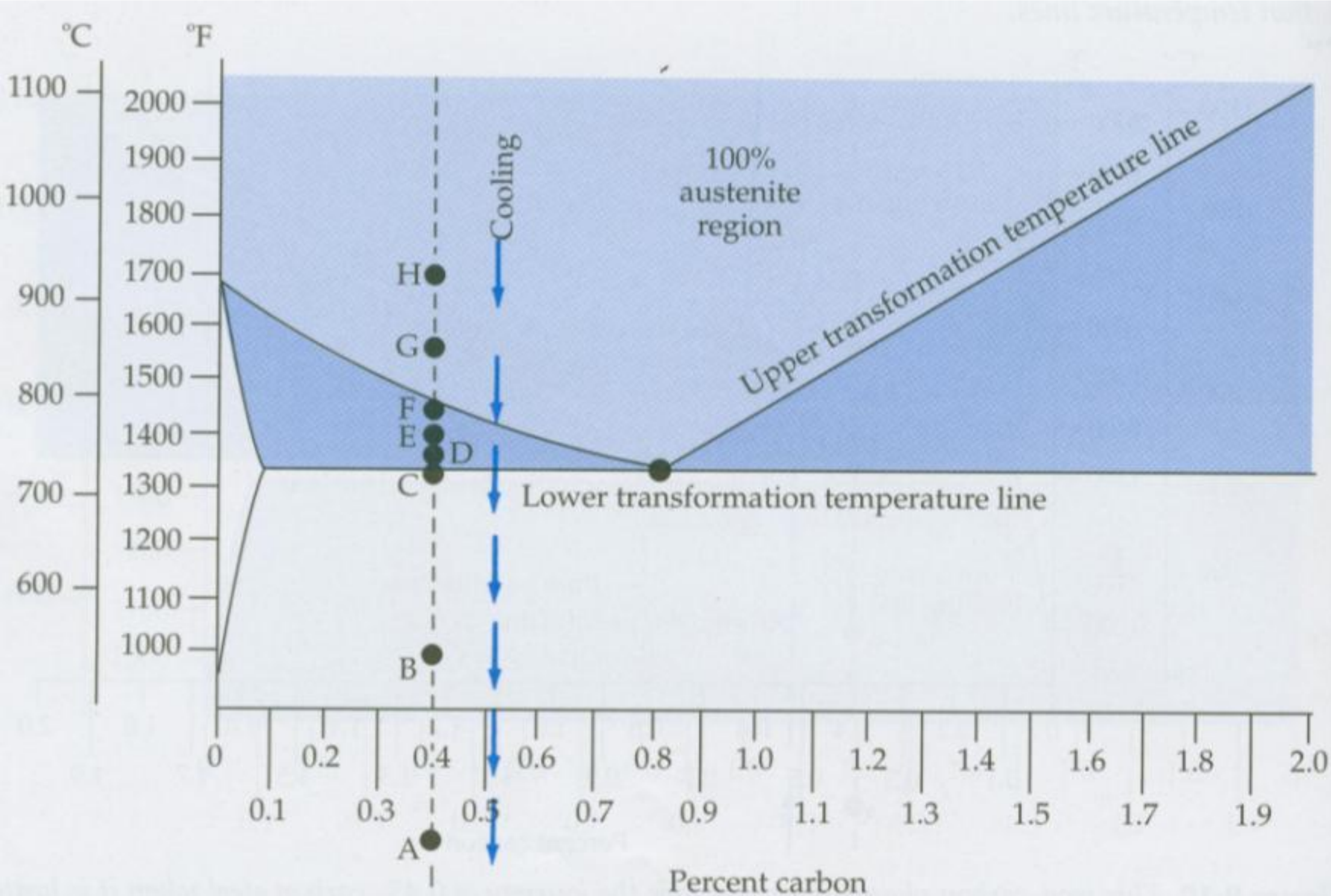
°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Temperature
Hypoeutectoid region
Hypereutectoid region
Upper transformation temperature line
Lower transformation temperature line
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Percent carbon



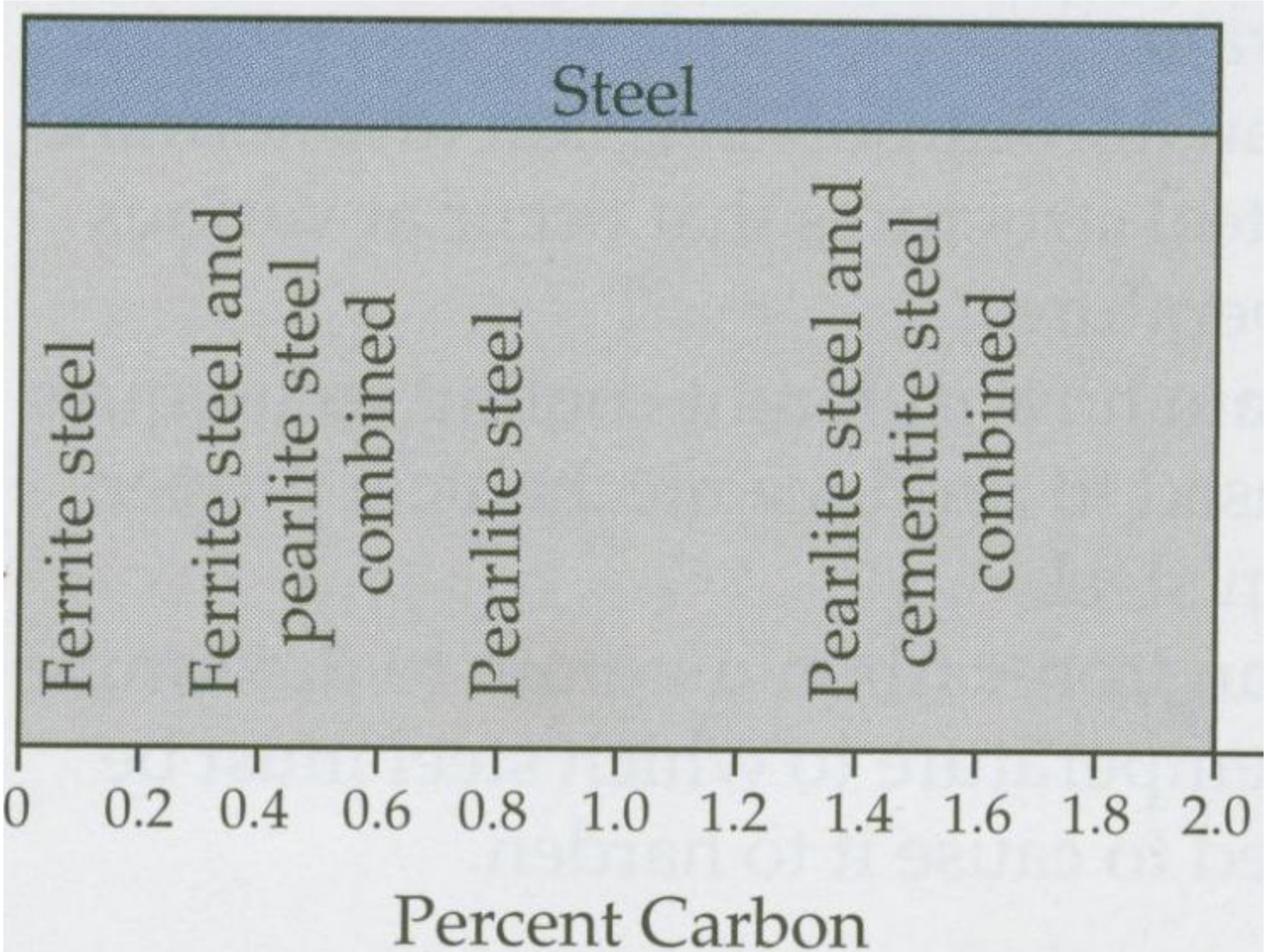
°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Temperature
Ferrite
and
austenite
transformation
region
Upper transformation temperature line
Cementite
and
austenite
transformation
region
Lower transformation temperature line
100% Ferrite region
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon

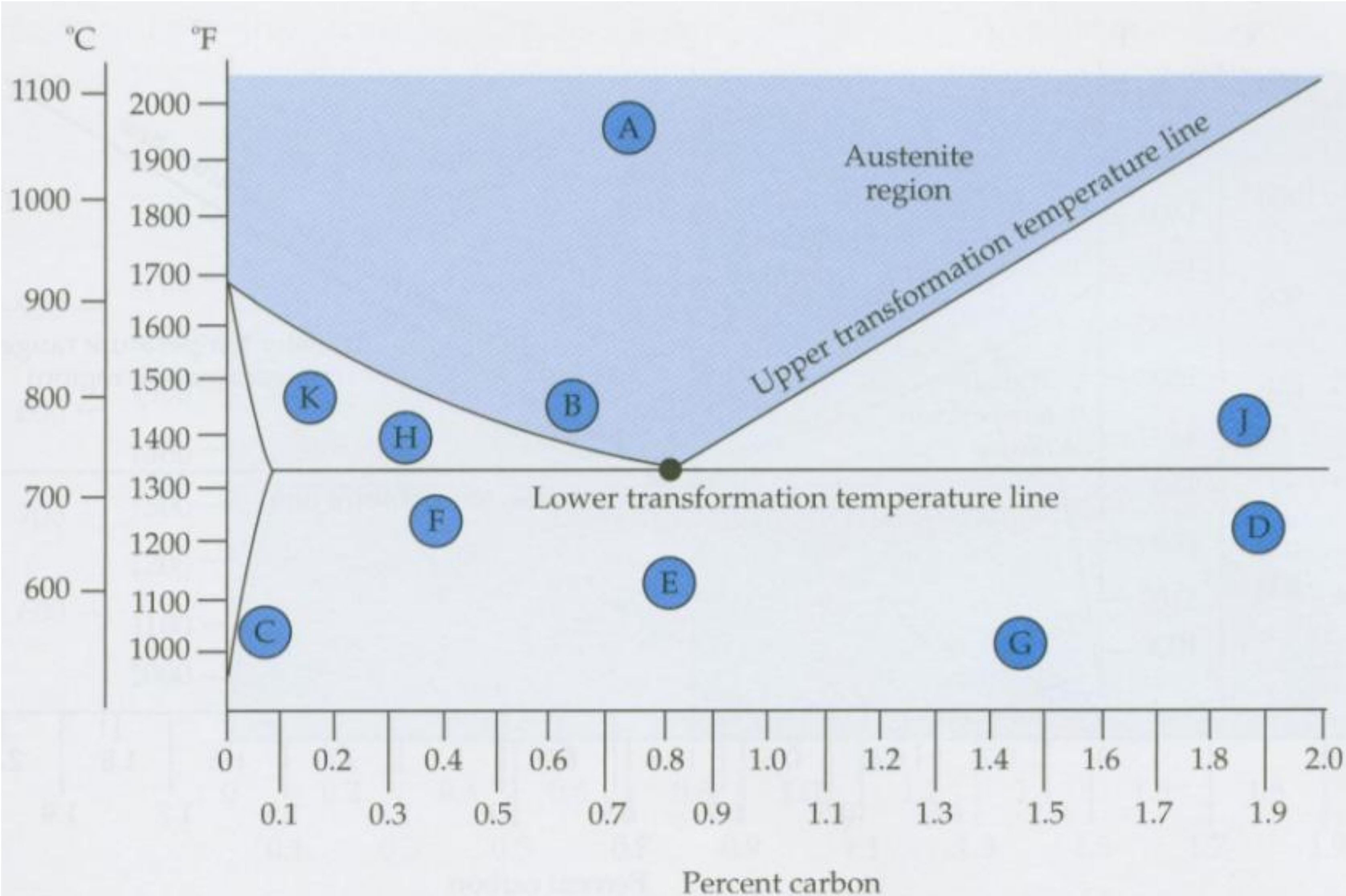


°C
°F
Temperature
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
63%
37%
50% ferrite/
austenite line
Heating
H
G
F
E
D
C
B
A
Pure austenite
limiting line
Upper transformation temperature line
Lower transformation temperature line
48%
52%
Pure ferrite
limiting line
Pure pearlite line
50% ferrite/pearlite line
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon



°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Cooling
100% austenite region
Upper transformation temperature line
Lower transformation temperature line
H
G
F
E
D
C
B
A
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon

