Ferrous Metals

Introduction

As the most abundant of all commercial metals, alloys of iron and steel continue to cover a broad range of structural applications. Iron ore is readily available, constituting about 5% of the earth's crust, and is easy to convert to a useful form. Iron is obtained by fusing the ore to drive off oxygen, sulfur, and other impurities. The ore is melted in a furnace in direct contact with the fuel using limestone as a flux. The limestone combines with impurities and forms a slag, which is easily removed.

- **Cast Iron**
- **Carbon Steel**
- **Alloy Steel**
- **Stainless Steel**
- **Tool Steel**
- **HSLA Steel**

Cast Iron

Cast iron is defined as an iron alloy with more than 2% carbon as the main alloying element. In addition to carbon, cast irons must also contain from 1 to 3% silicon which combined with the carbon give them excellent castability. Cast iron has a much lower melting temperature than steel and is more fluid and less reactive with molding materials. However, they do not have enough ductility to be rolled or forged.

The precipitation of carbon (as graphite) during solidification is the key to cast iron's distinctive properties. The graphite provides excellent machinability (even at wear-resisting hardness levels), damps vibration, and aids lubrication on wearing surfaces (even under borderline lubrication conditions).

Steels and cast irons are both primarily iron with carbon (C) as the main alloying element. Steels contain less than 2% and usually less than 1% C, while all cast irons contain more than 2% C. About 2% is the maximum C content at which iron can solidify as a single phase alloy with all of the C in solution in austenite. Thus, the cast irons by definition solidify as heterogeneous alloys and always have more than one constituent in their microstructure.

In addition to C, cast irons also must contain appreciable silicon (Si), usually from 1–3%, and thus they are actually iron-carbon-silicon alloys. The high C content and the Si in cast irons make them excellent casting alloys.

Range of Compositions for Typical Unalloyed Cast Irons (Values in Percent (%))

Type of Iron	Carbon	Silicon	Manganese	Sulfur	Phosphorus
Gray	2.5 - 4.0	1.0 - 3.0	0.2 - 1.0	0.02 - 0.25	0.02 - 1.0
Ductile	3.0 - 4.0	1.8 - 2.8	0.1 - 1.0	0.01 - 0.03	0.01 - 0.1
Compacted Graphite	2.5 - 4.0	1.0 - 3.0	0.2 - 1.0	0.01 - 0.03	0.01 - 0.1
Malleable (Cast White)	2.0 - 2.9	0.9 - 1.9	0.15 - 1.2	0.02 - 0.2	0.02 - 0.2
White	1.8 - 3.6	0.5 - 1.9	0.25 - 0.8	0.06 - 0.2	0.06 - 0.2

Carbon Steel

Carbon steel is a malleable, iron-based metal containing less than 2% carbon (usually less than 1%), small amounts of manganese, and other trace elements. Steels can either be cast to shape or wrought into various mill forms from which finished parts are formed, machined, forged, stamped, or otherwise shaped. Carbon steels are specified by chemical composition, mechanical properties, method of deoxidation, or thermal treatment.

Alloy Steel

Steels that contain specified amounts of alloying elements -- other than carbon and the commonly accepted amounts of manganese, copper, silicon, sulfur, and phosphorus -- are known as alloy steels. Alloying elements are added to change mechanical or physical properties. A steel is considered to be an alloy when the maximum of the range given for the content of alloying elements exceeds one or more of these limits: 1.65% Mn, 0.60% Si, or 0.60% Cu; or when a definite range or minimum amount of any of the following elements is specified or required within the limits recognized for constructional alloy steels: aluminum, chromium (to 3.99%), cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium or other element added to obtain an alloying effect. Technically, then, tool and stainless steels are alloy steels.

Steel Alloy Designation System	
AISI-SAE Designation Number	**Type and Description**
Carbon steels	
10xx	Plain Carbon (Mn. 1.00% max.)
11xx	Resulfurized
12xx	Resulfurized and rephosphorized
15xx	Plain Carbon (max. Mn. range 1.00-1.65%)
Manganese steels	
13xx	Mn 1.75
Nickel steels	
23xx	Ni 3.50
25xx	Ni 5.00

