Lecture 8:
Alloy Steels

MMat 380

Lecture outline

- Alloy steels
  - Base material, trends
  - TTT curves & effects of alloying elements
- Hardenability
  - Grossman Method
  - Jominy Method
  - %C, grain size and alloying elements

Steels

Extremely wide range of properties and applications

- **Plain carbon steels**
- **Alloy steels – this is the focus for today**

Alloy steels – base material

- Most carbon levels @ ~ 0.4%
- Higher %C means harder martensite
  - higher after temper hardness (less tough)
  - Example: 4130 tougher than 4140

Modern trends

- With modern control of chemistries
  - alloy and Mn levels at low end of the nominal range
  - cheaper
  - "new" steels may not be as "hardenable" as the old steels
  - ie if Mo range was 0.20-0.30 **now** Mo will be 0.195-0.2%
- Most common grade 4140 (Cr-Mo)
  - 4120; 4130; 4140

Effect of alloying elements on TTT curves

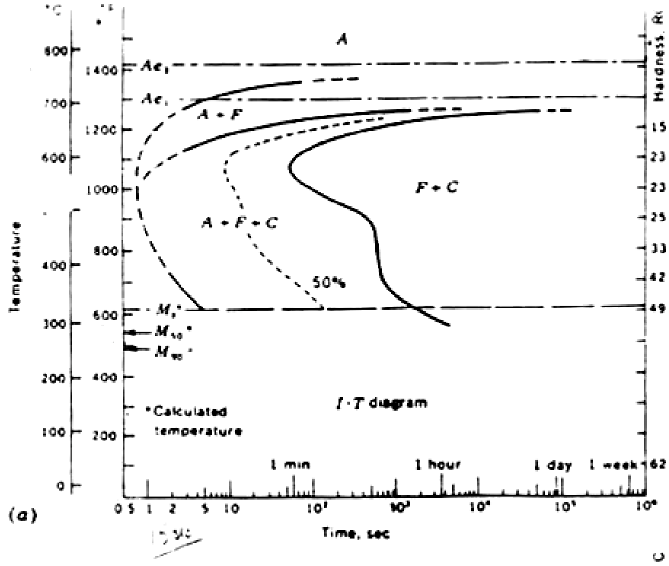
Medium C steel

- 1040 (0.4%C + 1%Mn)
- 5140 (0.4%C + 1%Mn + 0.9%Cr)
- 4140 (0.4%C + 1%Mn + 1.0%Cr + 0.2%Mo)
- 4340 (0.4%C + 1%Mn + 0.8%Cr + 0.3%Mo + 1.85Ni)