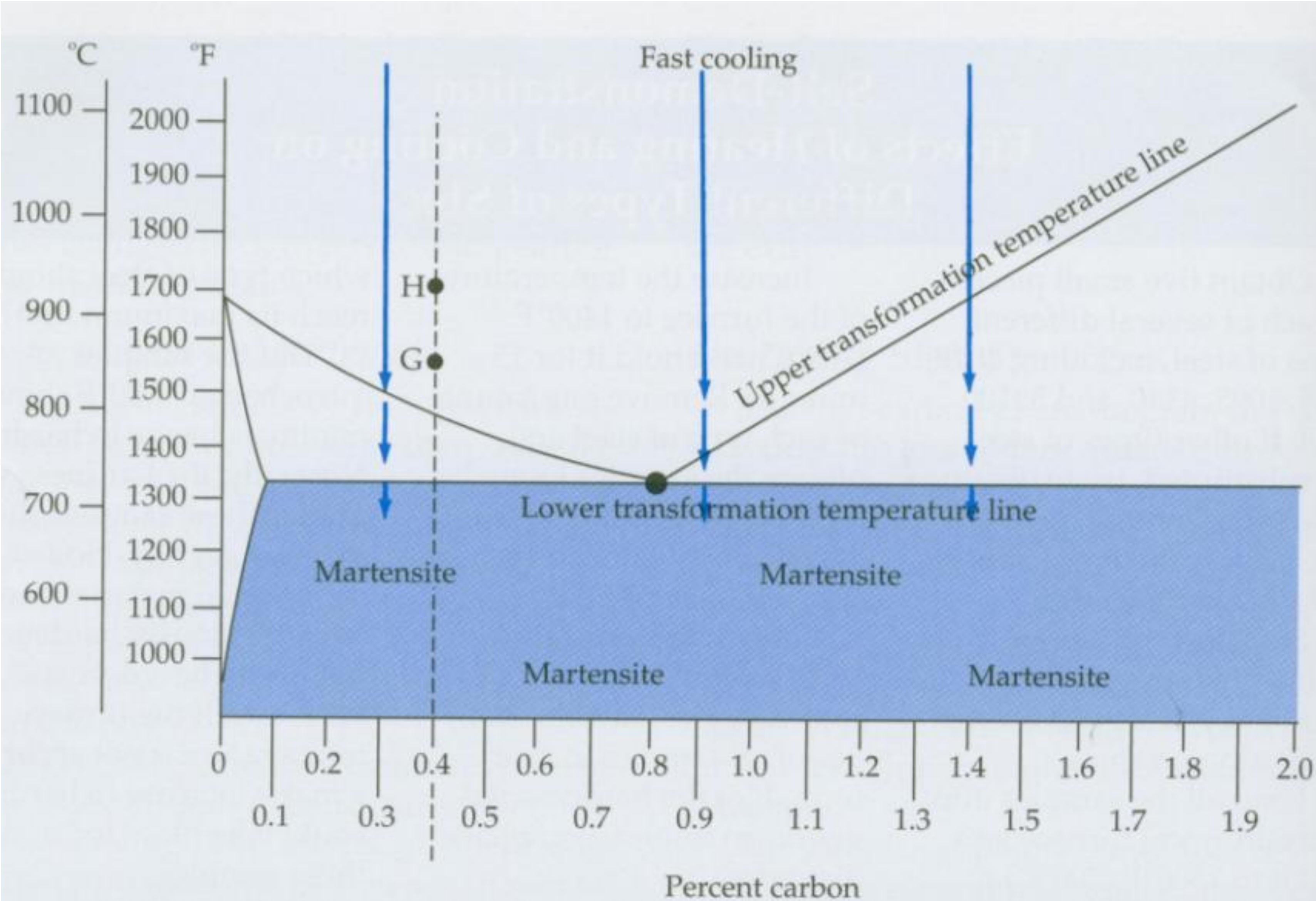

Steel
Ferrite steel
Ferrite steel and pearlite steel combined
Pearlite steel
Pearlite steel and cementite steel combined
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Percent Carbon



°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
A
Austenite region
Upper transformation temperature line
B
K
H
J
Lower transformation temperature line
F
D
E
C
G
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon

Remove Heat quickly:

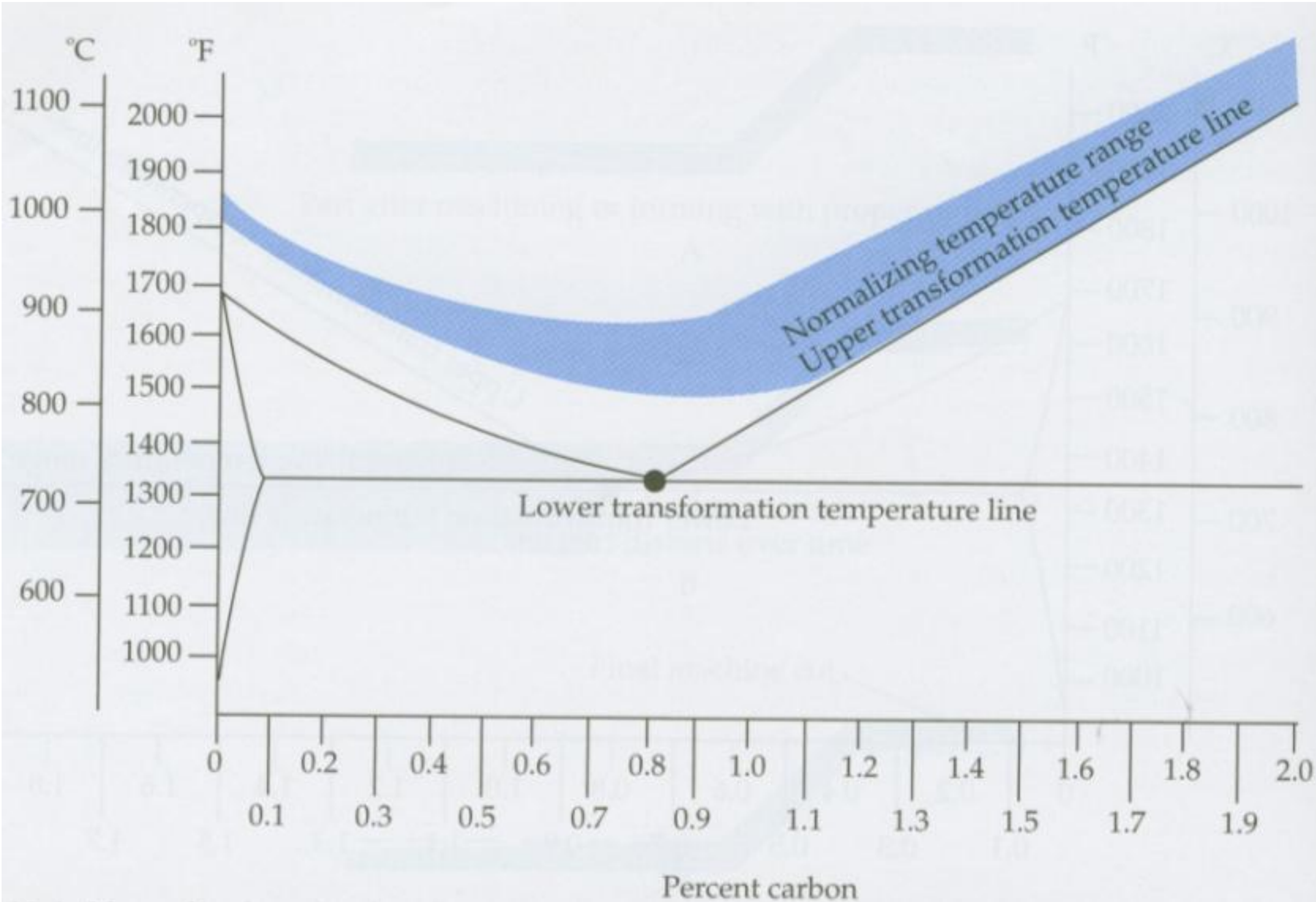
- Austenite transforms to
  - Martensite
    - Very strained
    - Very Brittle
    - Very Hard


°C
°F
Fast cooling
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
H
G
Upper transformation temperature line
Lower transformation temperature line
Martensite
Martensite
Martensite
Martensite
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon

Where is Martensite on the phase diagram??

- Martensite is NOT on the equilibrium phase diagram because Martensite is NOT an equilibrium phase. In the Iron-Carbon system, martensite is only formed with rapid quenching, quenching so fast that the crystal structures cannot get into equilibrium. It contains trapped energy in the strained crystal structures.

Next topic – how to improve the martensite containing steel with more heat treatment



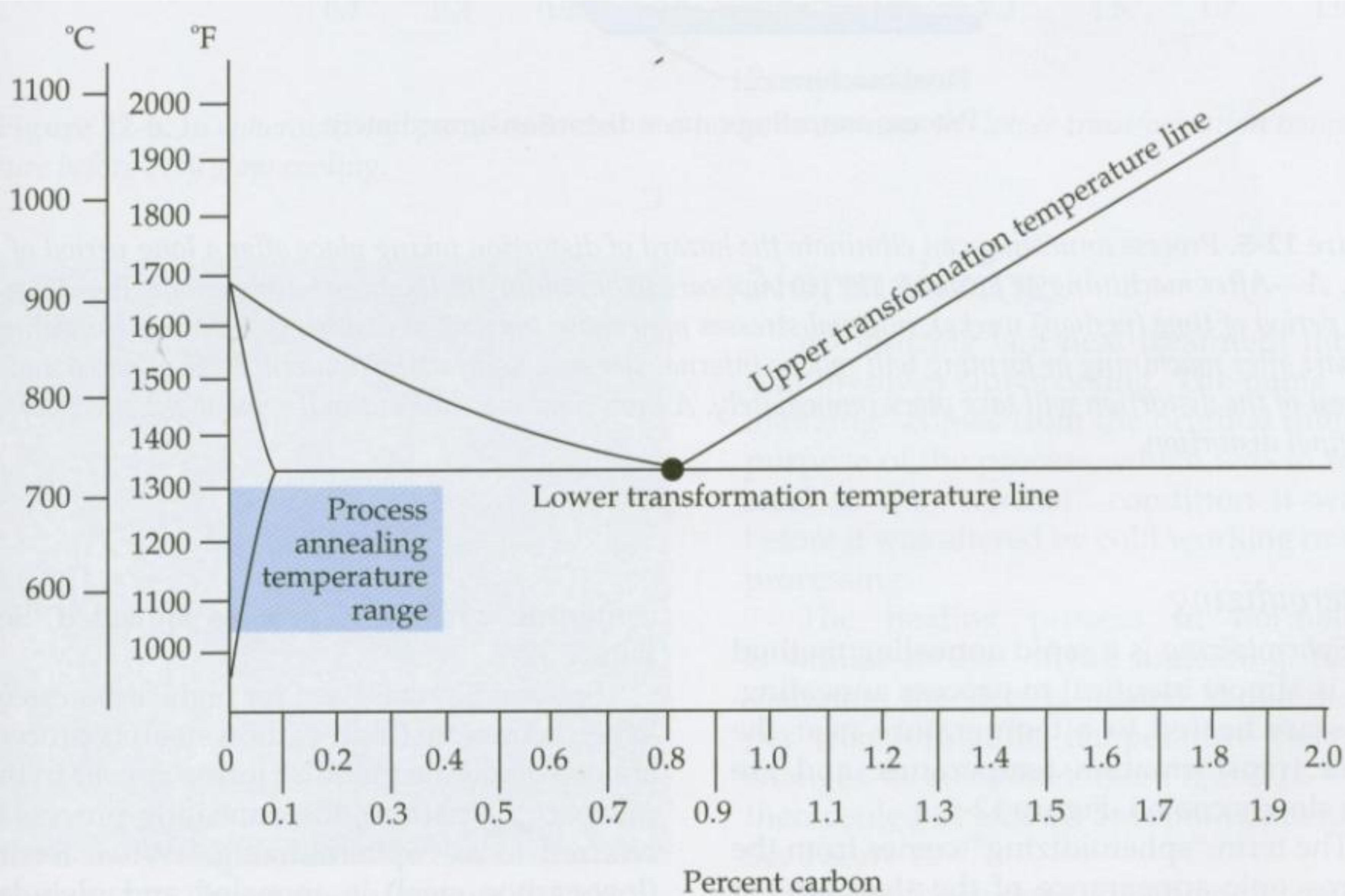
°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Normalizing temperature range
Upper transformation temperature line
Lower transformation temperature line
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Percent carbon

Annealing and Normalization

- Heat above transformation temperature
  - Heat soak one hour per inch of thickness
- Either **Anneal** – cool 100 degrees per hour
- Or **Normalize** – take out of oven and air cool to room temperature (faster cooling than annealing)
- Eliminates or reduces martensite

Process Annealing

- Heat to relieve stresses in lower carbon steels
- Prevents distortion from stresses caused by machining and other work processes
- Does not form austenite



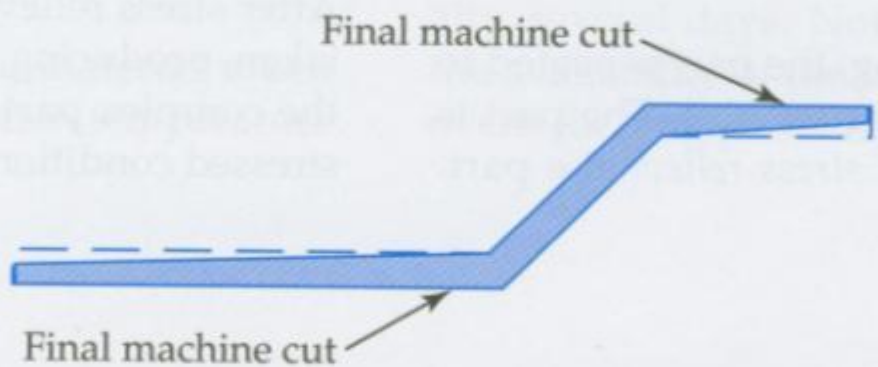
°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Upper transformation temperature line
Lower transformation temperature line
Process annealing temperature range
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Percent carbon

