Chapters 9 & 10 – Steels

Steel nomenclature:

fine pearlite
coarse pearlite
upper bainite
spheroidite
low alloy steel
stainless steel
austenitize
anneal (full)
temper
hardness
secondary hardening
M_s M_f M_d temperatures
prior austenite grain size
retained austenite
IT diagrams (TTT curves)
CCT diagrams
medium pearlite
martensite
lower bainite
ε-carbide
tool steel
cast iron
normalize
anneal (process)
quenched & tempered
hardenability

Heat treatments:

Austenitize – heat to form austenite (e.g., heat to 875 C and hold for 1 hr)

Normalize – austenitize and air cool

Anneal (full) –austenitize and furnace cool

Spheroidize – heat just below eutectoid temperature and hold for long time (e.g., 24 hr)

Tempered martensite – austenitize, oil or water quench, and heat at intermediate temperature (e.g., heat to 450 C and hold 2 hr)

Others – e.g., austenitize and isothermally transform to bainite

Steel microstructures:

Pearlite - coarse, medium, fine
Proeutectoid ferrite
Proeutectoid cementite
Bainite – upper, lower
Spheroidite
Martensite – lath (massive), lenticular (plate)
Tempered martensite

Characteristics of ferrous martensites:

Martensitic transformations:

- a general type of metallurgical solid state transformation
- speed: rapid, instantaneous
- diffusionless
- shear mechanism involved
- athermal transformation (depends primarily on temperature, independent of time)
- crystallographic relationship between the transformed martensite and the parent structure

Ferrous martensite:

- single phase
- metastable phase
- can only be formed by rapid cooling (quenching) of austenite
- crystallographically related to austenite from which it formed (dependent on chemical composition); for example, $\{111\}_\gamma$ habit planes with $(111)_\gamma // (011)_\alpha$
- has same chemical composition as the austenite from which it formed
- body centered tetragonal crystal structure; c/a ratio a function of C content
- supersaturated interstitial solid solution of C in Fe
- usually hard, strong (dependent on C content)
- usually low in ductility and toughness (dependent on C content)
- contains high residual stresses
- observed in two morphologies: lath and plate (dependent on C content)
    - lath:
        - found in low to mid-range C level steels
        - high dislocation density (10^{15} dislocations/m^2)
        - comprised of bundles of flat narrow (submicron width) laths that grow side by side
    - plate:
        - found in higher C level steels
        - highly microtwinned
        - narrow (several microns wide) plates grow individually

IT (TTT) diagrams:

Concerned with the *isothermal* transformation of austenite

Diagrams read from top to bottom, left to right

Each diagram relates to only one steel composition

When reading the diagram, once the austenite is fully transformed, the diagram should not be used anymore

Four transformations are possible for most steel compositions:

- proeutectoid transformation (either ferrite or cementite)
- eutectoid transformation (pearlite)
- bainitic transformation (bainite)
- martensitic transformation (martensite)
- each transformation has a start & finish line

CCT diagrams:

Useful for practical heat treatments which involve cooling from the austenitization temperature at a constant rate, rather than via a “quench” & an isothermal transformation

Derived from IT diagrams and Jominy end-quench hardenability tests

Each diagram relates to only one steel composition

CCT curves show the basic transformation lines that exist on the IT diagram, except they are shifted down and to the right

Expected microstructures are obtained by following a particular cooling rate line down from the austenitization temperature to room temperature

Effects of alloying additions on steels:

Alloying element additions to steels:

(1) increase hardenability
(2) may go into solid solution
(3) may form complex alloy carbides
(4) change the Fe-Fe_3C phase diagram

Hardenability:

1. a measure of the ease with which martensite can be formed
2. first and foremost, alloying elements are added to low alloy steels to improve hardenability
3. increasing alloying content dramatically affects Jominy curves (hardness maintained further from quenched end)
4. increasing alloying content dramatically affects IT and CCT diagrams:
   - transformation lines shifted to right and down, particularly the pearlite transformation
   - "double" nose curve develops for higher alloying contents, exhibiting clearly separated pearlite and bainite transformation noses
   - generally, M_s and M_f temperatures are decreased