TTT curve - 1040

1040

C+Mn

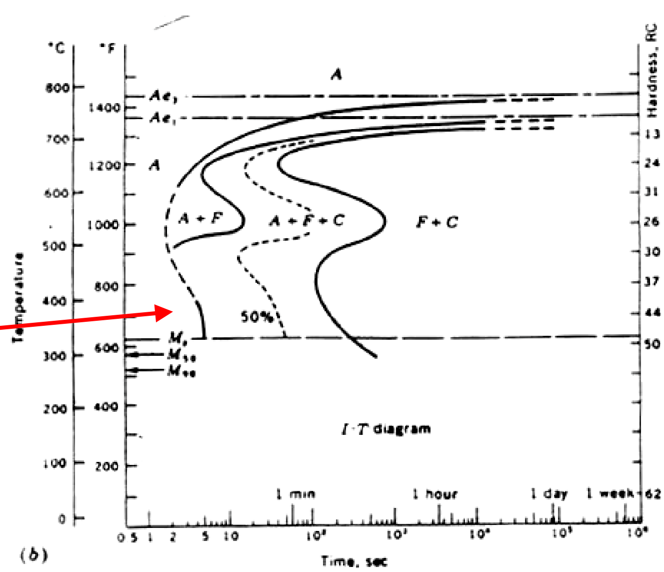


TTT curve - 5140

5140

C+Mn+Cr

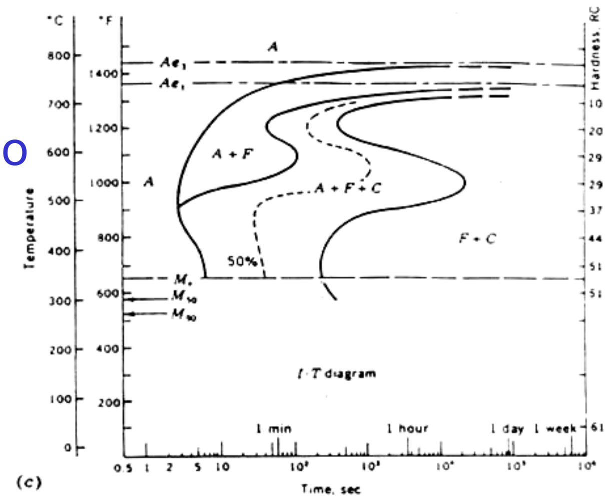
Curve shifted to right



TTT curve - 4140

4140

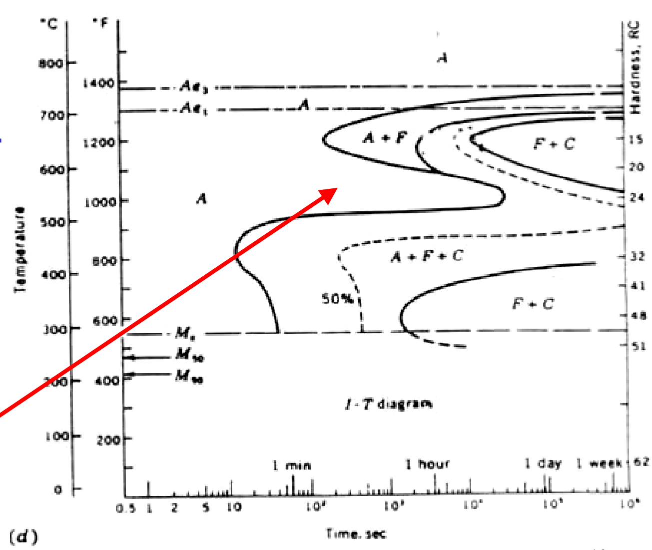
C+Mn+Cr+Mo



TTT curve - 4340

4340

C+Mn+Cr+
Ni+Mo



Separation of
pearlite and
bainite nose

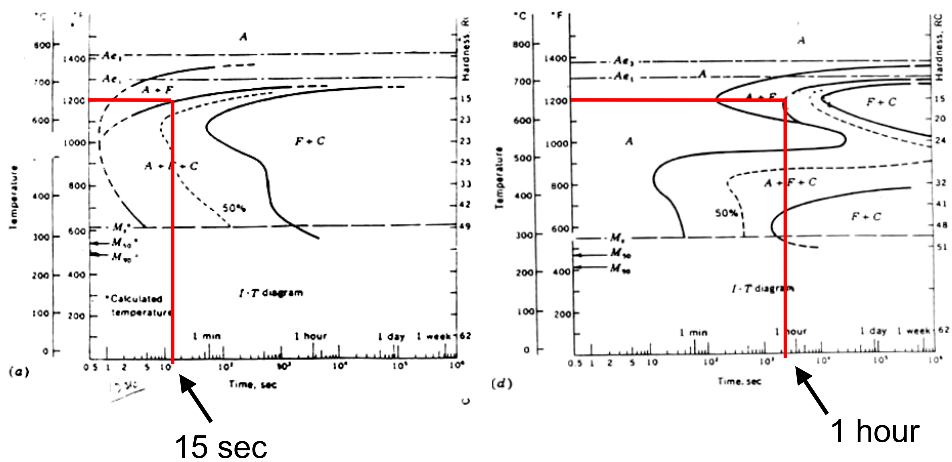
TTT Curves (1040, 5140, 4140, 4340)

- With increased alloys, P+B noses **shift right**
  - i.e. hardenability increases
- Plain C steels can't be hardened to form martensite except at very high cooling rates
  - i.e. small section sizes
  - dotted lines indicate times too fast for P transformation to be accurately recorded

TTT Curves (1040, 5140, 4140, 4340)

- P + B noses **separate**
- P nose pushed back more than B nose
  - difficult to form P in high alloy 4340
    - Ex: 1 hr @ 650°C vs. 15 sec @ 650°C for 1040.
  - Proeutectoid α 1.5 sec vs. 4 min.
  - Easy to form bainite

1040 4340



TTT Curves (1040, 5140, 4140, 4340)

5. B_f (bainite finish) times @ T_{transf} 345°C

Grade	B_f time (seconds)	(minutes)
1040	800	13
5140	200	3.5
4140	280	4.5
4340	2000	33

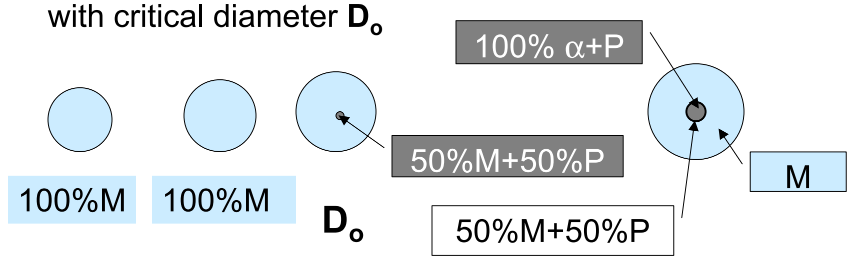
Hardenability

Property that determines the depth and distribution of hardness induced by quenching from austenite

- Determined by the following factors:
  - Chemical composition
  - Austenite grain size
  - Structure of the steel before quenching
- Determine hardenability by:
  - Grossman testing
  - Jominy method