Nickel-chromium steels	
31xx	Ni 1.25; Cr 0.65, 0.80
32xx	Ni 1.75; Cr 1.07
33xx	Ni 3.50; Cr 1.50, 1.57
34xx	Ni 3.00; Cr 0.77
Molybdenum steels	
40xx	Mo 0.20, 0.25
44xx	Mo 0.40, 0.52
Chromium-molybdenum steels	
41xx	Cr 0.50, 0.80, 0.95; Mo 0.12, 0.20, 0.25, 0.30
Nickel-chromium-molybdenum steels	
43xx	Ni 1.82; Cr 0.50, 0.80; Mo 0.25
43BVxx	Ni 1.82; Cr 0.50; Mo 0.12, 0.25; V 0.03 min.
47xx	Ni 1.05; Cr 0.45; Mo 0.20, 0.35
81xx	Ni 0.30; Cr 0.40; Mo 0.12
86xx	Ni 0.55; Cr 0.50; Mo 0.20
87xx	Ni 0.55; Cr 0.50; Mo 0.25
88xx	Ni 0.55; Cr 0.50; Mo 0.35
93xx	Ni 3.25; Cr 1.20; Mo 0.12
94xx	Ni 0.45; Cr 0.40; Mo 0.12
97xx	Ni 1.00; Cr 0.20; Mo 0.20
98xx	Ni 1.00; Cr 0.80; Mo 0.25
Nickel-molybdenum steels	
46xx	Ni 0.85, 1.82; Mo 0.20, 0.25
48xx	Ni 3.50; Mo 0.25
Chromium steels	
50xx	Cr 0.27, 0.40, 0.50, 0.65
51xx	Cr 0.80, 0.87, 0.92, 0.95, 1.00, 1.05
50xxx	Cr 0.50; C 1.00 min.
51xxx	Cr 1.02; C 1.00 min.
52xxx	Cr 1.45; C 1.00 min.
Chromium-vanadium steels	

61xx	Cr 0.60, 0.80, 0.95; V 0.10, 0.15
Tungsten-chromium steels	
72xx	W 1.75; Cr 0.75
Silicon-manganese steels	
92xx	Si 1.40, 2.00; Mn 0.65, 0.82, 0.85; Cr 0.00, 0.65
High-strength low-alloy steels	
9xx	Various SAE grades
Boron steels	
xxBxx	B denotes boron steels
Leaded steels	
xxLxx	L denotes leaded steels

Stainless Steel

Stainless steel is the generic name for a number of different steels used primarily for their resistance to corrosion. The one key element they all share is a certain minimum percentage (by mass) of chromium: 10.5%. Although other elements, particularly nickel and molybdenum, are added to improve corrosion resistance, chromium is always the deciding factor. The vast majority of steel produced in the world is carbon and alloy steel, with the more expensive stainless steels representing a small, but valuable niche market.

Stainless steels are commonly divided into five groups:

1. martensitic stainless steels
2. ferritic stainless steels
3. austenitic stainless steels,
4. duplex (ferritic-austenitic) stainless steels
5. precipitation-hardening stainless steels

Martensitic stainless steels, typified by types 410/420/440, containing about 12Cr and 0.1C wt% as the basic composition. They are not as corrosion resistant as the other classes, but are extremely strong and tough as well as highly machineable, and can be hardened by heat treatment. They contain 11.5 to 18% chromium and significant amounts of carbon. Some grades include additional alloying elements in small quantities.

Ferritic stainless steels contain larger amounts of Cr which stabilizes the ferritic phase. Ferritic stainless steels are highly corrosion resistant, but far less durable than austenitic grades and cannot be hardened by heat treatment. They contain between 10.5% and 27% chromium and very little nickel, if any. Typical applications may include appliances, automotive and architectural trim (i.e., decorative purposes), as the cheapest stainless steels are found in this family (type 409).

Austenitic stainless steels, such as type 304 typically contain 18Cr and 8Ni wt% (aka 18/8 stainless).. Austenitic stainless steels comprise over 70% of total stainless steel production. They contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy. Other standard grades have different preferred applications; for example, type 316 which contains up to 3 wt% Mo, offers an improved general and pitting corrosion resistance, making it the material of choice for marine applications and coastal environments.

Duplex stainless steels are two-phase alloys based on the Fe-Cr-Ni system. The specific advantages offered by duplex stainless steels over conventional 300 series stainless steels are strength (approximately twice that of austenitic stainless steels), improved toughness and ductility (compared to ferritic grades), and a superior chloride SCC resistance and pitting resistance.

The high yield strength offers designers the use of thin-wall material (which can lead to major reductions in weight) with adequate pressure-containing and load-bearing capacity. Duplex stainless steels have found widespread use in a range of industries, particularly the oil and gas, petrochemical, and pulp and paper industries.

Specialist grades include the precipitation hardened or oxide dispersion strengthened alloys.

Properties of Stainless Steel

(Tabulated in accordance with the Unified Numbering System for Metals and Alloys (UNS), Society of Automotive Engineers, Warrendale, Pa., 1975. This reference contains the cross reference numbers for AISI, ASTM, FED, MIL SPEC, and SAE specifications. All yield strengths are obtained using the 0.2 percent offset method. Multiply strength in kpsi be 6.89 to get strength in MPa.)