Part after machining or forming with proper dimensions

A

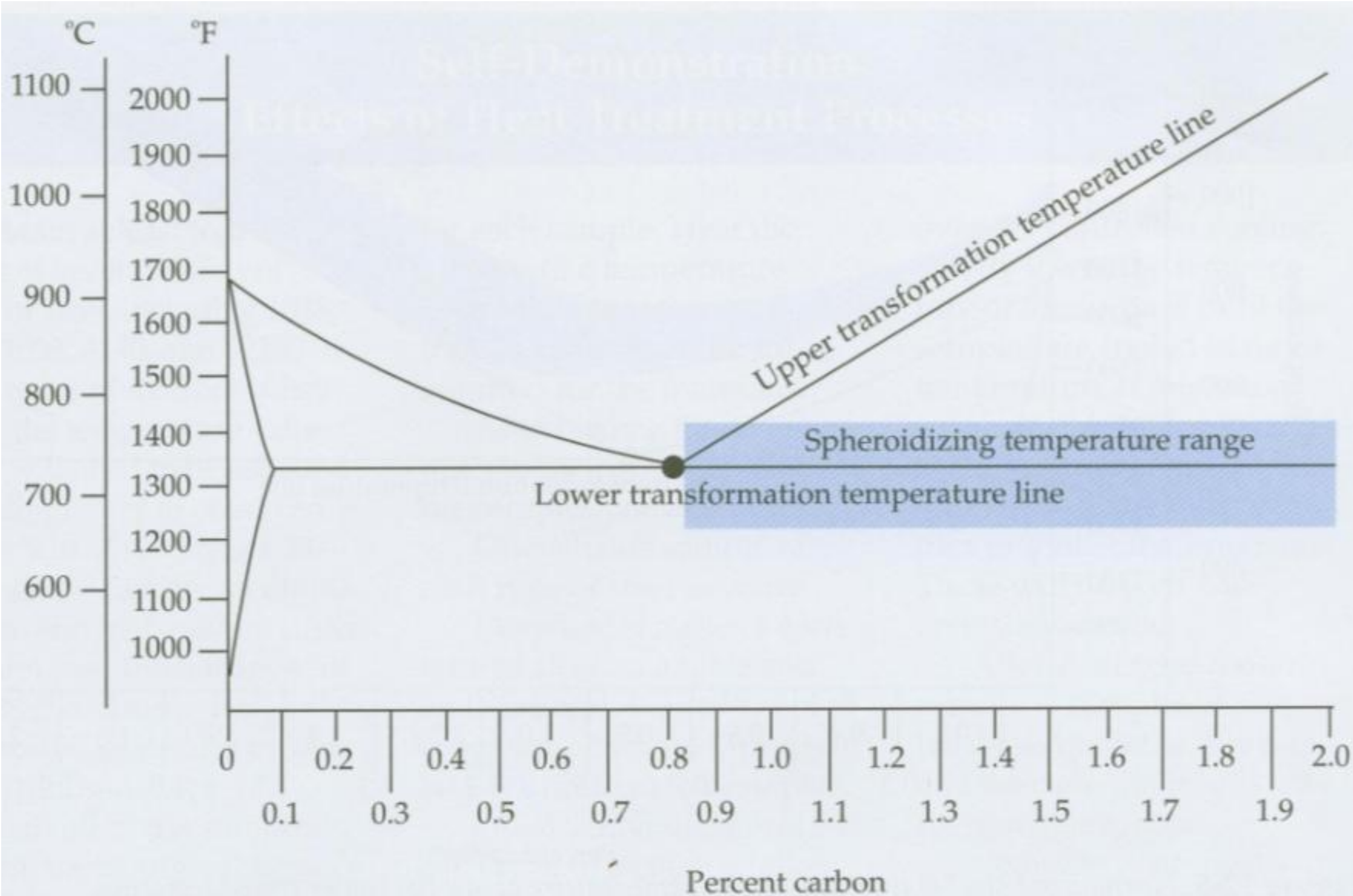
With no heat treatment,
the part distorts over time

B



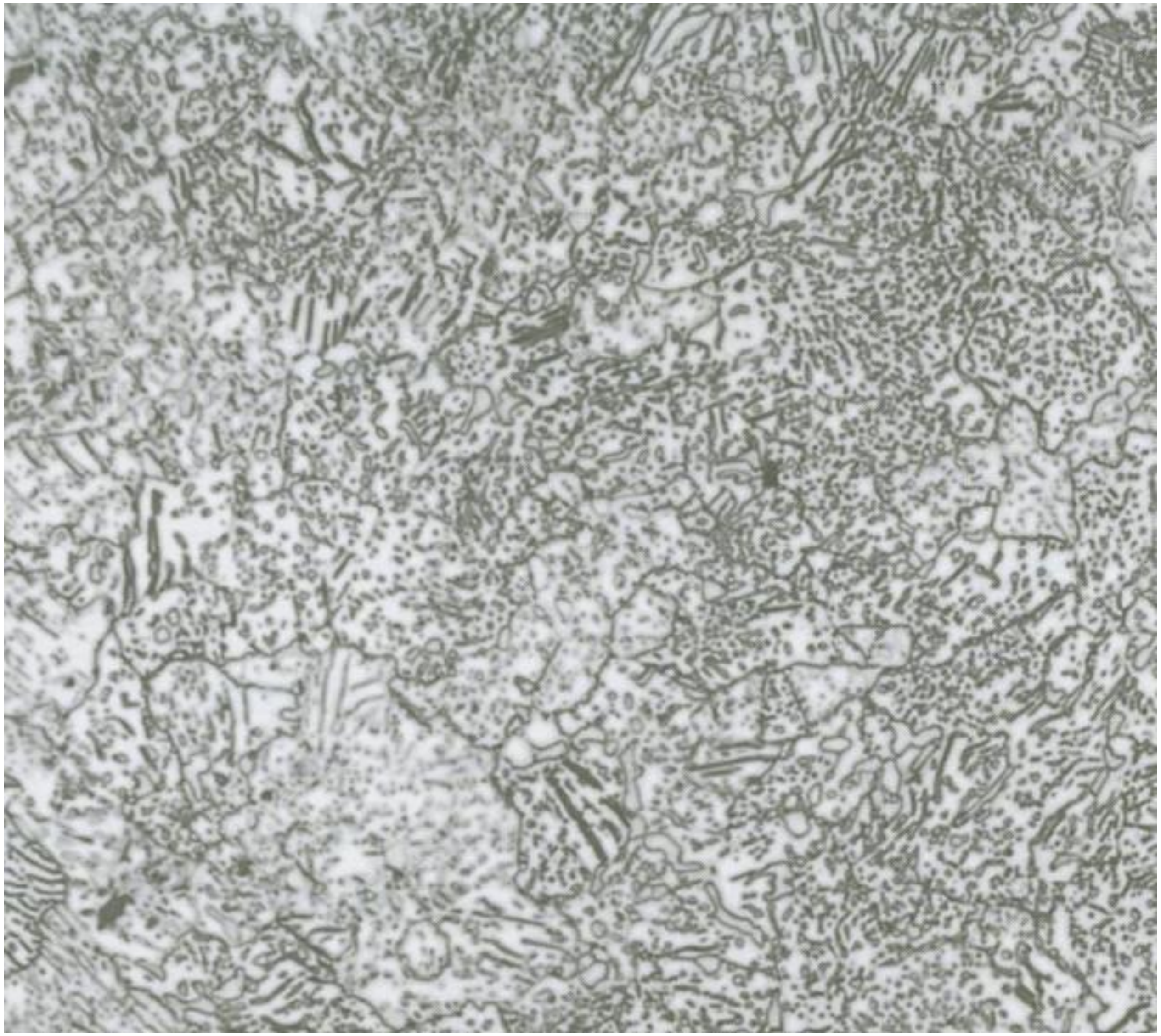
Process annealing causes distortion immediately

- If we do process annealing with a hypereutectoid steel it is called **spheroidizing**.



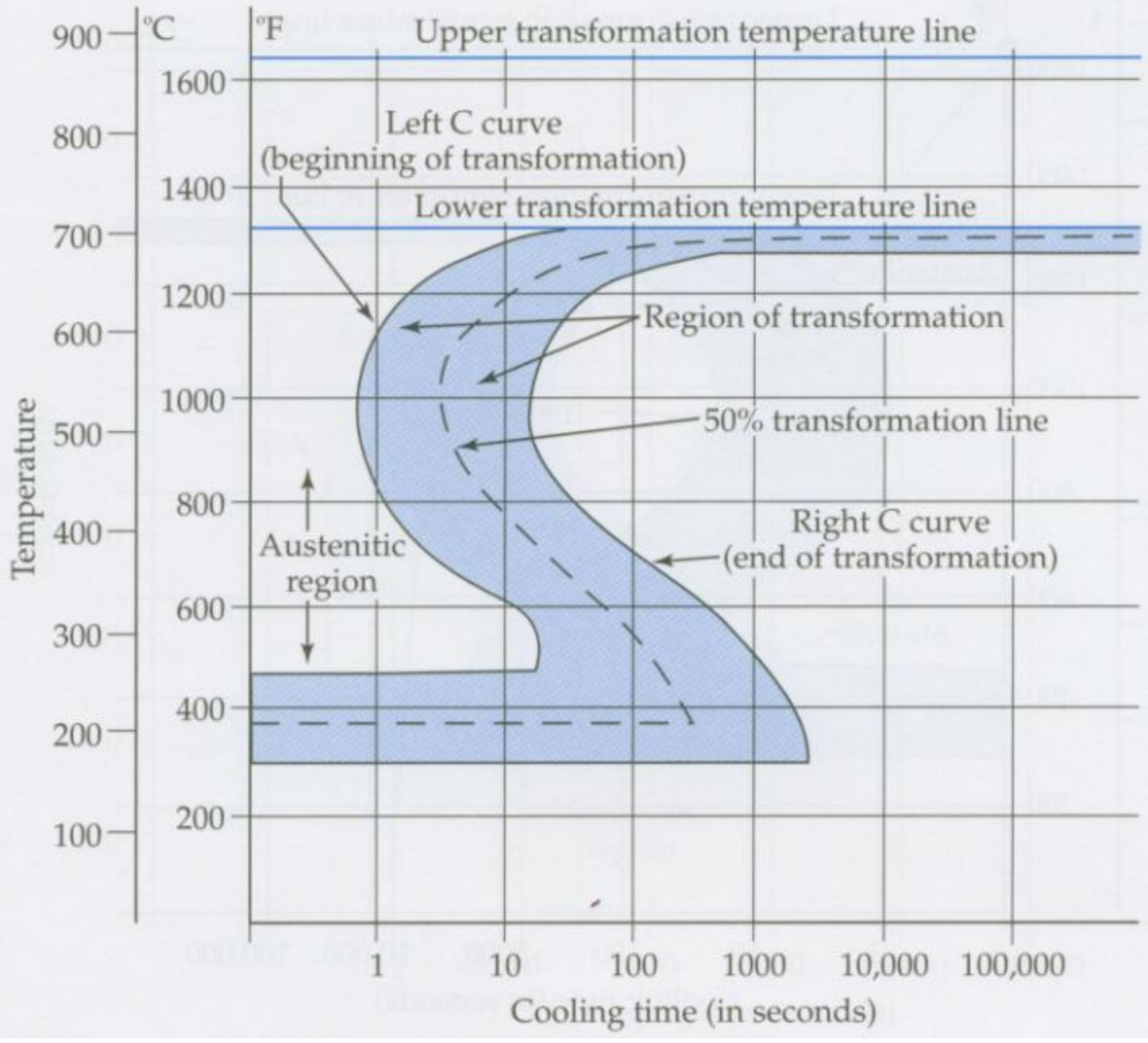
°C
°F
1100
1000
900
800
700
600
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Upper transformation temperature line
Spheroidizing temperature range
Lower transformation temperature line
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Percent carbon