Grossman hardenability

- Critical diameter of hardenable steel bar:
  - Bars of different diameters quenched in different media
  - Bar with 50% martensite at its centre selected as the bar with critical diameter $\mathbf{D_o}$



ie. Can't through harden a bar>D_o

D_o – 99% martensite for the whole part

Too complicated, costly and time consuming

Vocabulary

H = quench severity factor (oil 0.2 - brine 5.0)
D_o (D, D_c) = actual critical bar ϕ to produce 50% martensite at its centre for a **known** H
D_I = ideal ϕ (critical ϕ) to produce 50% martensite at f for **H =** ∞ (ideal quench)

- Relationship between D_o, D_I, and the severity of the quench

Application of Grossman method

- Machine a series of cylindrical steel bars i.e. ϕ 0.5-2.5 in.
- Quench each from γ in a given quenching medium (known H)
- Section and determine bar ϕ with 50% martensite in centre
  - Defines critical diameter D_o (in inches) as bar with 50% martensite in the centre
  - i.e. can't through harden a bar > D_o

Ideal critical diameter (D_I)

- Convert D_o to D_I (more general)
- Ideal critical diameter (D_I)
  - Eliminates cooling rate variability
  - Diameter of bar to form 50% martensite at centre with ideal quench
- Ideal quench: Heat removed from surface as fast as it reaches it
  - i.e. assume surface instantaneously assumes the T of the quench and stays there
  - $H = \infty = \phi/k$ = heat transfer coefficient/thermal conductivity

Factors that affect D_I

- For constant grain size
  - D_I increases with increase in %C
  - (i.e, higher hardenability with increase in %C)
- For constant carbon
  - D_I increases with increase in γ grain size (smaller ASTM grain size number)

Calculating base D_I

- [Figure 4-4](#) pg. 135 Smith
- Calculate multiplying factors for each element ([Figure 4-5](#), pg. 136 Smith)
- Ideal critical diameter found by multiplying base diameter by the multiplying factors

Effect of γ grain size and %C on D_I

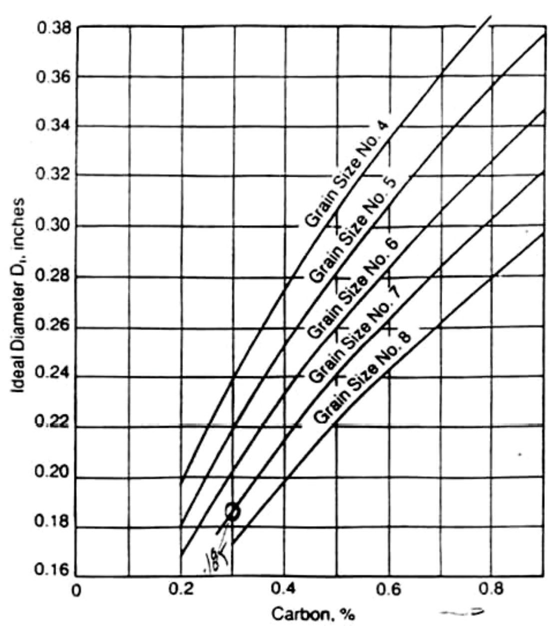


Figure 4-4 Smith

Multiplying factor for each alloy addition

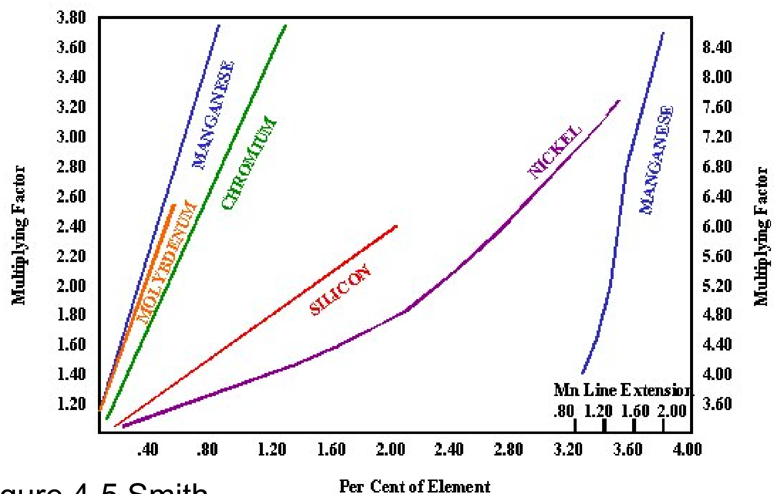


Figure 4-5 Smith

Example

D_I = 2.2 in. What is the actual critical diameter D_o if the steel is subjected to an oil quench with moderate agitation?

