Chapter 2
Carbon and Alloy Steels

2.1 Carbon steels

Steels are, essentially, alloys of iron and carbon, theoretically containing up to 2 % of carbon. Steel is made by oxidizing away the impurities that are present in the iron produced in the blast furnace. It may contain appreciable concentrations of other alloying elements; there are thousands of alloys that have different compositions and/or heat treatments.

Some of the more common carbon steels are classified according to carbon concentration—namely, into low-, medium-, and high-carbon types. Subclasses also exist within each group according to the concentration of other alloying elements. *Plain carbon steels* contain only residual concentrations of impurities other than carbon and a little manganese. For *alloy steels*, more alloying elements are intentionally added in specific concentrations.

2.1.1 Low-Carbon Steels

Of all the different steels, those produced in the greatest quantities fall within the low carbon classification. These generally contain less than about 0.25 wt% C and are unresponsive to heat treatments intended to form martensite; strengthening is accomplished by cold work. Microstructures consist of ferrite and pearlite constituents.

As a consequence, these alloys are relatively soft and weak but have outstanding ductility and toughness; in addition, they are machinable, weldable, and, of all steels, are the least expensive to produce. Typical applications include automobile body components, structural shapes (I-beams, channel and angle iron), and sheets that are used in pipelines, buildings, bridges, and tin cans. Tables 2.1 and 2.2 present the compositions and mechanical properties of several low-carbon steels. They typically have yield strength of 275 MPa, tensile strengths between 415 and 550 MPa, and a ductility of 25%EL.

Table 2.1 Compositions of Plain Low-Carbon Steels and High-Strength, Low-Alloy Steels

Designation[a]		*Composition (wt%)[b]*		
AISI/SAE or ASTM Number	***UNS Number***	***C***	***Mn***	***Other***
		Plain Low-Carbon Steels		
1010	G10100	0.10	0.45	
1020	G10200	0.20	0.45	
A36	K02600	0.29	1.00	0.20 Cu (min)
A516 Grade 70	K02700	0.31	1.00	0.25 Si
		High-Strength, Low-Alloy Steels		
A440	K12810	0.28	1.35	0.30 Si (max), 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb
A656 Grade 1	K11804	0.18	1.60	0.60 Si, 0.1 V, 0.20 Al, 0.015 N

Table 2.2 Mechanical Characteristics and Typical Applications for Various Plain Low-Carbon and High-Strength, Low-Alloy Steels

AISI/SAE or ASTM Number	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
		Plain Low-Carbon Steels		
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	205 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
		High-Strength, Low-Alloy Steels		
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Grade 1	655 (95)	552 (80)	15	Truck frames and railway cars

Another group of low-carbon alloys are the high-strength, low-alloy (HSLA) steels. They contain other alloying elements such as copper, vanadium, nickel, and molybdenum in combined concentrations as high as 10 wt%, and possess higher strengths than the plain low-carbon steels. Most may be strengthened by heat treatment, giving tensile strengths in excess of 480 MPa; in addition, they are ductile, formable, and Machin able. In normal atmospheres, the HSLA steels are more resistant to corrosion than the plain carbon steels, which they have replaced in many applications where structural strength is critical (e.g., bridges, towers, support columns in high-rise buildings, and pressure vessels).

2.1.2 Medium-Carbon Steels

The medium-carbon steels have carbon concentrations between 0.25 and 0.60 wt%. These alloys may be heat treated by austenitizing, quenching, and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructures of tempered martensite. The medium carbon steels have low hardenabilities and can be successfully heat treated only in very thin sections and with very rapid quenching rates. Additions of chromium, nickel, and molybdenum improve the capacity of these alloys to be heat treated, giving rise to a variety of strength ductility combinations. These heat treated alloys are stronger than the low carbon steels, but at a sacrifice of ductility and toughness. Applications include railway wheels and tracks, gears, crankshafts, and other machine parts and high-strength structural components calling for a combination of high strength, wear resistance, and toughness.

The compositions of several of these alloyed medium-carbon steels are presented in Table 2.3. Some comment is in order regarding the designation schemes that are also included. The Society of Automotive Engineers (SAE), the American Iron and Steel Institute (AISI), and the American Society for Testing and Materials (ASTM) are responsible for the classification and specification of steels as well as other alloys. The AISI/SAE designation for these steels is a four-digit number: the first two digits indicate the alloy content; the last two give the carbon concentration. For plain carbon steels, the first two digits are 1 and 0; alloy steels are designated by other initial two-digit combinations (e.g., 13, 41, and 43).The third and fourth digits represent the weight percent carbon multiplied by 100. For example, 1060 steel is a plain carbon steel containing 0.60 wt% C.