Solid solution vs. carbide formation:

Alloying Element	Tends to Form Solid Solution	Carbide
P	X	
Si	X	
Al	X	
Ni	X	
Co	X	
Mn	X	
Cr	X	X
Mo		X
W		X
V		X
Nb		X
Ti		X

* Carbide formers are of particular significance for providing high temperature strength and hardness: applications ➔ tool steels

* Extensive alloy carbide formation ➔ "secondary hardening"

Changes to the Fe-Fe_3C phase diagram:

* Alloying elements are classified as either austenite stabilizers (Type A) or ferrite stabilizers (Type B) – they alter the γ field.

* Alloying elements decrease or increase the eutectoid transformation temperature and the eutectoid composition. The eutectoid transformation may be suppressed completely.

(nomenclature from Bain & Paxton's book *Alloying Elements in Steel*) thus, from Bain and Paxton:

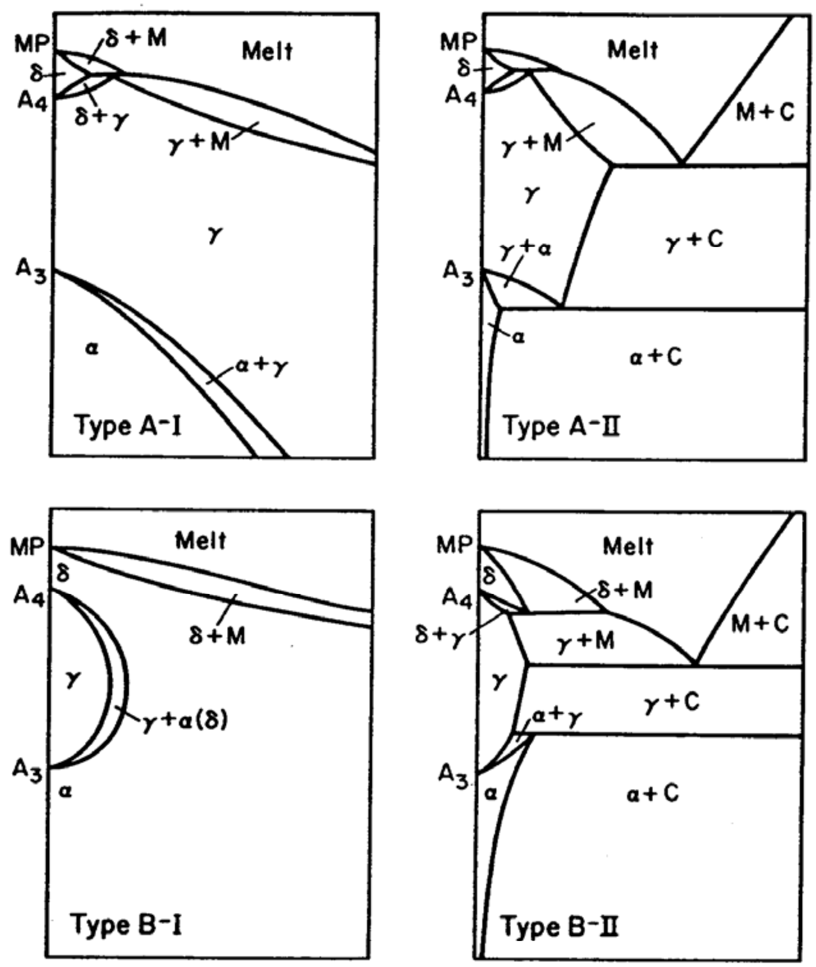


Fig. 2. Two possible types, A and B, and the subdivisions, I and II, of phase equilibrium diagrams for iron alloys. (After Wever)