- Find H: Table 4-4 pg. 133 **H = 0.4**
- determine D_o : Figure 4-3 pg. 134
  D_o = 0.9 in.
- Calculation of D_I ASTM standard A255

“H” factors for various quench media

Coefficient of severity of quench: H			
Agitation	**cooling medium**		
	Oil	**Water**	**Brine**
None	0.25-0.30	0.9-1.0	2.0
Mild	0.30-0.35	1.0-1.1	2.0-2.2
Moderate	0.35-0.40	1.2-1.3	
Good	0.4-0.5	1.4-1.5	
Strong	0.5-0.8	1.6-2.0	
Violent	0.8-1.1	4.0	5.0

Table 4-4 Smith

Effect of D_I and “H” on D

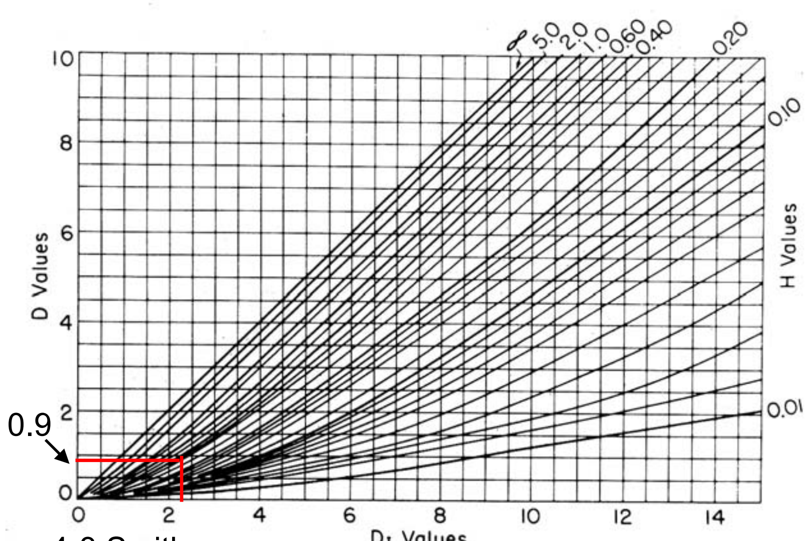


Figure 4-3 Smith

Effect of austenite grain size on hardenability

- The more γ-grain boundary surface the easier it is for pearlite to form rather than martensite
  - Smaller γ-grain size → lower hardenability
  - Larger γ-grain size → higher hardenability

Effect of alloy composition on hardenability

- Increasing %C increasing hardenability
- Generally other alloy additions increases hardenability
- **Exceptions**
  - S (because of MnS)
  - Co (because it increases the rate of nucleation and growth of pearlite)
  - Ti (because it reacts with C to form TiC)
- Tables indicate effect of each alloy addition

Example

Calculate the approximate hardenability of an 8630 (0.3%C, 0.3%Si, 0.7%Mn, 0.5%Cr, 0.6%Ni, 0.2%Mo) alloy steel with an ASTM grain size of 7

- Calculate base D_I (Figure 4-4 pg. 135 Smith)
- Calculate multiplying factors for each element (Figure 4-5, pg. 136 Smith)
- Ideal critical diameter found by multiplying base diameter by the multiplying factors

Figure 4-4 from text

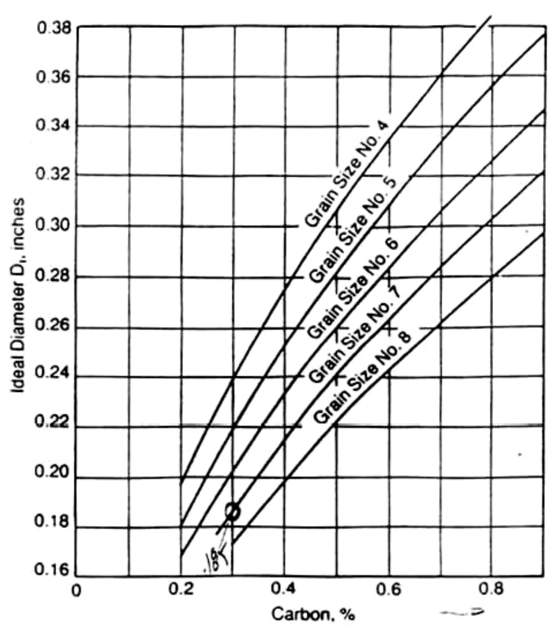
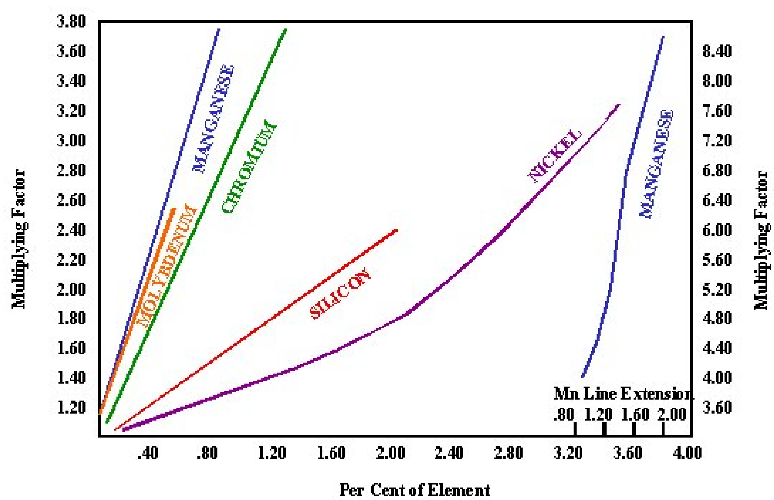


