Chapter 2
Classification of Metallic Engineering Materials

Abstract Materials are classified under the three categories of (i) metals (ii) non-metals and composites. Of these, metals and its alloys broadly meet all requirements to be considered as the most suitable engineering material. Amongst metals, the largest use in the petrochemical industry is of ferrous metals and alloys like carbon and low alloy steels and stainless steels. Once selected, it is necessary to finalize the material specification as per requirement and adhere to the same for all procurements during construction and maintenance. Though limited to some specific services, non-ferrous metals and alloys are also used in petrochemical industry. In the first part of the chapter, a brief description and composition of the commonly used grades of carbon and alloy steels are given, followed by those of the conventional and high performance austenitic, ferritic and duplex stainless steels. Compositions of some important non-ferrous alloys have also been included. In the second part, the importance of standardization and material specification has been discussed which sets the requirements with regard to chemical analysis, mechanical properties heat treatment, dimensional tolerance, etc., that a product should satisfy. In a way, specification is considered as a contract between users and manufacturers.

Keywords Engineering materials · Carbon and alloy steels · Stainless steels · Non-ferrous alloys · Material specification

2.1 Introduction

In the early state of civilization, the only known constructional materials were mud, wood and stone which were used for construction of dwellings, containers and hunting weapons. This was followed by use of bronze and finally iron and these are known in archaeological terms as stone, bronze and iron ages. It is difficult to visualize the past scenario when today different metals and alloys are available and new developments are taking place in the production of materials having specific properties. If the non-metallics are also taken into consideration, there appears to be

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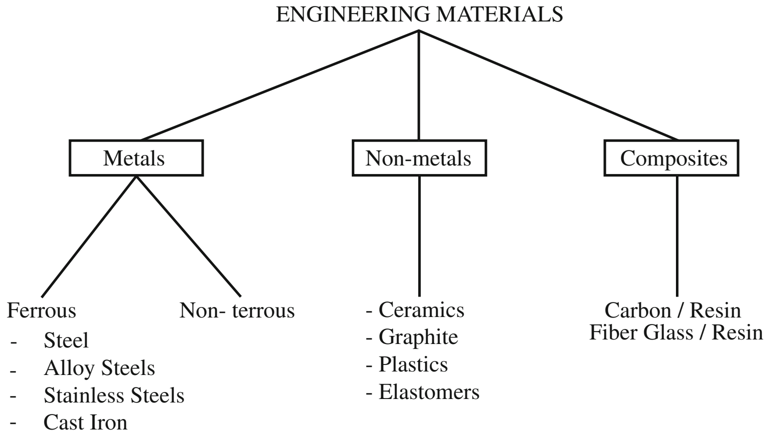

Fig. 2.1 Classification of engineering materials

no end to the range of materials which are available and will be available in the coming years.

Figure 2.1 gives some of the important and commonly used groups of materials, which can be broadly defined into metallic, non-metallic and the composites. Among these, metals and alloys form the bulk of engineering materials. In the present book, the emphasis is on metallic materials and their uses in petrochemical and chemical process industries. As of 2016 out of 118 confirmed elements the periodic table shows presence of 94 naturally occurring elements (rest of 24 occurs only when synthesized in the laboratory) and a large number of them fall under the category of metals. However, only a few of the metals are of practical value as far as their usability as engineering material is concerned. This is because any metallic engineering material should meet certain specific properties, viz. strength, ductility, workability, comparative ease of production and availability. If we consider the metallic materials, it is found that:

* There are two basic groups, ferrous and non-ferrous, and
* Most of the engineering materials are alloys and only a few are used as pure metals.

It is interesting to note that though Iron Age followed Bronze Age, finally it is the ferrous base alloys which occupy the leading position as the 'most used' engineering material. The reasons for this are:

* Abundance of iron ore in the earth crust,
* Comparatively easier and cheaper methods of production of iron and its alloys,
* Some special inherent features of iron which can be utilized by suitable alloying and heat treatment to obtain a wide range of strength combined

with toughness; from soft low strength Armco iron to ultra-high strength steels,

* Producing materials by suitable alloying, having requisite mechanical properties, suitable for use at as low as −270 °C or as high as 1150 °C.
* Vast improvement in corrosion and oxidation resistance properties that can be attained by alloying.