Type A-I - Mn, Ni, Co

Type A-II- Cu,Zn,Au,N,C

Type B-I- Si,Cr,W,Mo,P,V,Ti,Be,Sn,Sb,As,Al

Type B-II- Ta, Zr,B,S,Ce,Nb

Elements of most interest in tool steels besides C include Cr, Mo,W, V (Type B-1)

from Bain and Paxton, Figures 81 and 82 show effects of increasing Cr and Mo additions on austenite field, respectively:

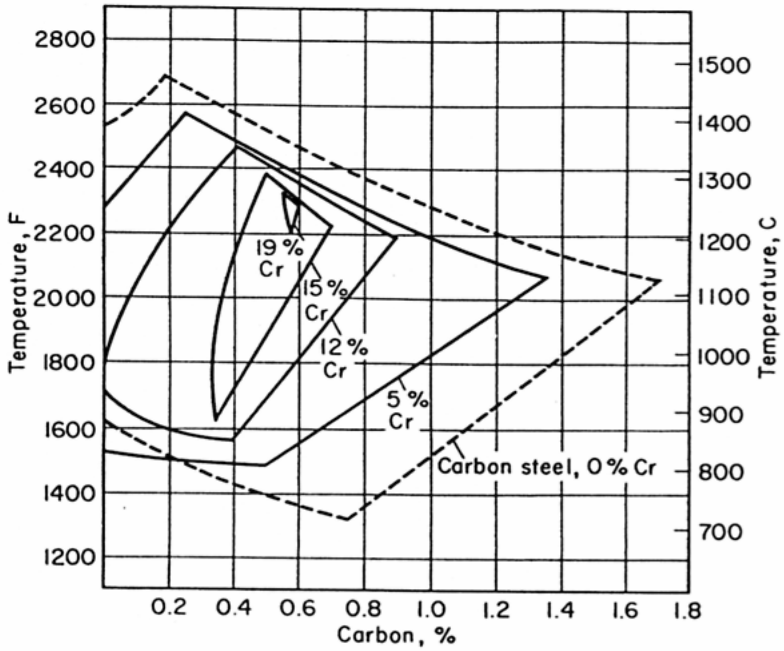


Fig. 81. Effect of several uniform chromium contents on the carbon limitations for pure austenite at elevated temperatures. (After data of Tofaute, Küttner and Büttinghaus, reference 6, Chapter 3)

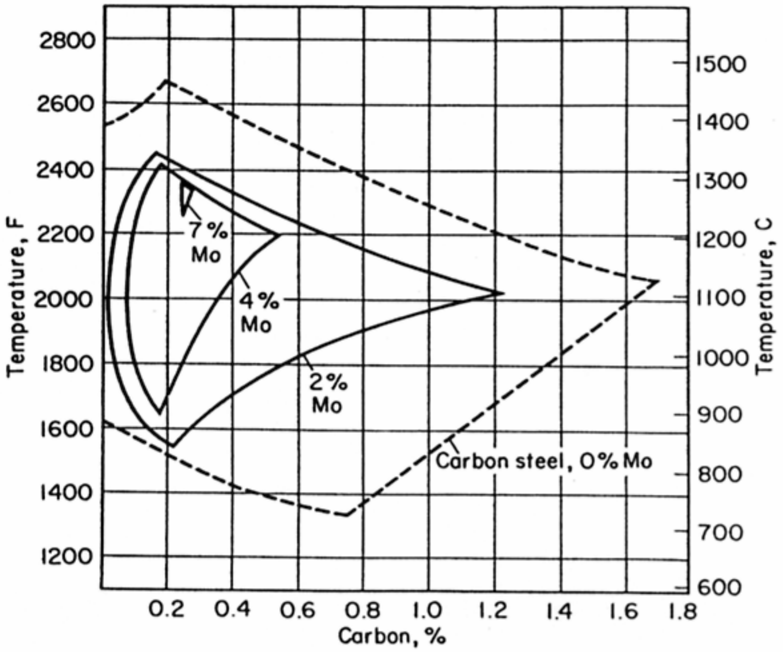


Fig. 82. Effect of several uniform molybdenum contents on the carbon limitations for pure austenite at elevated temperatures. (After data of Takei, reference 8, Chapter 3)