Figure 4-5 from text and website



Calculation

% alloying element	Multiplying factor
0.3 Si	**1.2**
0.7 Mn	**3.4**
0.5 Cr	**2.1**
0.6 Ni	**1.2**
0.2 Mo	**1.6**

D_I = **0.185 x 1.2 x 3.4 x 2.1 x 1.2 x 1.6 = 3.04 in.**

Example 2

Alloy 8740 grain size 7

- Find composition Table 4-1 & nomenclature

  87: Ni 0.55, Cr 0.5, Mo 0.25
  40: C 0.40
  Assume Si again 1.2, Mn again 0.7

- Find base D_I Figure 4-4 $D_I = 0.215$
- Find multiplying factors from Figure 4-5

Calculation

% alloying element	Multiplying factor
0.3 Si	1.2
0.7 Mn	3.4
0.5 Cr	2.1
0.55 Ni	1.2
0.25 Mo	1.7

D_I = **0.215 x 1.2 x 3.4 x 2.1 x 1.2 x 1.7 = 3.76 in.**

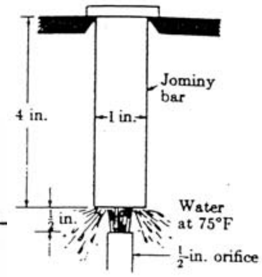
Hardenabilities (as range of D_i values) for various steels

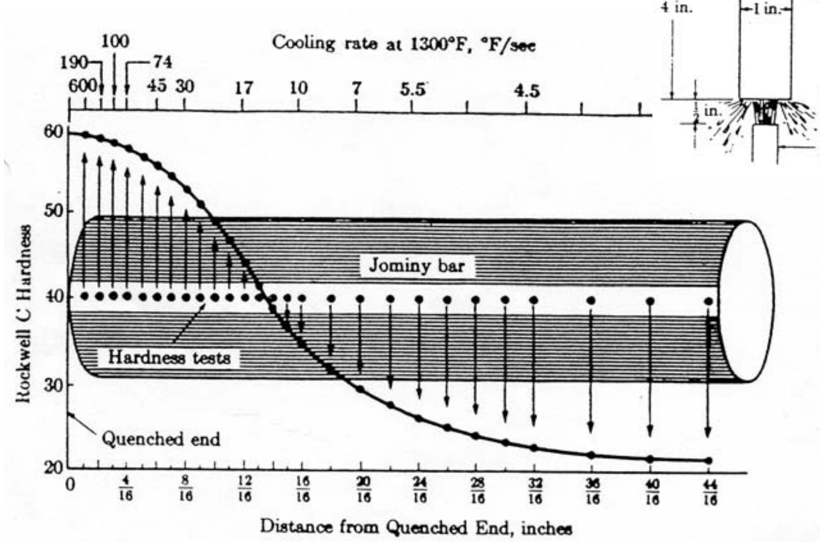
Steel	D_I	Steel	D_I	Steel	D_I
1045	0.9 to 1.3	4135 H	2.5 to 3.3	8625 H	1.6 to 2.4
1090	1.2 to 1.6	4140 H	3.1 to 4.7	8627 H	1.7 to 2.7
1320 H	1.4 to 2.5	4317 H	1.7 to 2.4	8630 H	2.1 to 2.8
1330 H	1.9 to 2.7	4320 H	1.8 to 2.6	8632 H	2.2 to 2.9
1335 H	2.0 to 2.8	4340 H	4.6 to 6.0	8635 H	2.4 to 3.4
1340 H	2.3 to 3.2	X4620 H	1.4 to 2.2	8637 H	2.6 to 3.6
2330 H	2.3 to 3.2	4620 H	1.5 to 2.2	8640 H	2.7 to 3.7
2345	2.5 to 3.2	4621 H	1.9 to 2.6	8641 H	2.7 to 3.7
2512 H	1.5 to 2.5	4640 H	2.6 to 3.4	8642 H	2.8 to 3.9
2515 H	1.8 to 2.9	4812 H	1.7 to 2.7	8645 H	3.1 to 4.1
2517 H	2.0 to 3.0	4815 H	1.8 to 2.8	8647 H	3.0 to 4.1
3120 H	1.5 to 2.3	4817 H	2.2 to 2.9	8650 H	3.3 to 4.5
3130 H	2.0 to 2.8	4820 H	2.2 to 3.2	8720 H	1.8 to 2.4
3135 H	2.2 to 3.1	5120 H	1.2 to 1.9	8735 H	2.7 to 3.6
3140 H	2.6 to 3.4	5130 H	2.1 to 2.9	8740 H	2.7 to 3.7
3340	8.0 to 10.0	5132 H	2.2 to 2.9	8742 H	3.0 to 4.0
4032 H	1.6 to 2.2	5135 H	2.2 to 2.9	8745 H	3.2 to 4.3
4037 H	1.7 to 2.4	5140 H	2.2 to 3.1	8747 H	3.5 to 4.6
4042 H	1.7 to 2.4	5145 H	2.3 to 3.5	8750 H	3.8 to 4.9
4047 H	1.8 to 2.7	5150 H	2.5 to 3.7	9260 H	2.0 to 3.3
4047 H	1.7 to 2.4	5152 H	3.3 to 4.7	9261 H	2.6 to 3.7
4053 H	2.1 to 2.9	5160 H	2.8 to 4.0	9262 H	2.8 to 4.2
4063 H	2.2 to 3.5	6150 H	2.8 to 3.9	9437 H	2.4 to 3.7
4068 H	2.3 to 3.6	8617 H	1.3 to 2.3	9440 H	2.4 to 3.8
4130 H	1.8 to 2.6	8620 H	1.6 to 2.3	9442 H	2.8 to 4.2
4132 H	1.8 to 2.5	8622 H	1.6 to 2.3	9445 H	2.8 to 4.4