Spheroidizing

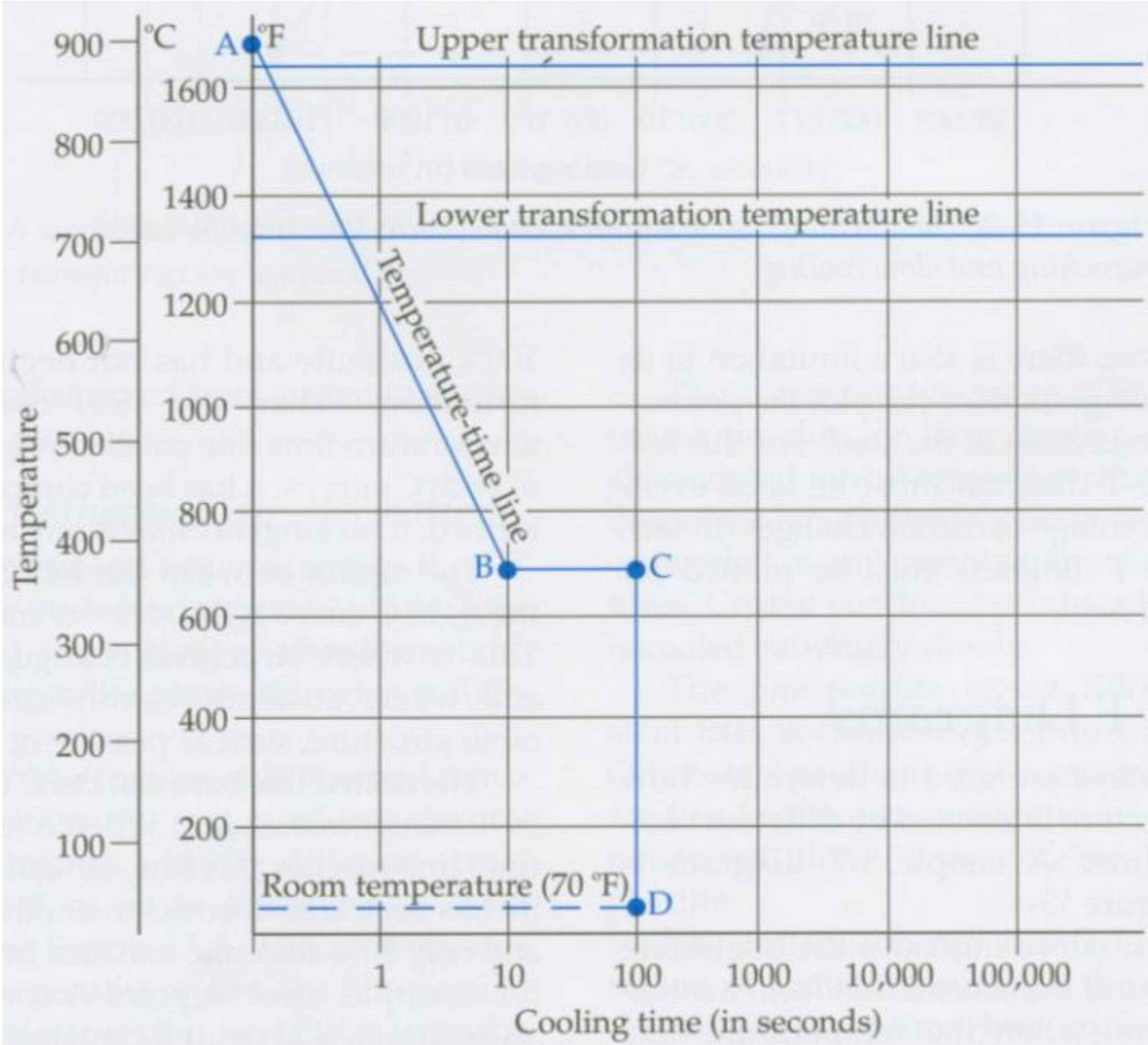


Effects of Annealing, Normalizing, and Quenching on Metal					
Full Annealing	Normalizing	Air Quenching	Oil Quenching	Water Quenching	Brine Quenching
← Softer, less strong		Harder and stronger →			
← More ductile		More brittle →			
← Less internal stress		More internal stress →			
← Less distortion, cracking		More distortion, cracking →			

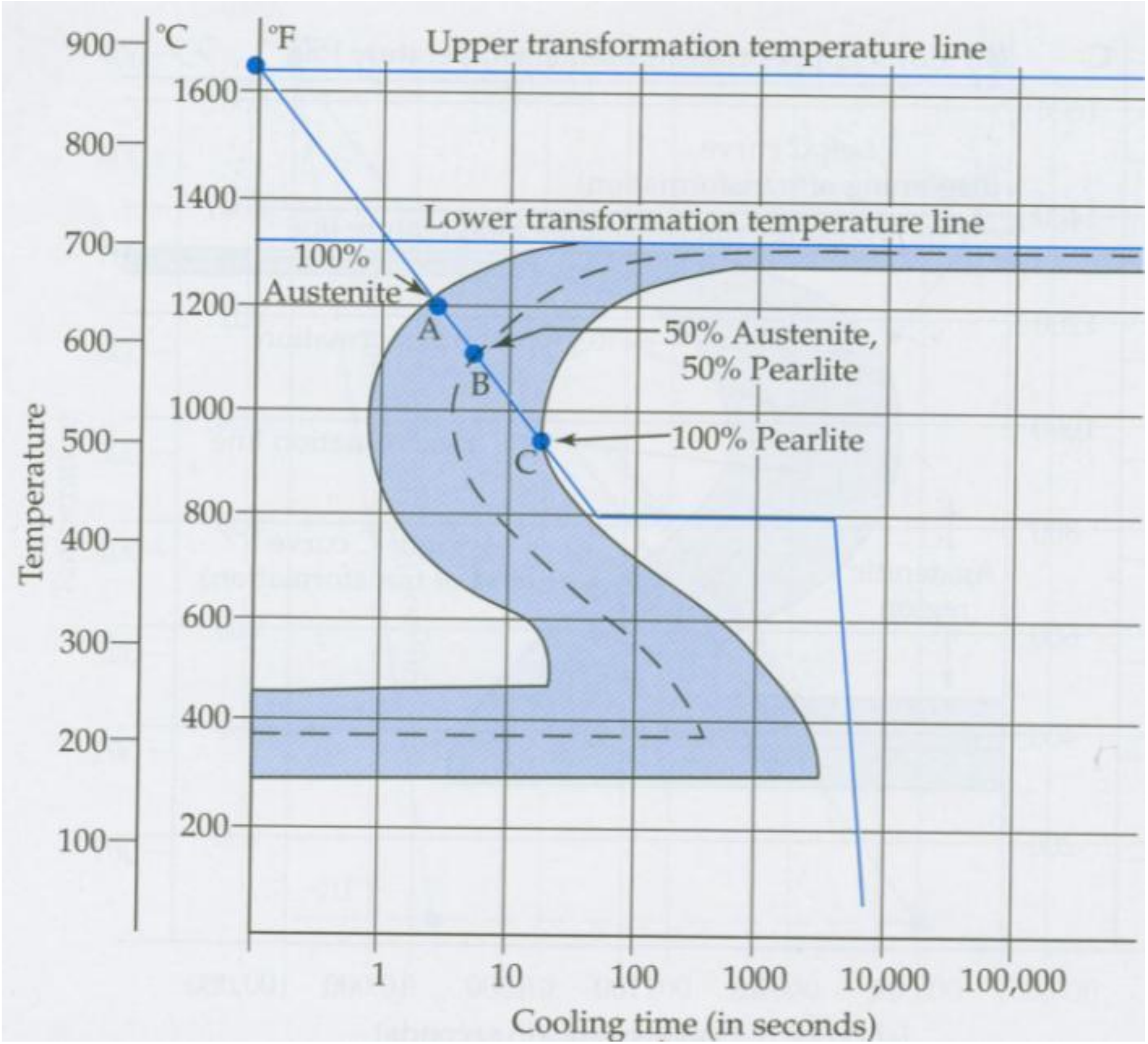
Now we are going to talk about the second diagram, the Isothermal Transformation Diagram.



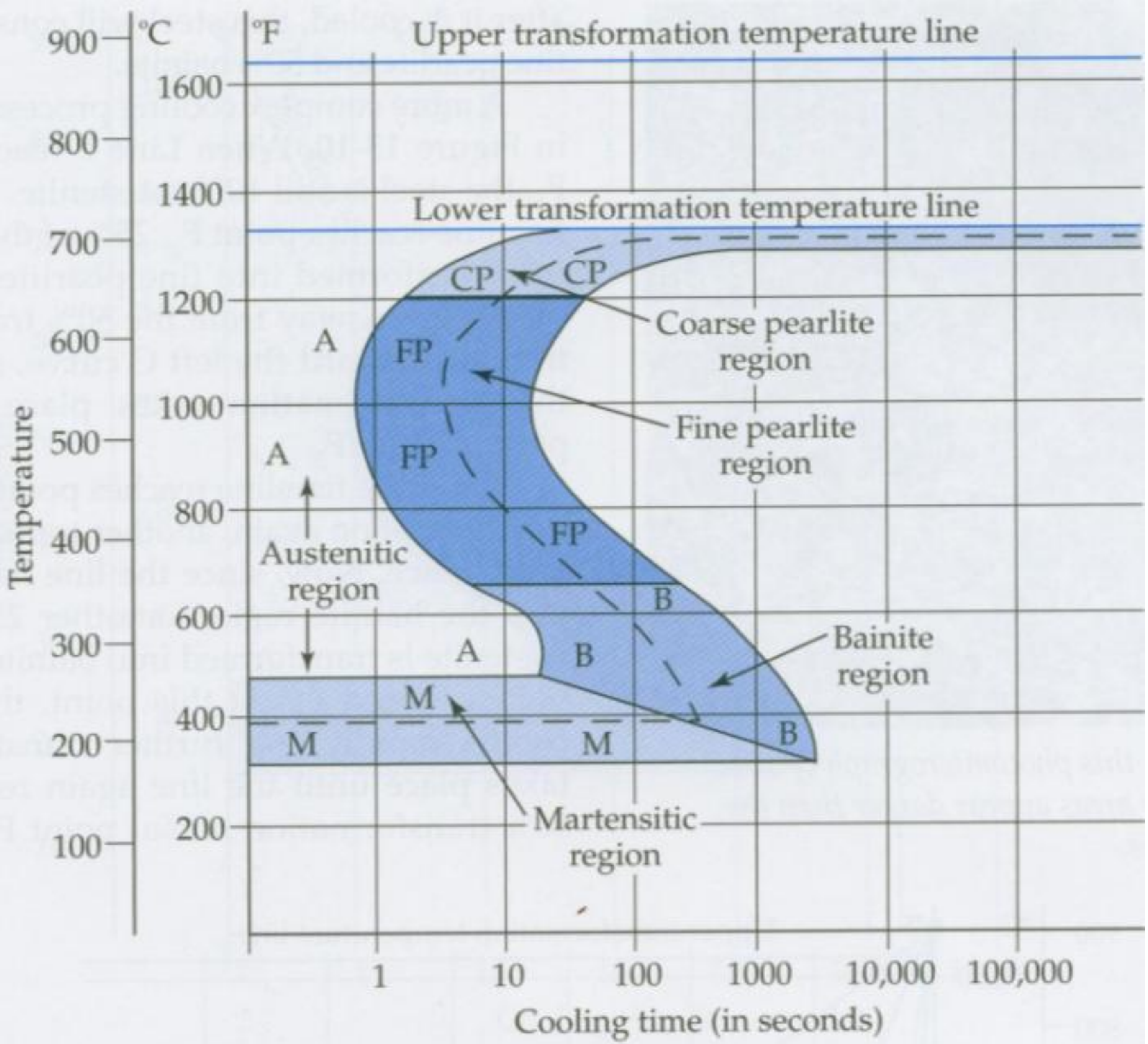
900
800
700
600
500
400
300
200
100
°C
°F
1600
1400
1200
1000
800
600
400
200
Temperature
Upper transformation temperature line
Left C curve
(beginning of transformation)
Lower transformation temperature line
Region of transformation
50% transformation line
Right C curve
(end of transformation)
Austenitic
region
1
10
100
1000
10,000
100,000
Cooling time (in seconds)