Jominy end-quench hardenability tests:

Surface at quenched end transforms to martensite; remainder of the bar undergoes this transformation or other transformations, depending on the cooling rate at a particular location and the hardenability characteristics of the steel composition

Mechanical properties of heat treated steels:

Hardness, strength, ductility, fracture toughness, fatigue resistance, etc., vary with the microconstituents. For example:

Hardness and strength increase in the following order:

spheroidite (softest, lowest strength)

coarse pearlite

medium pearlite

fine pearlite

upper bainite

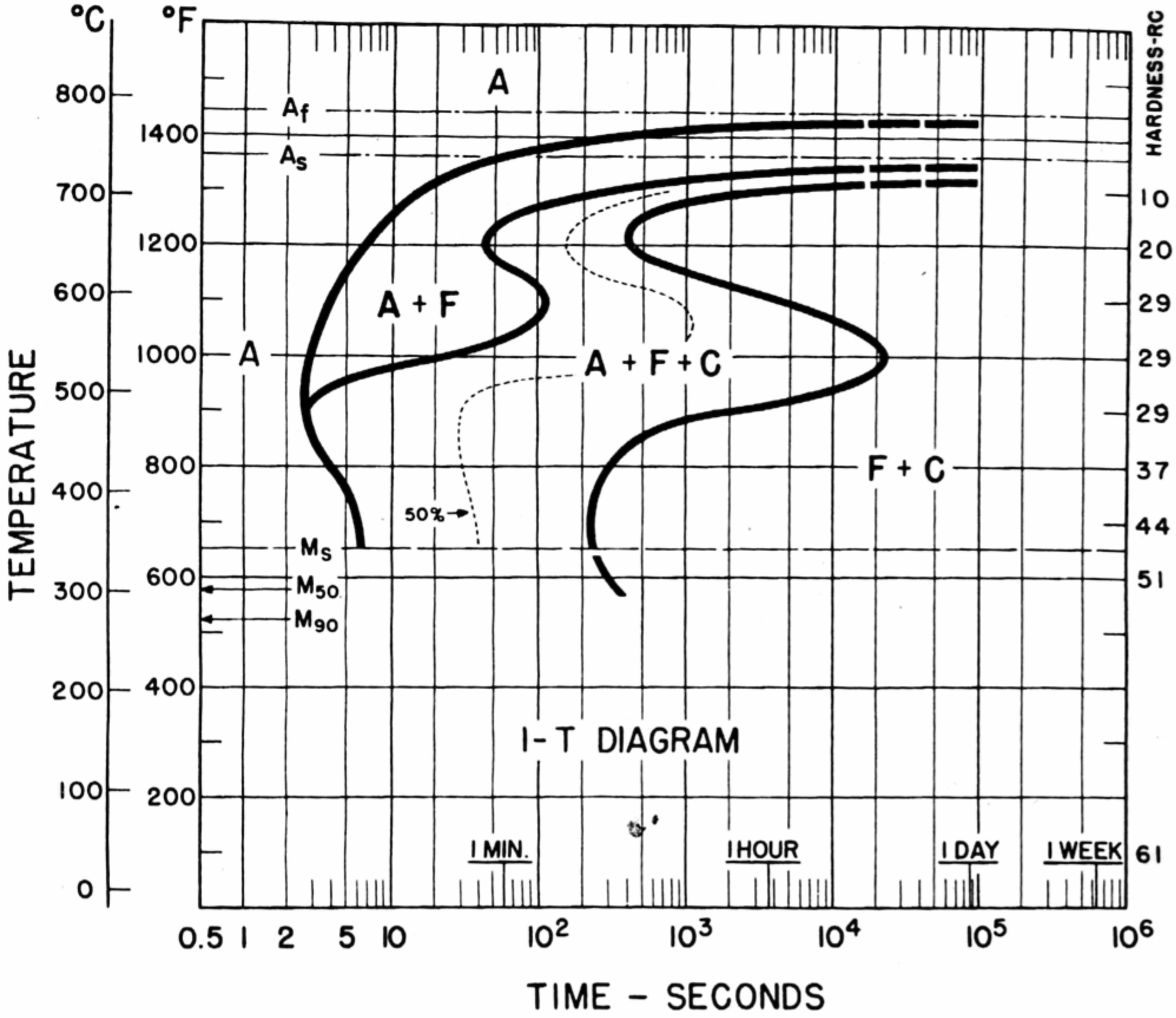
lower bainite

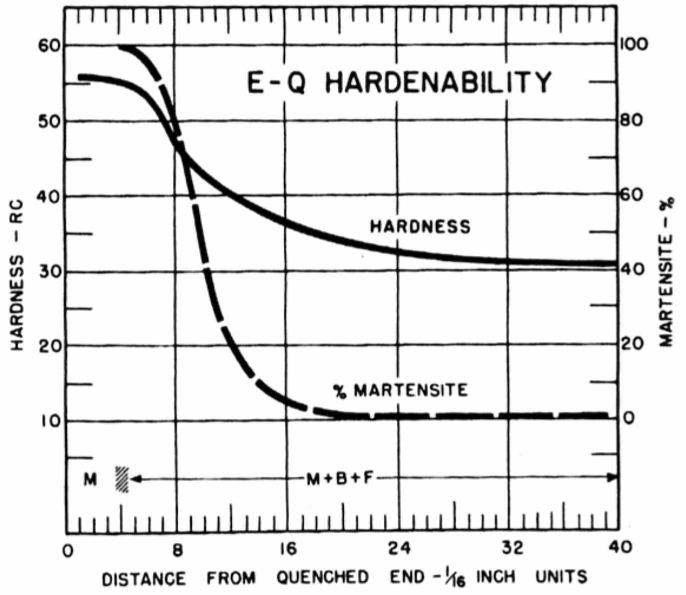
tempered martensite (hardest, highest strength*)

* Note: all of the above microconstituents have the same phases, α & carbide

* Strengths of lower bainites and tempered martensites are highly dependent on transformation temperature (bainite) or tempering temperature (martensite). Consequently, some lower bainites may have higher strengths than some tempered martensites.