Jominy Method

Jominy test

Jominy Quench

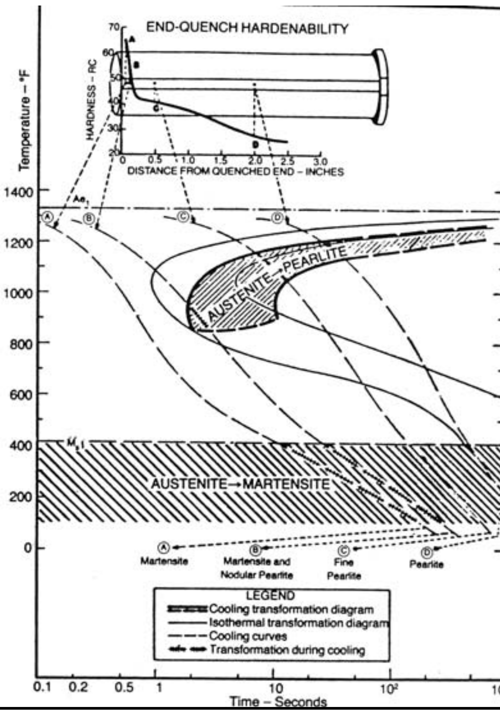




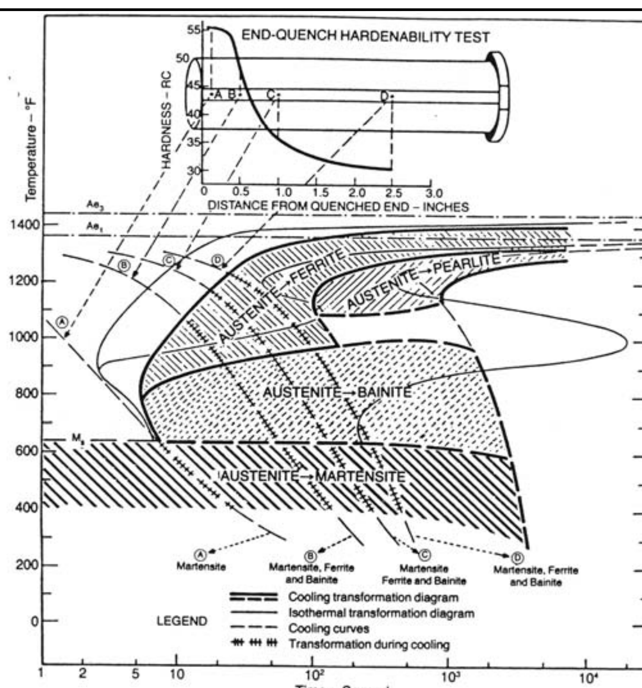
Jominy Method

- Bar 1in. diameter x 4in. length
- Place in fixture; water quench **end** of specimen
- After cooling grind flat, R_c measurements made **along length** of bar
- Section and examine metallography **along length** to determine microstructure
- Correlate structure and properties
  - Now know cooling rate needed to get a given property
  - Can make CCT diagram with quantitative microstructure and hardness