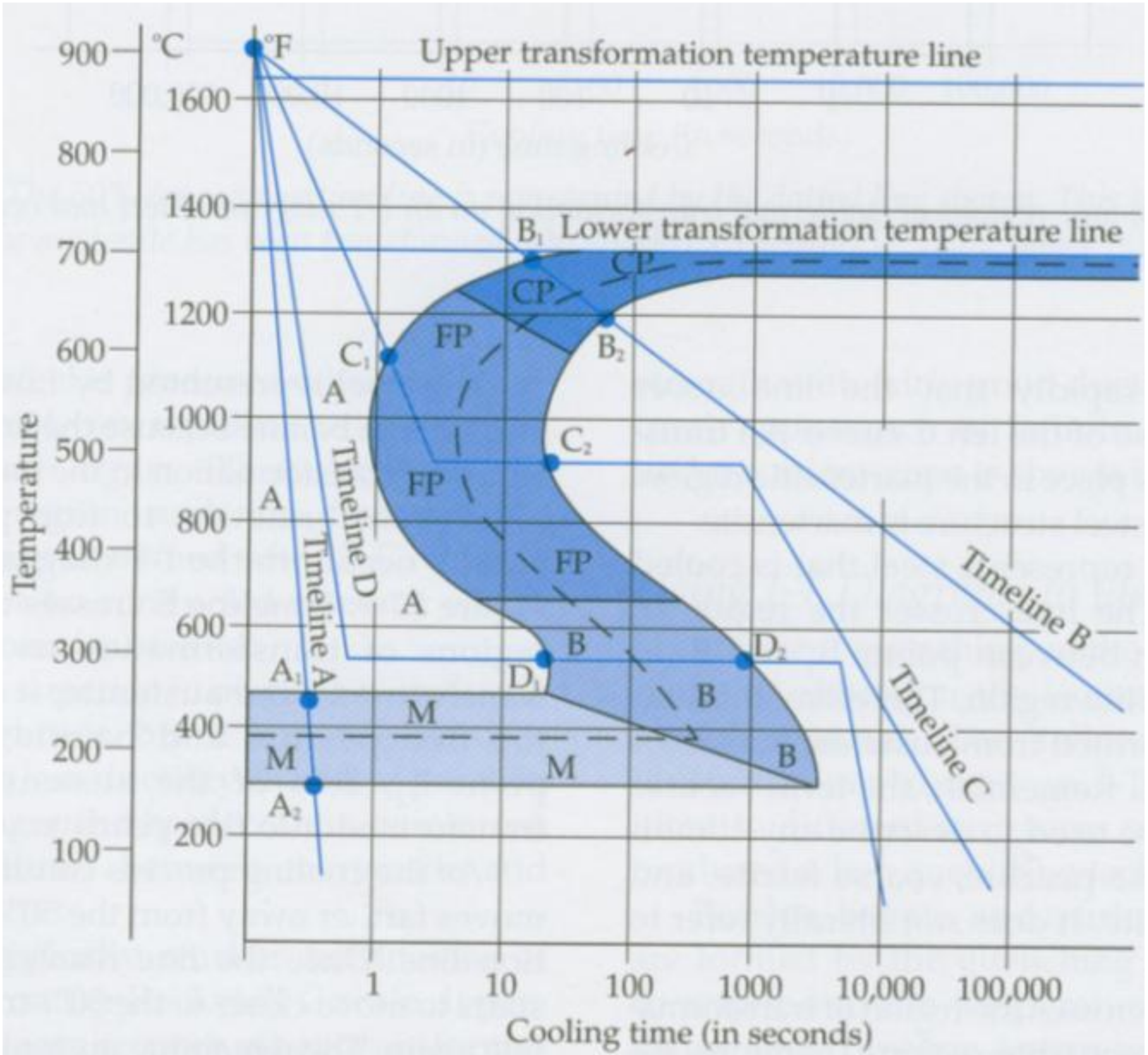
Upper transformation temperature line
Lower transformation temperature line
Temperature-time line
Room temperature (70 °F)
A
B
C
D
°C
°F
900
800
700
600
500
400
300
200
100
1600
1400
1200
1000
800
600
400
200
Temperature
1
10
100
1000
10,000
100,000
Cooling time (in seconds)



°C
°F
Upper transformation temperature line
Lower transformation temperature line
100% Austenite
A
B
C
50% Austenite, 50% Pearlite
100% Pearlite
Temperature
900
800
700
600
500
400
300
200
100
1600
1400
1200
1000
800
600
400
200
1
10
100
1000
10,000
100,000
Cooling time (in seconds)

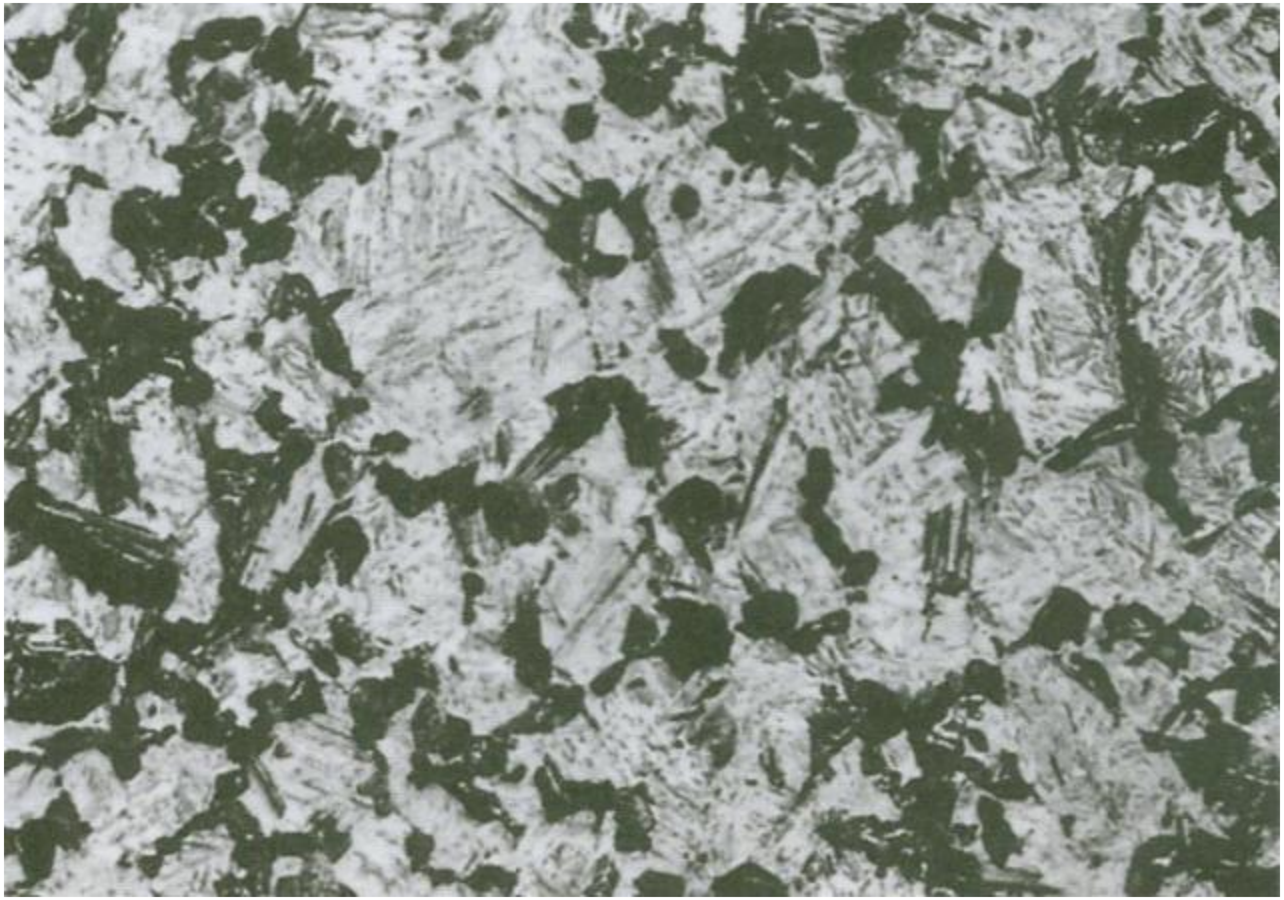


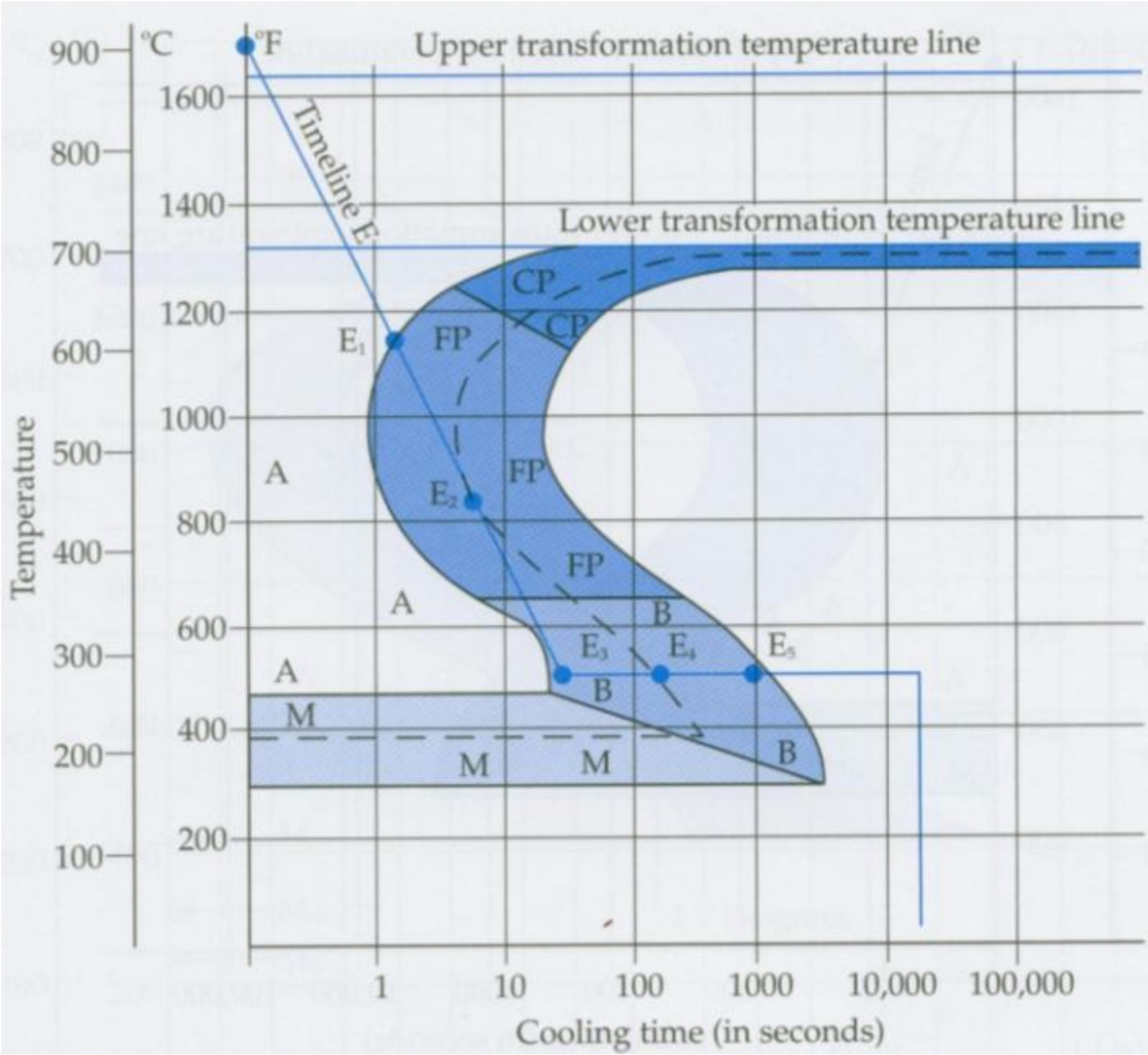
°C
°F
900
800
700
600
500
400
300
200
100
1600
1400
1200
1000
800
600
400
200
Temperature
Upper transformation temperature line
Lower transformation temperature line
CP
CP
Coarse pearlite region
A
FP
FP
FP
Fine pearlite region
A
Austenitic region
B
B
A
Bainite region
M
M
M
B
Martensitic region
1
10
100
1000
10,000
100,000
Cooling time (in seconds)



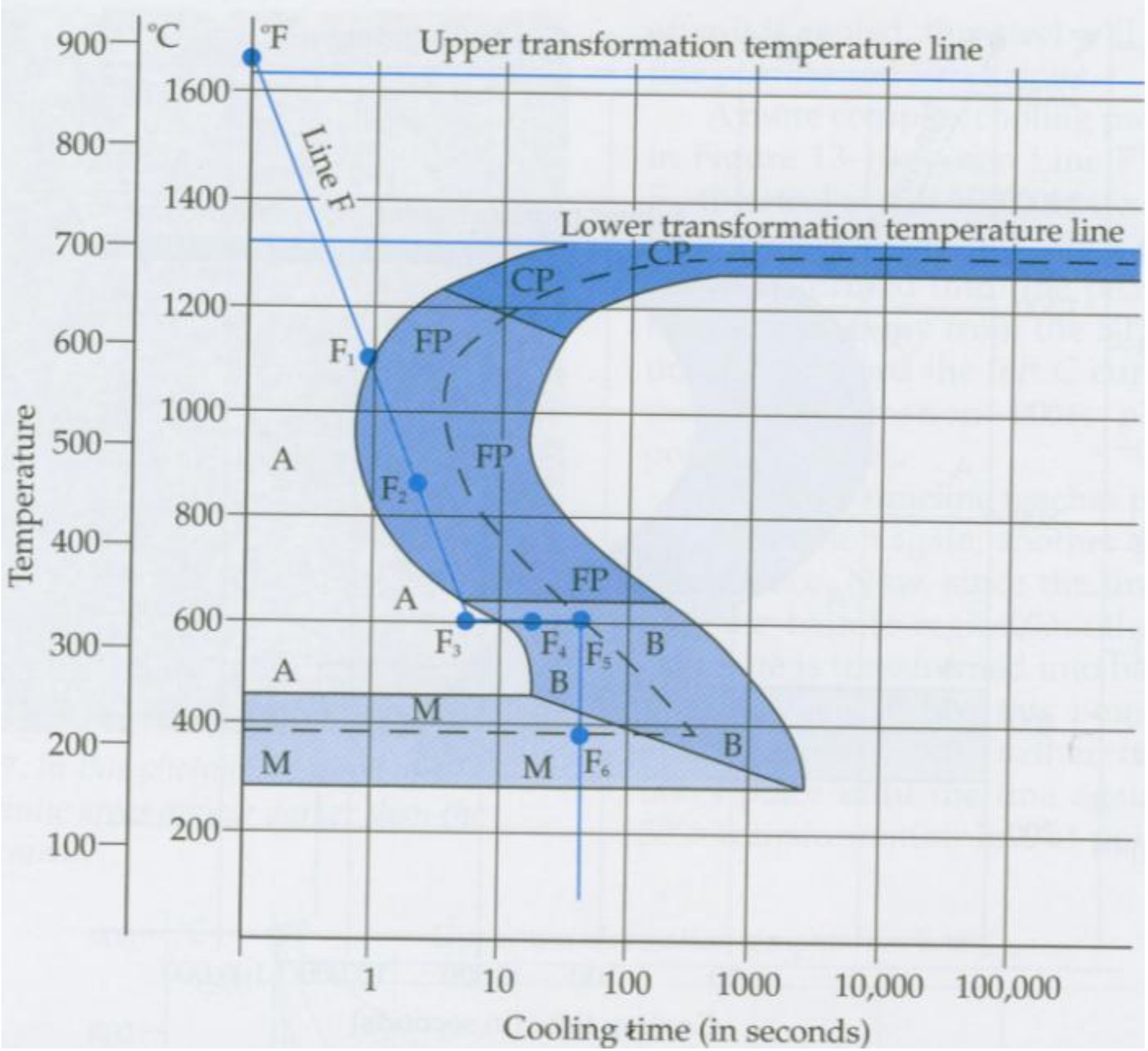
°C
°F
Temperature
900
800
700
600
500
400
300
200
100
1600
1400
1200
1000
800
600
400
200
Upper transformation temperature line
B1 Lower transformation temperature line
CP
CP
FP
FP
FP
B
B
B
A
A
A
M
M
M
C1
C2
B2
A1
A2
D1
D2
Timeline A
Timeline B
Timeline C
Timeline D
1
10
100
1000
10,000
100,000
Cooling time (in seconds)