4140





4140

C-0.37 Mn-0.77
Cr-0.98 Mo-0.21

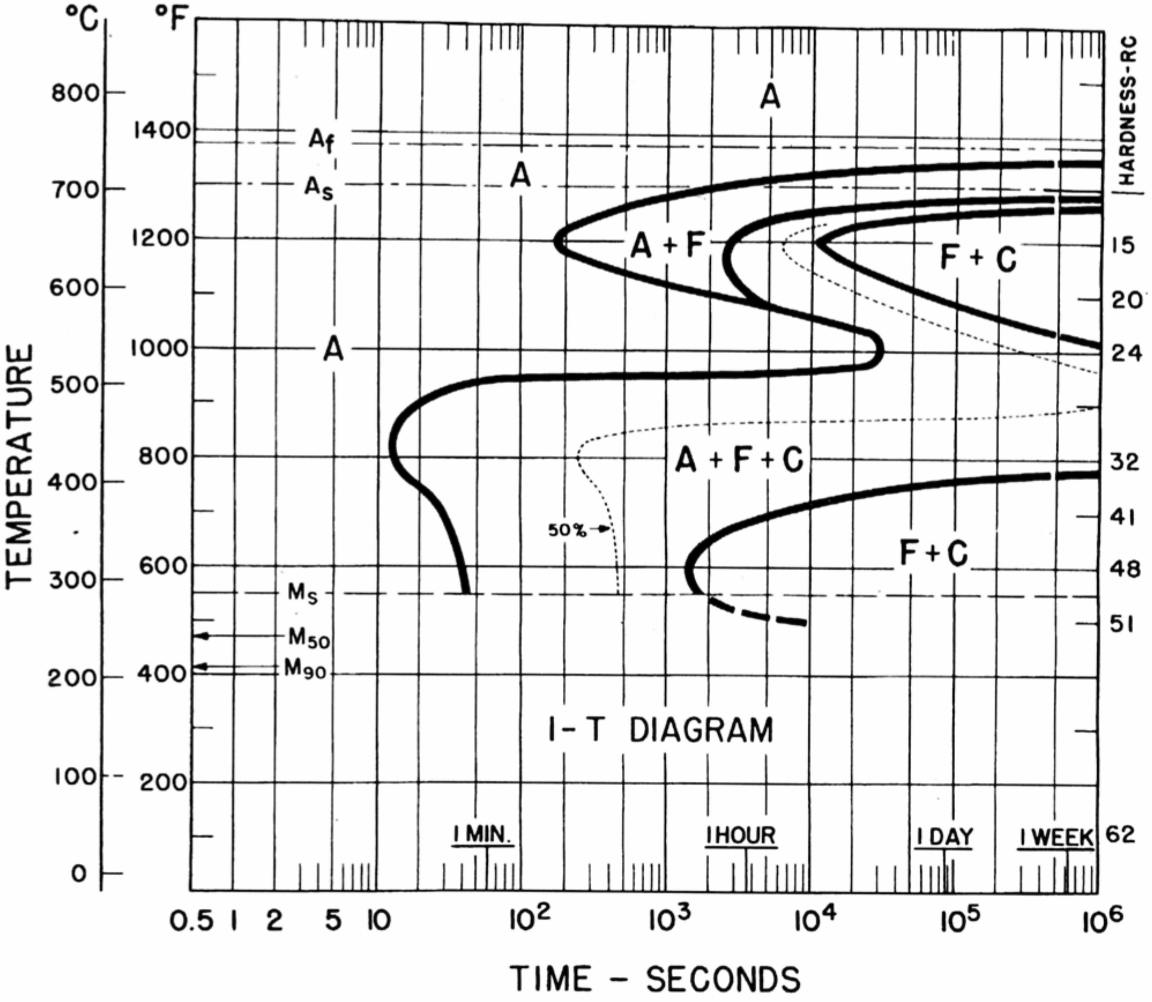
Austenitized at 1550°F

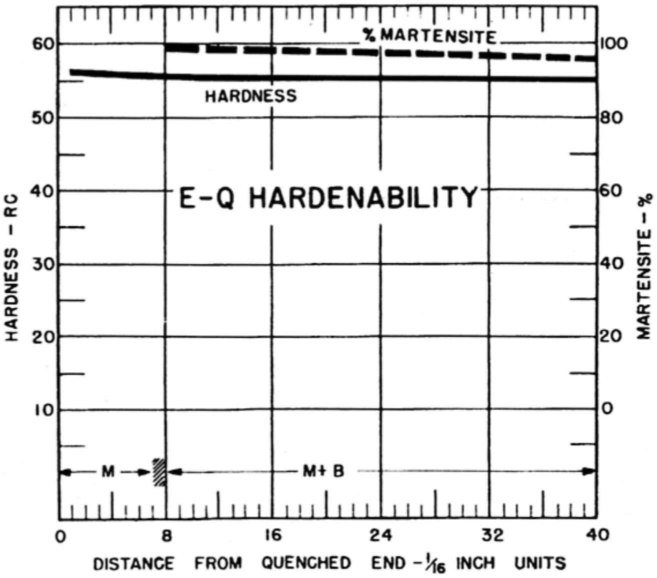
Grain Size: 7-8

LEGEND

A = Austenite
F = Ferrite
C = Carbide
M = Martensite
B = Bainite
P = Pearlite

4340





4340

C-0.42 Mn-0.78

Ni-1.79 Cr -0.80

Mo-0.33

Austenitized at 1550°F

Grain Size: 7-8

LEGEND

A = Austenite
F = Ferrite
C = Carbide

M = Martensite
B = Bainite
P = Pearlite

THE SCIENCE & ENGINEERING OF MATERIALS
D.R. ASKELAND

TABLE 12-1 Compositions of selected AISI-SAE **steels**

AISI-SAE Number	% C	% Mn	% Si	% Ni	% Cr	Others
1020	0.18–0.23	0.30–0.60				
1040	0.37–0.44	0.60–0.90				
1060	0.55–0.65	0.60–0.90				
1080	0.75–0.88	0.60–0.90				
1095	0.90–1.03	0.30–0.50				
1140	0.37–0.44	0.70–1.00				0.08–0.13% S
1340	0.38–0.43	1.60–1.90	0.15–0.30			
1541	0.36–0.44	1.35–1.65				
4140	0.38–0.43	0.75–1.00	0.15–0.30		0.80–1.10	0.15–0.25% Mo
4340	0.38–0.43	0.60–0.80	0.15–0.30	1.65–2.00	0.70–0.90	0.20–0.30% Mo
4620	0.17–0.22	0.45–0.65	0.15–0.30	1.65–2.00		0.20–0.30% Mo
4820	0.18–0.23	0.50–0.70	0.15–0.30	3.25–3.75		0.20–0.30% Mo
5120	0.17–0.22	0.70–0.90	0.15–0.30		0.70–0.90	
52100	0.98–1.10	0.25–0.45	0.15–0.30		1.30–1.60	
6150	0.48–0.53	0.70–0.90	0.15–0.30		0.80–1.10	0.15% min. V
8620	0.18–0.23	0.70–0.90	0.15–0.30	0.40–0.70	0.40–0.60	0.15–0.25% V
9260	0.56–0.64	0.75–1.00	1.80–2.20			

ENGINEERING MATERIALS
3rd ED.
K.G. BUDINSKI

TABLE 9-9 EFFECT OF ALLOYING ELEMENTS

	Typical Ranges in Alloy Steels (%)	Principal Effects
Aluminum	<2	Aids nitriding Restricts grain growth Removes oxygen in steel melting
Sulfur	<0.5	Adds machinability Reduces weldability and ductility
Chromium	0.3 to 4	Increases resistance to corrosion and oxidation Increases hardenability Increases high-temperature strength Can combine with carbon to form hard, wear-resistant microconstituents