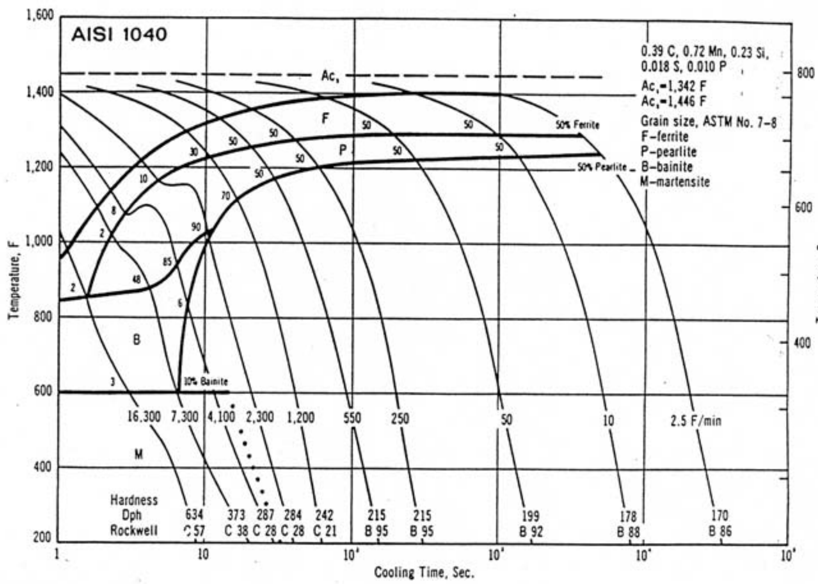
CCT from Jominy



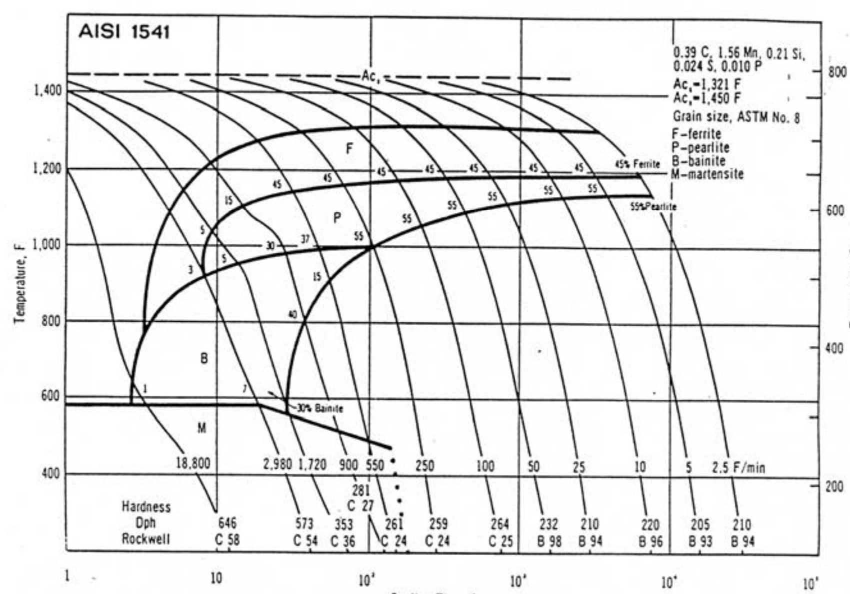
CCT from Jominy



Quantitative CCT diagram 1040



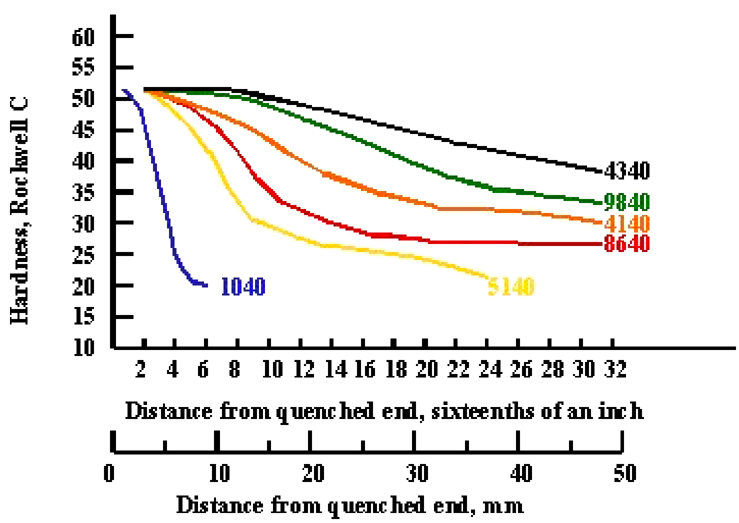
Quantitative CCT diagram 1541



Factors affecting hardenability

- %C: ↑ %C ↑ hardenability and hardness
- Alloy content: ↑ in alloy content ↑ hardenability
  - High martensite content at slow cooling rates
  - If you don't form martensite then will get bainite
  - i.e. 4140 & 4340 will have martensite and bainite @ 1-2 in.
  - 1040 would be ferrite + bainite
- γ grain size – ↑ in grain size will ↑ hardenability
- "H" Steels (i.e., 4140H)
  - H steels - guaranteed restricted hardenability band