1045 Martinsite Bainite



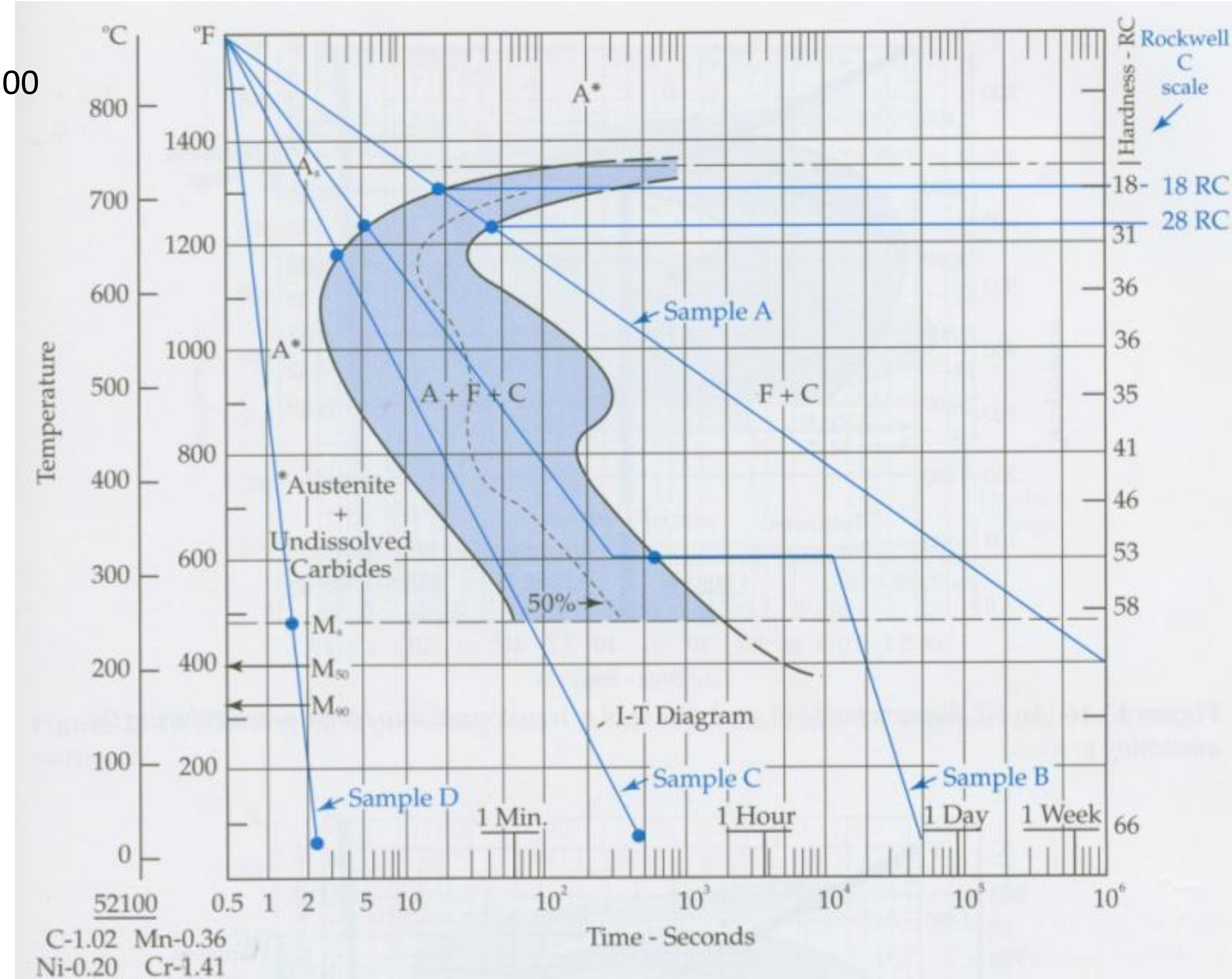


°C
°F
Upper transformation temperature line
Lower transformation temperature line
Timeline E
Temperature
900
800
700
600
500
400
300
200
100
1600
1400
1200
1000
800
600
400
200
CP
CP
FP
FP
FP
E₁
E₂
E₃
E₄
E₅
A
A
A
B
B
B
M
M
M
1
10
100
1000
10,000
100,000
Cooling time (in seconds)

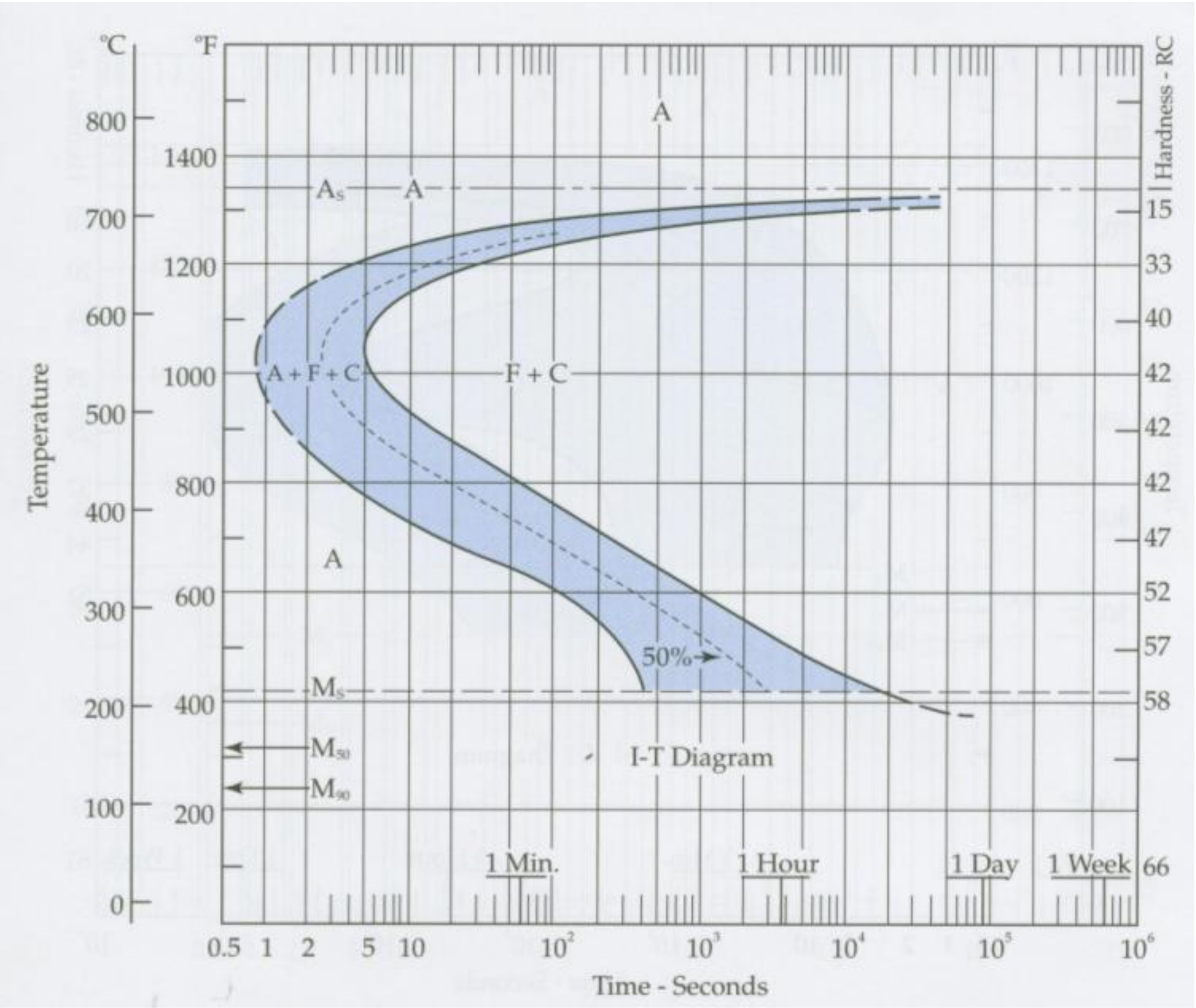


°C
°F
Upper transformation temperature line
Lower transformation temperature line
Line F
Temperature
900
800
700
600
500
400
300
200
100
1600
1400
1200
1000
800
600
400
200
CP
CP
FP
FP
FP
A
A
A
M
M
M
B
B
B
F1
F2
F3
F4
F5
F6
1
10
100
1000
10,000
100,000
Cooling time (in seconds)

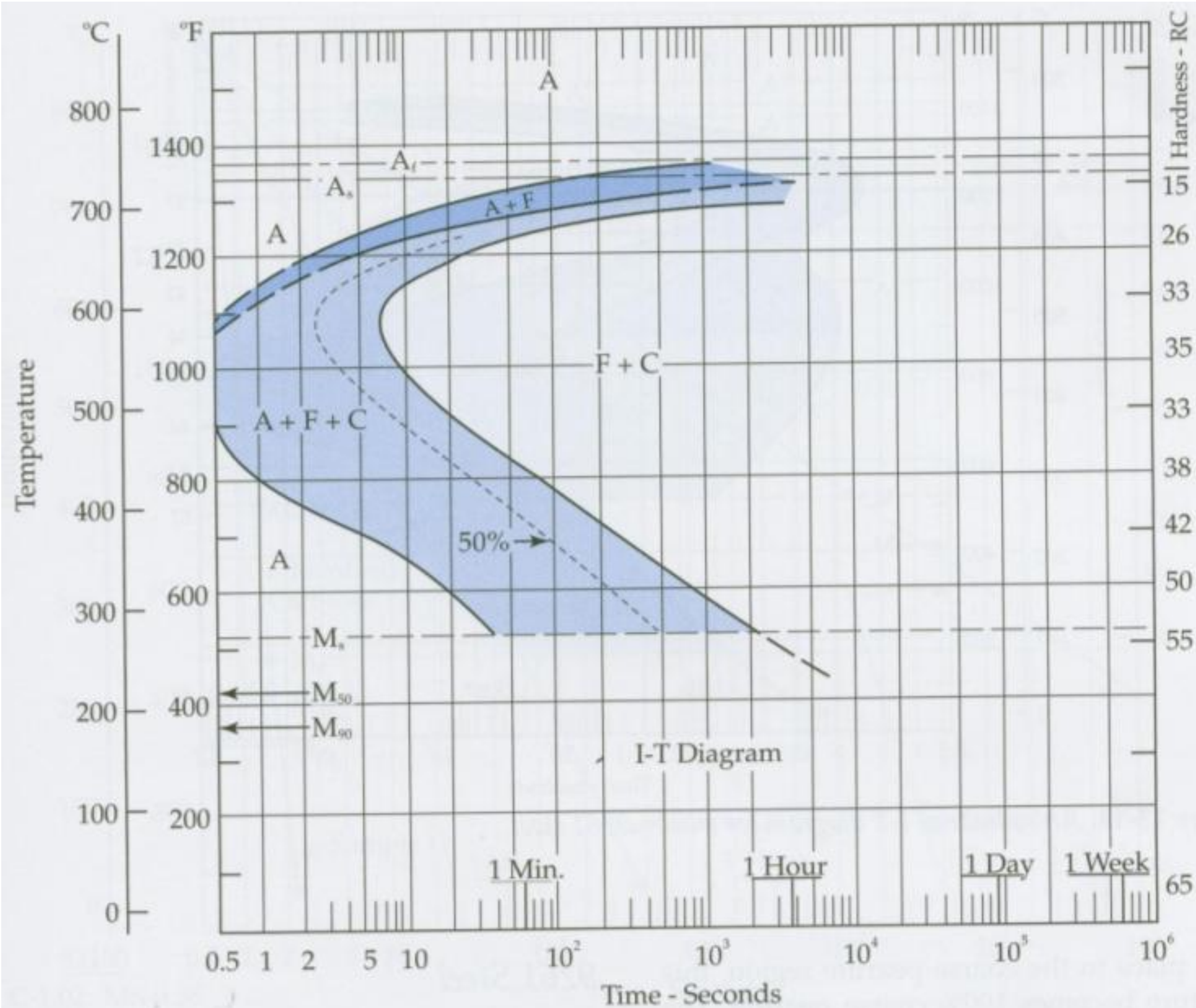
52100



°C
°F
Rockwell C scale
Hardness - RC
800
1400
700
1200
600
1000
500
800
400
600
300
400
200
200
100
0
A*
A_s
18 RC
28 RC
18
31
36
36
35
41
46
53
58
66
Sample A
Sample B
Sample C
Sample D
A + F + C
F + C
*Austenite + Undissolved Carbides
50%
M_s
M_{50}
M_{90}
I-T Diagram
1 Min.
1 Hour
1 Day
1 Week
Temperature
0.5
1
2
5
10
10^2
10^3
10^4
10^5
10^6
Time - Seconds
52100
C-1.02 Mn-0.36
Ni-0.20 Cr-1.41