Nickel	0.3 to 5	Promotes an austenitic structure Increases hardenability Increases toughness
Copper	0.2 to 0.5	Promotes tenacious oxide film to aid atmospheric corrosion resistance
Manganese	0.3 to 2	Increases hardenability Promotes an austenitic structure Combines with sulfur to reduce its adverse effects
Silicon	0.2 to 2.5	Removes oxygen in steel making Improves toughness Increases hardenability
Molybdenum	0.1 to 0.5	Promotes grain refinement Increases hardenability Improves high-temperature strength
Vanadium	0.1 to 0.3	Promotes grain refinement Increases hardenability Will combine with carbon to form wear-resistant microconstituents

Table 6.3 Transformations Occurring During Tempering of Ferrous Martensites

Temperature/°C	Transformation	Remarks
25–100	Carbon segregation to dislocations and boundaries; pre-precipitation clustering and ordering	Clustering predominant in high-carbon steels
100–200	Transition-carbide precipitation, diam. 2 nm (first stage of tempering)	Carbides may be $\eta(Fe_2C)$ or $\varepsilon(Fe_{2.4}C)$
200–350	Retained austenite transforms to ferrite and cementite (second stage)	Associated with tempered martensite embrittlement
250–350	Lath-like Fe_3C precipitation (third stage)	
350–550	Segregation of impurity and alloying elements	Responsible for temper embrittlement
400–600	Recovery of dislocation substructure. Lath-like Fe_3C agglomerates to form spheroidal Fe_3C	Lath structure maintained
500–700	Formation of alloy carbides. (secondary hardening or fourth stage)	Occurs only in steels containing Ti, Cr, Mo, V, Nb, or W; Fe_3C may dissolve
600–700	Recrystallization and grain growth; coarsening of spheroidal Fe_3C	Recrystallization inhibited in medium-carbon and high-carbon steels; equiaxed ferrite formed