Table 2.3 AISI/SAE and UNS Designation Systems and Composition Ranges for Plain Carbon Steel and Various Low-Alloy Steels

AISI/SAE Designation[a]	*UNS Designation*	*Composition Ranges (wt% of Alloying Elements in Addition to C)*[b]			
		Ni	*Cr*	*Mo*	*Other*
10xx, Plain carbon	G10xx0				
11xx, Free machining	G11xx0				0.08–0.33S
12xx, Free machining	G12xx0				0.10–0.35S, 0.04–0.12P
13xx	G13xx0				1.60–1.90Mn
40xx	G40xx0			0.20–0.30	
41xx	G41xx0		0.80–1.10	0.15–0.25	
43xx	G43xx0	1.65–2.00	0.40–0.90	0.20–0.30	
46xx	G46xx0	0.70–2.00		0.15–0.30	
48xx	G48xx0	3.25–3.75		0.20–0.30	
51xx	G51xx0		0.70–1.10		
61xx	G61xx0		0.50–1.10		0.10–0.15V
86xx	G86xx0	0.40–0.70	0.40–0.60	0.15–0.25	
92xx	G92xx0				1.80–2.20Si

A unified numbering system (UNS) is used for uniformly indexing both ferrous and nonferrous alloys. Each UNS number consists of a single letter prefix followed by a five digit number. The letter is indicative of the family of metals to which an alloy belongs. The UNS designation for these alloys begins with a G, followed by the AISI/SAE number; the fifth digit is a zero. Table 2.4

contains the mechanical characteristics and typical applications of several of these steels, which have been quenched and tempered.

Table 2.4 Typical Applications and Mechanical Property Ranges for Oil Quenched and Tempered Plain Carbon and Alloy Steels.

AISI Number	*UNS Number*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
			Plain Carbon Steels		
1040	G10400	605–780 (88–113)	430–585 (62–85)	33–19	Crankshafts, bolts
1080[a]	G10800	800–1310 (116–190)	480–980 (70–142)	24–13	Chisels, hammers
1095[a]	G10950	760–1280 (110–186)	510–830 (74–120)	26–10	Knives, hacksaw blades
			Alloy Steels		
4063	G40630	786–2380 (114–345)	710–1770 (103–257)	24–4	Springs, hand tools
4340	G43400	980–1960 (142–284)	895–1570 (130–228)	21–11	Bushings, aircraft tubing
6150	G61500	815–2170 (118–315)	745–1860 (108–270)	22–7	Shafts, pistons, gears

2.1.3 High-Carbon Steels

The high carbon steels, normally having carbon contents between 0.60 and 1.4 wt%, are the hardest, strongest, and yet least ductile of the carbon steels. They are almost always used in a hardened and tempered condition and, as such, are especially wear resistant and capable of holding a sharp cutting edge. The tool and die steels are high carbon alloys, usually containing chromium, vanadium, tungsten, and molybdenum. These alloying elements combine with carbon to form very hard and wear resistant carbide compounds (e.g., $Cr_{23}C_6$, V_4C_3, and WC). Some tool steel compositions and their applications are listed in Table 2.5.These steels are utilized as cutting tools and dies for forming and shaping materials, as well as in knives, razors, hacksaw blades, springs, and high-strength wire.

Table 2.5 Designations, Compositions, and Applications for Six Tool Steels

AISI Number	UNS Number	Composition (wt%)[a]						Typical Applications
		C	Cr	Ni	Mo	W	V	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lathe and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, woodworking tools

2.2 Alloy Steels

Pure metal objects are used where good electrical conductivity, good thermal conductivity, good corrosion resistance or a combination of these properties are required. Therefore alloys are mainly used for structural materials since they can be formulated to give superior mechanical properties.

Alloy steels are called as alloy steel because there are other elements added to the iron beside the carbon with specific amount for each element. These elements improve the properties of the alloying steel and make it used with applications more than the carbon steel. So the most commonly used elements with the alloy steel are Manganese (Mn), Chromium (Cr), Nickel (Ni), Tungsten (W), Cobalt, Molybdenum (Mo), Vanadium, Aluminum (Al), Copper (Cu) and Silicon (Si).