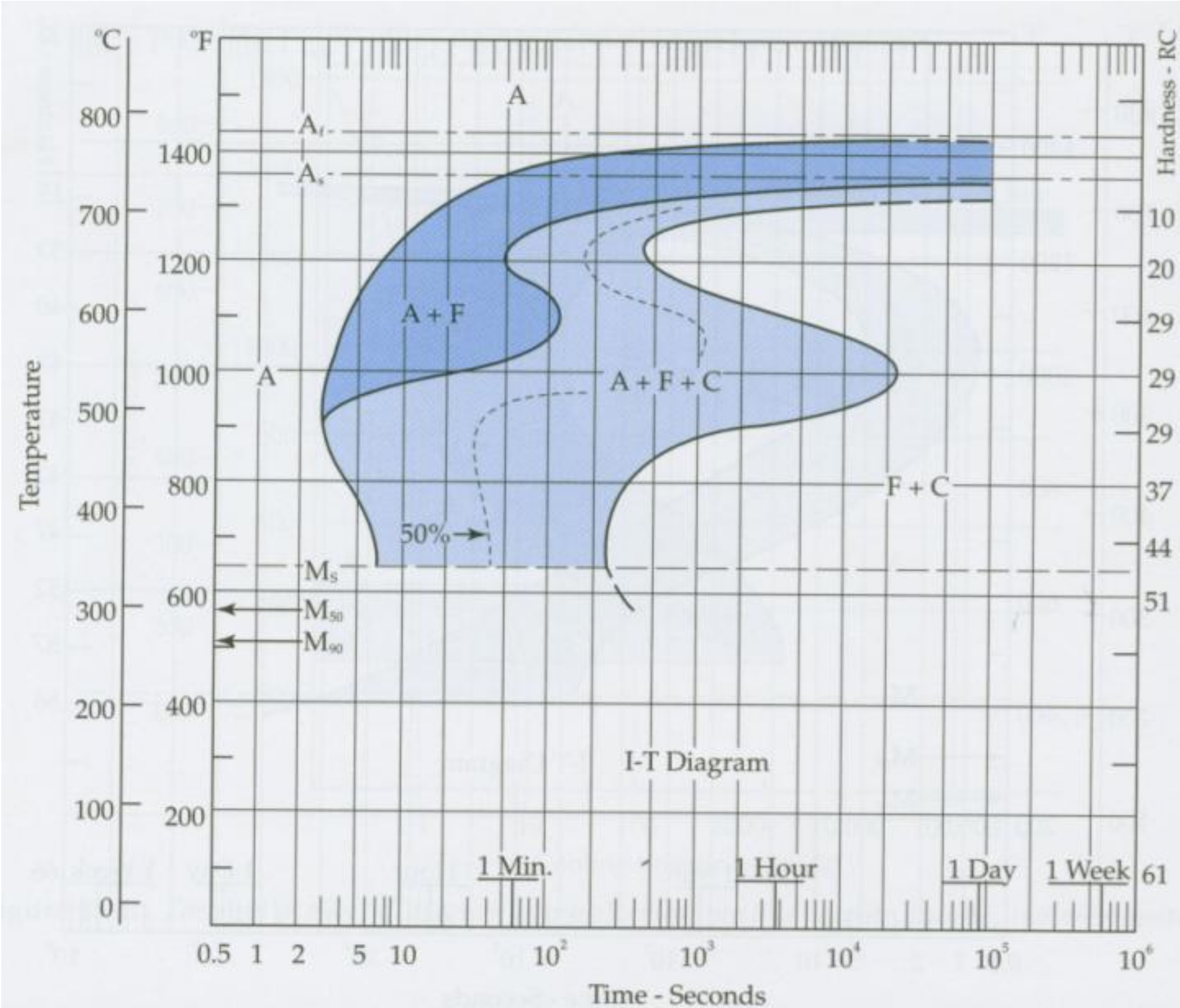

°C
°F
800
700
600
500
400
300
200
100
0
1400
1200
1000
800
600
400
200
A
A_S
A
A + F + C
F + C
A
50%
M_S
M_50
M_90
I-T Diagram
1 Min.
1 Hour
1 Day
1 Week
0.5
1
2
5
10
10^2
10^3
10^4
10^5
10^6
Time - Seconds
Temperature
Hardness - RC
15
33
40
42
42
42
47
52
57
58
66

1060



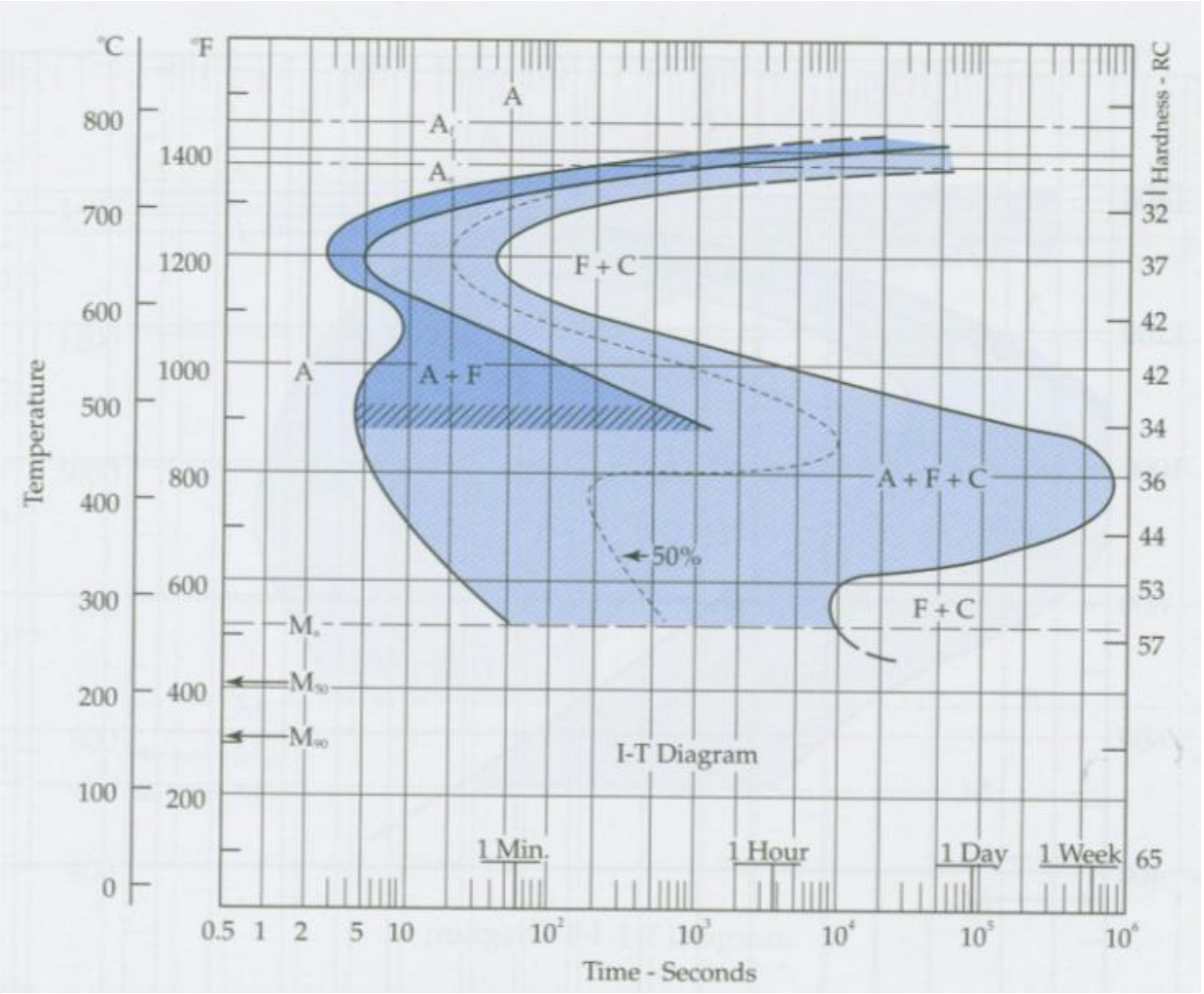
°C
°F
A
A + F
A_f
A_s
A
A + F + C
F + C
A
50%
M_s
M_{50}
M_{90}
I-T Diagram
Temperature
800
700
600
500
400
300
200
100
0
1400
1200
1000
800
600
400
200
Hardness - RC
15
26
33
35
33
38
42
50
55
65
1 Min.
1 Hour
1 Day
1 Week
0.5
1
2
5
10
10^2
10^3
10^4
10^5
10^6
Time - Seconds

4140

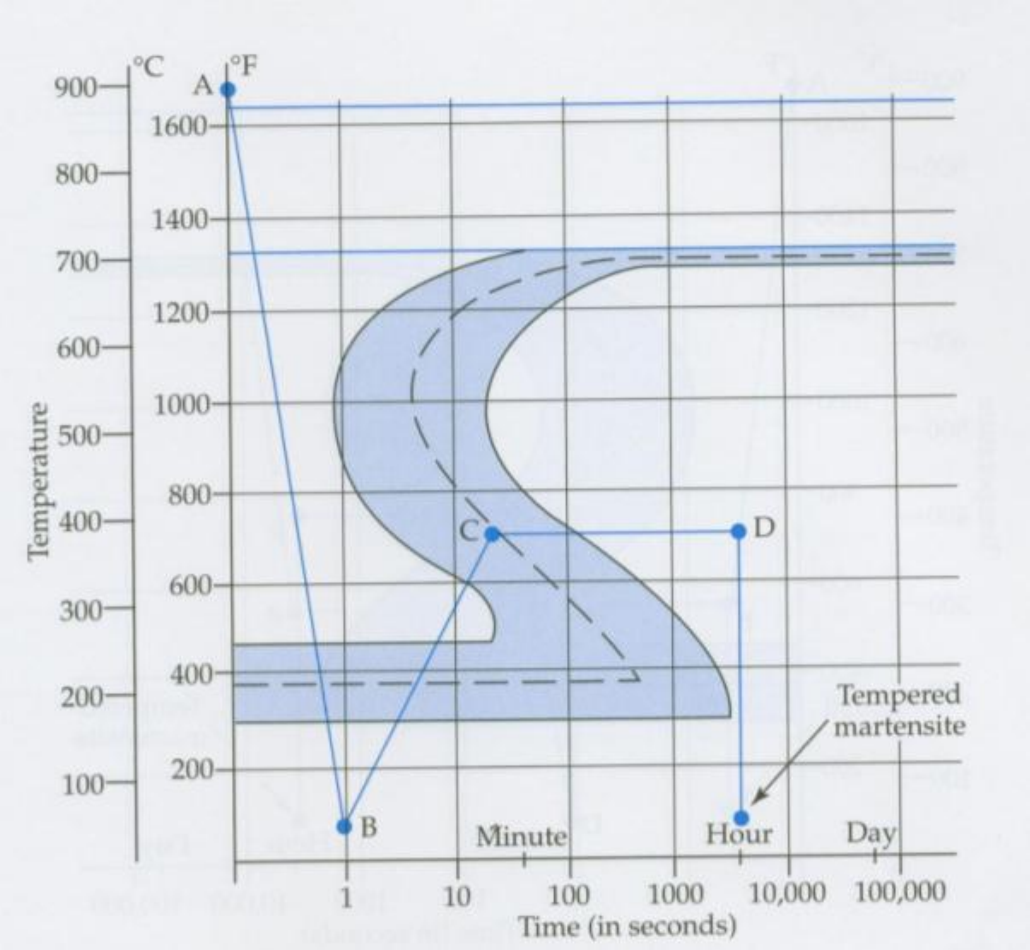


°C
°F
Hardness - RC
A
A_f
A_s
A + F
A
A + F + C
F + C
50%
M_s
M_{50}
M_{90}
I-T Diagram
1 Min.
1 Hour
1 Day
1 Week
Temperature
Time - Seconds
800
700
600
500
400
300
200
100
0
1400
1200
1000
800
600
400
200
10
20
29
29
29
37
44
51
61
0.5
1
2
5
10
10^2
10^3
10^4
10^5
10^6