Unlike ferrous materials, which have iron as the base metal, non-ferrous material includes all other metals. The important practical materials which fall under this group are copper, nickel, aluminium, titanium, zinc, tin and lead and their alloys. Metal like chromium, manganese, tungsten, antimony, bismuth, boron, etc., are used only as alloying elements. On the other hand, metals like zirconium, tantalum, silver, gold, etc., and their alloys are too expensive and are used for very specific applications.

2.2 Ferrous Materials

2.2.1 Cast Irons

Cast irons (CI) are Fe-alloys, with carbon varying from 2.5 to 4.5%. Depending on the composition and cooling rate from the molten state the carbon in CI is present as either Fe_3C (cementite) or free carbon (graphite) or both. The various types of cast irons have basic variations in the form and morphology of carbon distribution. The strength and brittleness of cast irons depend on the form in which the carbon is present and increase with increase in the amount of Fe_3C.

The graphite in normal cast iron (grey cast iron) is distributed in flake form in a ferritic or pearlitic matrix. The poor workability or brittleness of graphitic cast iron is due to the presence of graphite in flake form. However, by suitable treatment (during melting and alternately by suitable heat treatment), the shape of graphite can be modified into nodular form. Nodular and malleable cast iron fall under this category. The nature of graphite in two irons in shown in Fig. 2.2a [1] and b [2]. These have improved ductility and are less prone to failure under shock loading as compared to grey cast iron. The white cast irons, on the other hand, are hard and highly brittle and are used only where wear resistance is required.

Cast irons cannot be worked and easily welded and therefore used only in cast form, which does not involve any mechanical working. Some of the important components made of cast irons are: pumps, valves, pipes, gears, cover boxes, pump base plates, etc. Being brittle in nature, use of CI in hydrocarbon service is generally avoided.

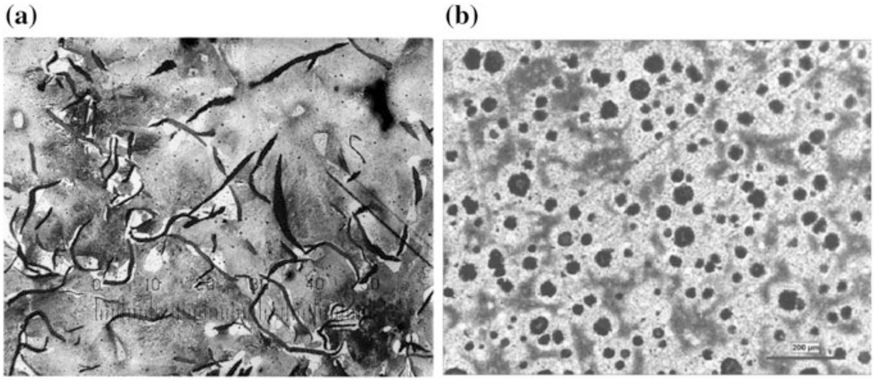

Fig. 2.2 **a** Graphite flakes seen in unetched *grey* cast iron [1]. **b** Nodular graphite observed in etched SG iron [2] X 100

2.2.1.1 Alloy Cast Irons

Cast irons, like other metals, can be alloyed with nickel, silicon, chromium, molybdenum, etc., either singly or in combination, to impart resistance to corrosion in various media and to impart high wear resistance. Ni-hard, austenitic cast irons (Ni-resist), high silicon iron are some of the commonly used alloyed cast irons. Ni-resist also possesses better mechanical properties, especially when graphite is in the nodular form.

2.2.2 Plain Carbon Steels

Plain carbon steels constitute the largest tonnage of ferrous material in use and cover alloys of iron and carbon, with small amounts of Mn, Si, S, P either added deliberately or present as impurities. As impurities, P and S are most deleterious and special care is needed to keep their contents at low levels. Sulphur (and also selenium) is, however, sometimes deliberately added to improve machinability of iron and its alloys. For structural, plates for pressure vessels, sheets, rods and pipes, the carbon content varies from 0.1 to 0.35%. For higher strength and wear resistance and for components requiring heat treatment, higher carbon, normally up to 1.0%, are used for specific end uses, e.g. files, saws, cutting tools, rails, shafts etc. For deep drawing purposes, for making components like cans and car bodies the low carbon steel (<0.1%C) is specified.