UNS Number	Processing	Yield Strength (Kpsi)	Tensile Strength (Kpsi)	Elongation in 2 in., %	Reduction in Area, %	Brinell Hardness H_b
S20100	Annealed	55	155	55		
S20100	1/4 hard	75	125	20		
S20100	1/2 hard	110	150	10		
S20100	3/4 hard	135	175	5		
S20100	Full hard	140	185	4		
S20200	Annealed	55	110	55		
S20200	1/4 hard	75	125	12		
S30100	Annealed	40	110	60		165
S30100	1/4 hard	75	125	25		
S30100	1/2 hard	110	150	15		
S30100	3/4 hard	135	175	12		
S30100	Full hard	140	185	8		
S30200	Annealed	37	90	55	65	155
S30200	1/4 hard	75	125	12		
S30300	Annealed	35	90	50	55	160
S30400	Annealed	35	85	55	65	150
S31000	Annealed	40	95	45	65	170
S31400	Annealed	50	100	45	60	170
S41400	Annealed	95	120	17	55	235
S41400	Drawn 400 F	150	200	15	55	415
S41400	Drawn 600 F	145	190	15	55	400
S41400	Drawn 800 F	150	200	16	58	415
S41400	Drawn 1000 F	120	145	20	60	325
S41400	Drawn 1200 F	105	120	20	65	260
S41600	Annealed	40	75	30	65	155
S41600	Drawn 400 F	145	190	15	55	390
S41600	Drawn 600 F	140	180	15	55	375
S41600	Drawn 800 F	150	195	17	55	390
S41600	Drawn 1000 F	115	145	20	65	300
S41600	Drawn 1200 F	85	110	23	65	225

S41600	Drawn 1400 F	60	90	30	70	180
S43100	Annealed	95	125	20	60	260
S43100	Drawn 400 F	155	205	15	55	415
S43100	Drawn 600 F	150	195	15	55	400
S43100	Drawn 800 F	155	205	15	60	415
S43100	Drawn 1200 F	95	125	20	60	260
S50100	Annealed	30	70	28	65	160
S50200	Annealed	30	70	30	75	150

Stainless Steel Categories

Martensitic

Martensitic stainless steels, typified by types 410/420/440, containing about 12Cr and 0.1C wt% as the basic composition. They are not as corrosion resistant as the other classes, but are extremely strong and tough as well as highly machineable, and can be hardened by heat treatment. They contain 11.5 to 18% chromium and significant amounts of carbon. Some grades include additional alloying elements in small quantities.

Martensitic Stainless Steels									
Grade	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**P**	**S**	**Comments/Applications**
410	0.15	1.0	0.5	11.5-13.0	-	-	0.04	0.03	The basic composition. Used for cutlery, steam and gas turbine blades and buckets, bushings...
416	0.15	1.25	1.0	12.0-14.0	-	0.60	0.04	0.15	Addition of sulphur for machinability, used for screws, gears *etc.* 416 Se replaces sulphur by selenium.
420	0.15-0.40	1.0	1.0	12.0-14.0	-	-	0.04	0.03	Dental and surgical instruments, cutlery....
431	0.20	1.0	1.0	15.0-17.0	-	1.25-2.0	0.04	0.03	Enhanced corrosion resistance, high strength.
440A	0.60-0.75	1.0	1.0	16.0-18.0	-	0.75	0.04	0.03	Ball bearings and races, gauge blocks, molds and dies, cutlery.
440B	0.75-0.95	1.0	1.0	16.0-18.0	-	0.75	0.04	0.03	As 440A, higher hardness
440C	0.95-1.20	1.0	1.0	16.0-18.0	-	0.75	0.04	0.03	As 440B, higher hardness

Tool Steels

Tool Steels' defining properties include resistance to wear, stability during heat treatment, strength at high temperatures, and toughness. To develop these properties, tool steels are always heat treated. Because the parts may distort during heat treatment, precision parts should be semifinished, heat treated, then finished. Tool steels are classified into several broad groups, some of which are further divided into subgroups according to alloy composition, hardenability, or mechanical similarities.

- **Type W** - Water-hardening, or carbon, tool steels rely on carbon content for their useful properties.
- **Type S** - Shock-resisting tool steels are strong and tough, but not as wear resistant as many other tool steels.
- **Types O, A, and D** Cold-work tool steels include oil and air-hardened types are often more costly but can be quenched less drastically than water-hardening types. Type O steels are oil hardening; Type A and D steels are air hardening (the least severe quench), and are best suited for applications such as machine ways, brick mold liners, and fuel-injector nozzles. The air-hardening types are specified for thin parts or parts with severe changes in cross section -- parts that are prone to crack or distort during hardening. Hardened parts from these steels have a high surface hardness; however, these steels should not be specified for service at elevated temperatures.
- **Type H** - Hot-work steels serve well at elevated temperatures.
- **Types T (tungsten alloy) and M (molybdenum alloy)** - High-speed tool steels make good cutting tools because they resist softening and maintain a sharp cutting edge at high service temperatures.
- **Type L** - A special-purpose, low-cost, low-alloy, tool steel often specified for machine parts when wear resistance combined with toughness is important.
- **Type F** - Carbon-tungsten alloys (Type F) are shallow hardening and wear resistant, but are not suited for high temperatures or for shock service.
- **Type P** - A mold steel are designed specifically for plastic-molding and zinc die-casting dies.

HSLA Steel

High-Strength Low-Alloy (HSLA) steels have a higher strength-to-weight ratio than conventional low-carbon steels for only a modest price premium. Because HSLA alloys are stronger, they can be used in thinner sections, making them particularly attractive for transportation-equipment components where weight reduction is important. HSLA steels are usually low-carbon steels with up to 1.5% manganese, strengthened by small additions of elements, such as columbium, copper, vanadium or titanium and sometimes by special rolling and cooling techniques.