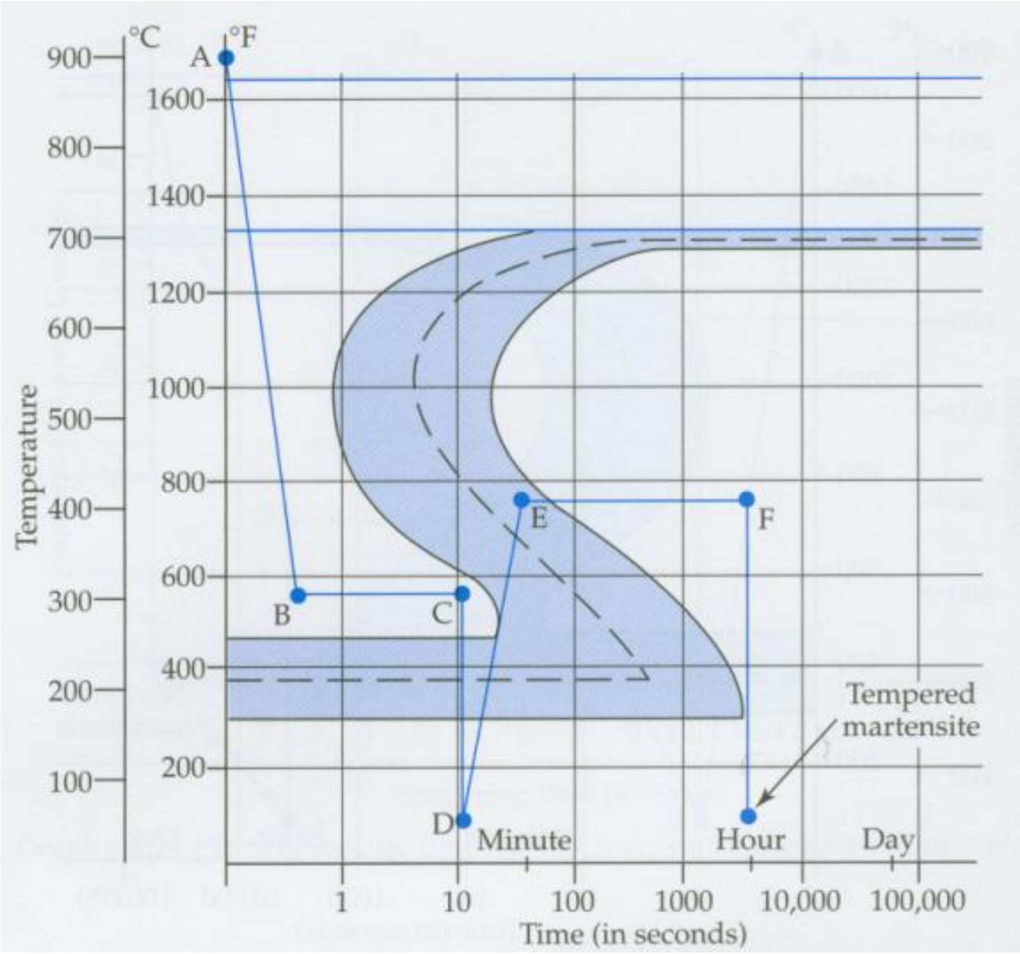
Silicon
9261



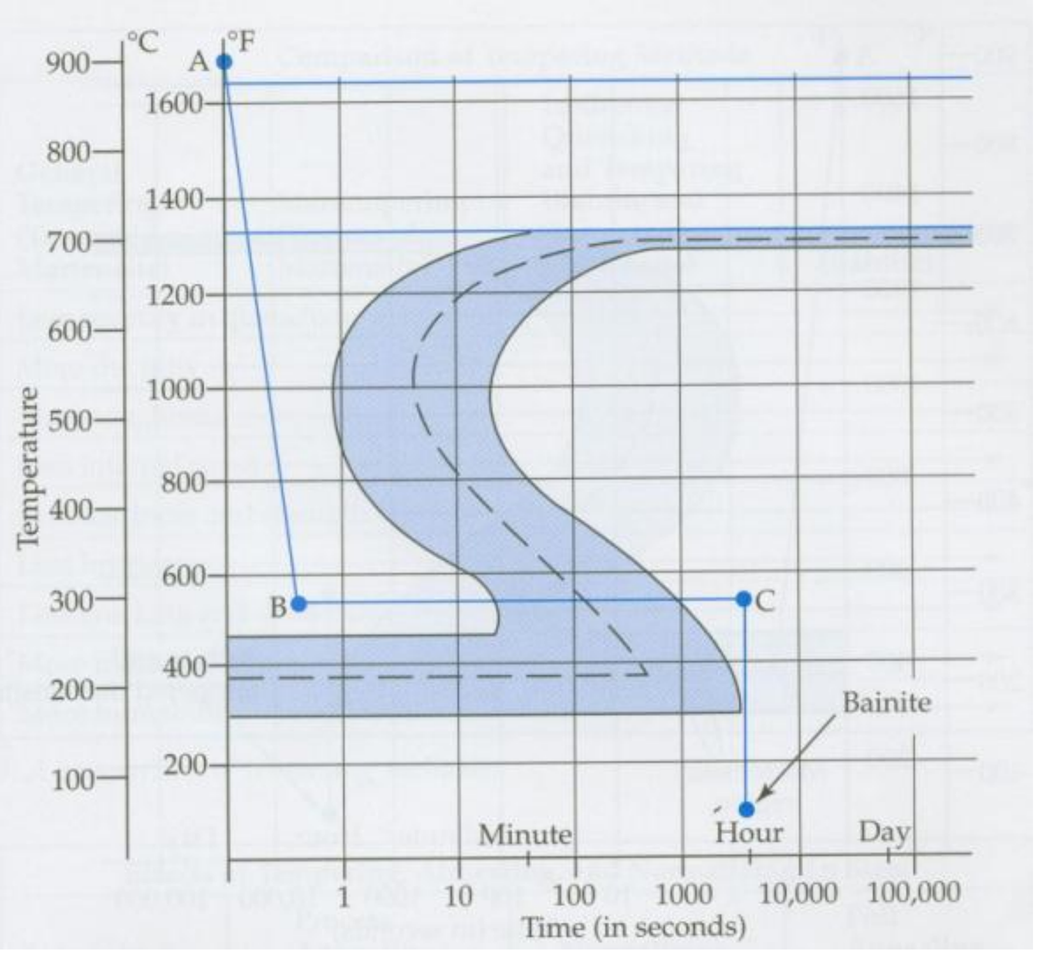
General Tempering



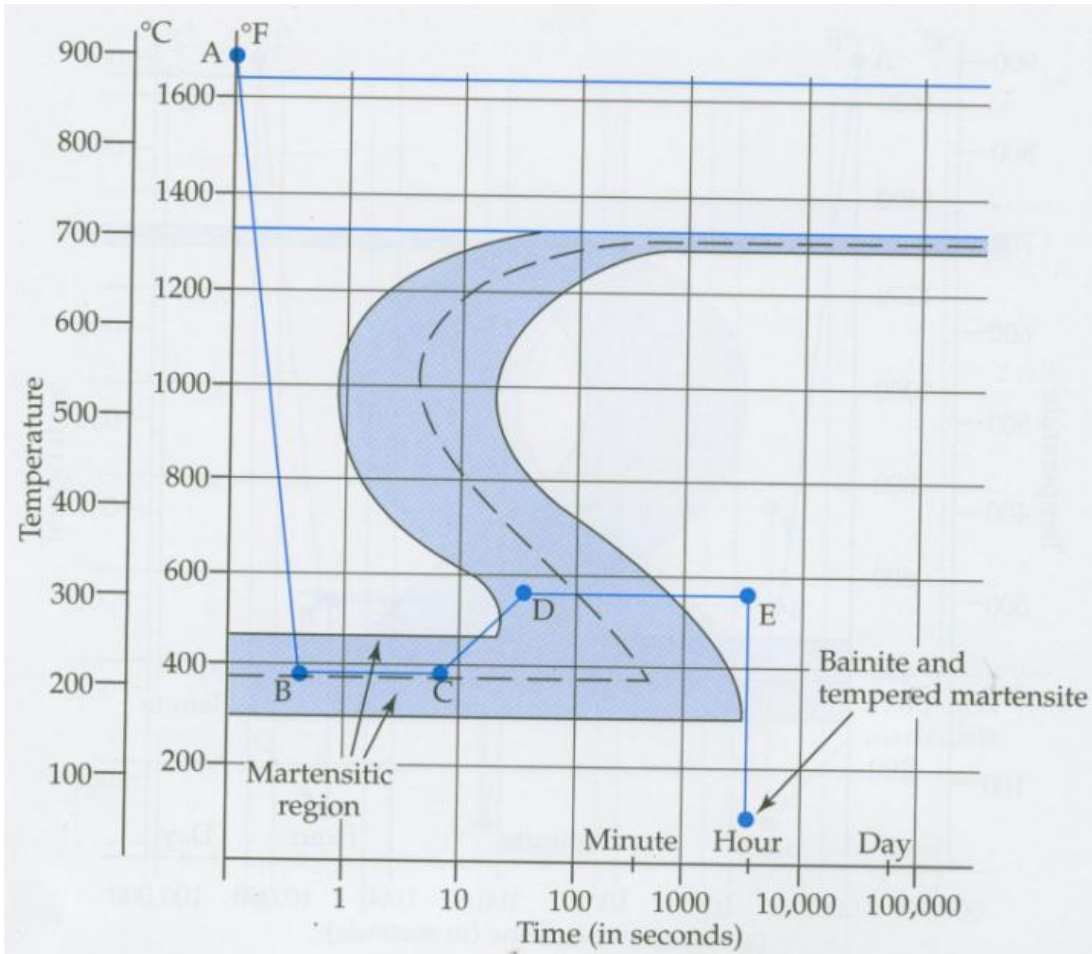
Martempering



Austempering



Isothermal Quenching and Tempering



Comparison of Tempering Methods

General Tempering (Tempered Martensite)	Martempering (Tempered Martensite)	Isothermal Quenching and Tempering (Bainite and Tempered Martensite)	Austempering (Bainite)
Less severity in quenching →			
More ductility →			
More toughness →			
Less internal stress →			
Less hardness and strength →			
Less brittleness →			
Less cracking and distortion →			
More machinability →			
More formability →			

	Fahr.	Cent.
LIGHT BLUE	640°	340°
FULL BLUE	590°	310°
PEACOCK	540°	280°
BRONZE	520°	270°
DEEP STRAW	475°	245°
STRAW	440°	225°
FAINT STRAW	400°	205°

Steel Numbering System

4140

Composition

Percent Carbon:
(100 = 1%)

Steel Numbering System	
Steel Numerical Name	**Key Alloys**
10XX	Carbon only
11XX	Carbon only (free cutting)
13XX	Manganese
23XX	Nickel
25XX	Nickel
31XX	Nickel-Chromium
33XX	Nickel-Chromium
303XX	Nickel-Chromium
40XX	Molybdenum
41XX	Chromium-Molybdenum
43XX	Nickel-Chromium-Molybdenum
44XX	Manganese-Molybdenum
46XX	Nickel-Molybdenum
47XX	Nickel-Chromium-Molybdenum
48XX	Nickel-Molybdenum
50XX	Chromium
51XX	Chromium
501XX	Chromium
511XX	Chromium
521XX	Chromium
514XX	Chromium
515XX	Chromium
61XX	Chromium-Vanadium
81XX	Nickel-Chromium-Molybdenum
86XX	Nickel-Chromium-Molybdenum
87XX	Nickel-Chromium-Molybdenum
88XX	Nickel-Chromium-Molybdenum
92XX	Silicon-Manganese
93XX	Nickel-Chromium-Molybdenum
94XX	Nickel-Chromium-Molybdenum-Manganese
98XX	Nickel-Chromium-Molybdenum
XXBXX	Boron
XXLXX	Lead

Effects of alloying elements on Steel

- C Carbon – *hardness, strength, wear*
- Mn Manganese – *Strength, hardenability, heat treatment response*
- Si Silicon – *Deoxidation, hardenability*
- Cr Chromium – *Corrosion Resistance, hardenability*
- Mo Molybdenum – *High Temperature Strength, machinability*
- W Tungsten – *High Temperature Strength, wear*
- V Vanadium – *Fine Grain, Toughness*
- Ni Nickel – *Toughness, Strength*
- Co Cobalt – *Hardness, Wear*