Hardenability curves of 6 steels



Hardenability of 6 steels

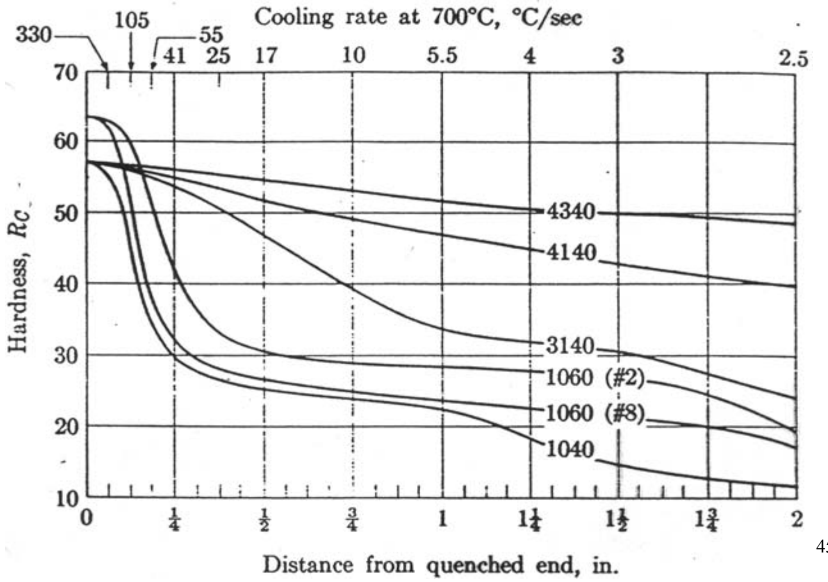


TABLE 4-1
Principal types of standard low alloy steels

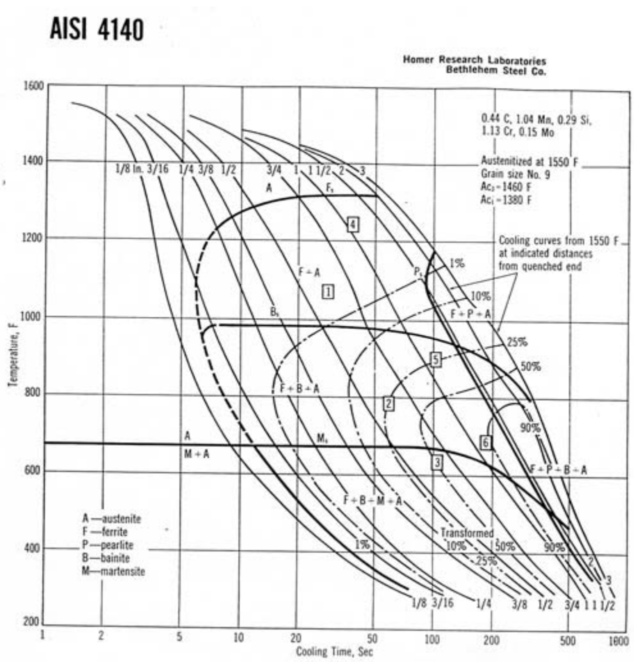
13xx	Manganese 1.75
40xx	Molybdenum 0.20 or 0.25; or molybdenum 0.25 and sulfur 0.042
41xx	Chromium 0.50, 0.80, or 0.95, molybdenum 0.12, 0.20, or 0.30
43xx	Nickel 1.83, chromium 0.50 or 0.80, molybdenum 0.25
44xx	Molybdenum 0.53
46xx	Nickel 0.85 or 1.83, molybdenum 0.20 or 0.25
47xx	Nickel 1.05, chromium 0.45, molybdenum 0.20 or 0.35
48xx	Nickel 3.50, molybdenum 0.25
50xx	Chromium 0.40
51xx	Chromium 0.80, 0.88, 0.93, 0.95, or 1.00
51xxx	Chromium 1.03
52xxx	Chromium1.45
61xx	Chromium 0.60 or 0.95, vanadium 0.13 or min 0.15
86xx	Nickel 0.55, chromium 0.50, molybdenum 0.20
87xx	Nickel 0.55, chromium 0.50, molybdenum 0.25
88xx	Nickel 0.55, chromium 0.50, molybdenum 0.35
92xx	Silicon 2.00; or silicon 1.40 and chromium 0.70
50Bxx	Chromium 0.28 or 0.50
51Bxx	Chromium 0.80
81Bxx	Nickel 0.30, chromium 0.45, molybdenum 0.12
94Bxx	Nickel 0.45, chromium 0.40, molybdenum 0.12

Note: B denotes boron steel.

Table 4-1 from text

Alloying elements

- Highest number Mn, Mo, Cr, Ni
- Si not a deliberate addition
- Carbon – grain size
- Number increases with %C and larger grain size
- Minor additions on impurities
- S -ve takes Mn out of solution as MnS
- Ti -ve takes C out of solution; very stable and does not easily dissolve



Cooling curves from Jominy

Also for AISI 4140 Jominy