Alloys steels are generally classified into two major types depending on the structural classification:

2.2.1 Low alloy steels

Alloy steel is one that possesses similar microstructure to, and requires similar heat treatment to, plain carbon steels. These generally contain less than 10 % of one or more alloying elements for purpose of increasing strength, toughness and harden ability. The applications of low alloy steels are similar to those of plain carbon steels of similar carbon contents. Low alloy steels containing nickel are particularly suitable for applications requiring resistance to fatigue.

2.2.2 High alloy steels

High alloy steels are steels that possess greater than 10 % of one or more alloying elements for purpose of increasing strength, toughness and harden ability. Unless large amounts of alloying elements are added, the micro constituents of alloy steels remain the same as in carbon steels. In general carbon remains the principal element affecting the properties of alloy steels. Although the alloying elements have specific effects on the properties, they mostly alter the properties by their influence on the amount and distribution of carbon and on the critical points. A few examples of alloying elements are given below:

1. High-speed tool steels

Tungsten and chromium form very hard and stable carbides. Both elements also raise the critical temperatures and, also, cause an increase in softening temperatures. High carbon steels rich in these elements provide hard wearing metal-cutting tools, which retain their high hardness at temperature up to 600˚C. A widely used high-speed tool steel composition is containing 18% of tungsten, 4% of chromium, 1% of vanadium and 0.8% of carbon.

This high-alloy content martensite does not soften appreciably unit, it is heated at temperatures is excess of 600˚Cmaking them usable as cutting tools at high cutting speeds.

2. Stainless Steels

When chromium is present in amounts in excess of 12% , the steel becomes highly resistance to corrosion, owing to protective film of chromium oxide that forms on the metal surface. Chromium also raises the transformation temperature of iron, and tends to stabilize ferrite in the structure.

The stainless steels are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere. Their predominant alloying element is chromium; a concentration of at least 11 wt% Cr is required. Corrosion resistance may also be enhanced by nickel and molybdenum additions.

Stainless steels are divided into three classes on the basis of the predominant phase constituent of the microstructure martensitic, ferritic, or austenitic.Table 2.6 lists several stainless steels, by class, along with composition, typical mechanical properties, and applications. A wide range of mechanical properties combined with excellent resistance to corrosion make stainless steels very versatile in their applicability.

Table 2.6 Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels

AISI Number	UNS Number	Composition (wt%)[a]	Condition[b]	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Ferritic							
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
Austenitic							
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction
Martensitic							
410	S41000	0.15 C, 12.5 Cr, 1.0 Mn	Annealed Q & T	485 (70) 825 (120)	275 (40) 620 (90)	20 12	Rifle barrels, cutlery, jet engine parts
440A	S44002	0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed Q & T	725 (105) 1790 (260)	415 (60) 1650 (240)	20 5	Cutlery, bearings, surgical tools
Precipitation Hardenable							
17-7PH	S17700	0.09 C, 17 Cr, 7 Ni, 1.0 Al, 1.0 Mn	Precipitation hardened	1450 (210)	1310 (190)	1–6	Springs, knives, pressure vessels

Martensitic stainless steels are capable of being heat treated in such a way that martensite is the prime micro-constituent. Additions of alloying elements in significant concentrations produce dramatic alterations in the iron–iron carbide phase diagram. For austenitic stainless steels, the austenite (or) phase field is extended to room temperature. Ferritic stainless steels are composed of the ferrite (BCC) phase. Austenitic and ferritic stainless steels are hardened and strengthened by cold work because they are not heat treatable. The austenitic stainless steels are the most corrosion resistant because of the high chromium contents and also the nickel additions; and they are produced in the largest quantities. Both martensitic and ferritic stainless steels are magnetic; the austenitic stainlesses are not.

Some stainless steels are frequently used at elevated temperatures and in severe environments because they resist oxidation and maintain their mechanical integrity under such conditions; the upper temperature limit in oxidizing atmospheres is about 1000ºC.

Equipment employing these steels includes gas turbines, high-temperature steam boilers, and heat treating furnaces, aircraft, missiles, and nuclear power generating units. Also included in Table 2.6 is one ultrahigh-strength stainless steel (17-7PH), which is unusually strong and corrosion resistant. Strengthening is accomplished by precipitation hardening heat treatments.