Carbon is the most important element to impart strength. Higher the carbon content higher is the strength. However, higher carbon adversely affects toughness and weldability. Thus to retain the strength and also good weldability, carbon steels containing lower carbon (0.2–0.30%) are used for pressure vessels. The carbon

Table 2.1 Typical composition of some plain carbon steels

AISI/SAE	%C	%Mn	%P max	%S max	UNS No.
1010	0.08–0.13	0.30–0.60	0.04	0.05	G10100
1015	0.13–0.18	0.30–0.60	0.04	0.05	G10150
1020	0.18–0.23	0.30–0.60	0.04	0.05	G10200
1025	0.22–0.28	0.30–0.60	0.04	0.05	G10250
1030	0.28–0.34	0.60–0.90	0.04	0.05	G10300
1040	0.37–0.44	0.60–0.90	0.04	0.05	G10400
1055	0.50–0.60	0.60–0.90	0.04	0.05	G10550
1080	0.75–0.88	0.60–0.90	0.04	0.05	G12250
1522	0.18–0.24	1.30–1.60	0.04	0.05	G15220

steels generally have adequate impact strength at low temperatures (−29 °C), but for still lower temperature fine-grained impact tested steels are used up to a temperature of −48 °C. For high temperature use (above creep limit), creep rupture strength and resistance to oxidation are the two important criteria. Almost all codes allow use of carbon steel up to 480 °C, though in earlier times it is used to be prescribed for temperatures as high as 520 °C (ASME Section VIII Div. 1 gives design stress of carbon steel up to 527 °C). The present-day accepted practice is to limit its use to a maximum temperature of 450 °C. Composition of some commonly used carbon steel containing different carbon is given in Table 2.1 [3].

2.2.3 *Low and Medium Alloy Steels*

Innumerable grades of steels containing comparatively small amounts of alloying elements, e.g. chromium, molybdenum, nickel, vanadium, boron, etc., in different combinations are in commercial use. The total alloying content in these steels may vary from 0.5 to 9.0%. The alloying elements are added to increase strength; to lower UTS/YS ratio; improve ductility, fracture toughness, heat treatment and carburizing properties; corrosion resistance in specific environments; high temperature creep strength and resistance to oxidation. Excluding carbon, the alloys of iron containing <5% and 5 to <10% alloying elements are broadly classified as low and medium alloy steels, respectively. The carbon and low and medium alloy steels are available both in wrought and cast forms and designated by numbering systems in different national and international specifications like SAE, AISI, DIN, BS, EN, etc. To have an idea of the range of different alloys available, composition of some of the low and medium alloy steels (AISI/SAE designation) are given in Table 2.2 [4]. The trend during the last 20 years has been to produce steels with high degree of cleanliness and low UTS/YS ratio, by micro-alloying and giving greater attention

Table 2.2 Typical composition of some alloy steels

AISI/SAE	%C	%Mn	%Ni	%Cr	%Mo	%V	UNS No.	Type
1330	0.28–0.33	1.60–1.90	–	–	–	–	G13300	Mn steel
1340	0.38–0.43	1.60–1.70	–	–	–	–	G13400	
2317	0.15–0.20	0.40–0.60	3.25–3.75	–	–	–	G23150	3% Ni steel
2330	0.38–0.43	0.70–0.90	3.25–3.75	–	–	–	G23300	
3115	0.13–0.18	0.40–0.60	1.10–1.40	0.55–0.75	–	–	G31150	Ni–Cr steel
3140	0.38–0.43	0.70–0.90	1.10–1.40	0.65–0.95	–	–	G31400	
4023	0.20–0.25	0.75–0.90	–	–	0.20–0.30	–	G40230	Mo steel
4037	0.35–0.4	0.70–0.90	–	–	0.20–0.30	–	G44190	
4130	0.28–0.33	0.75–1.00	–	0.80–1.00	0.15–0.25	–	G41300	Cr–Mo steel
4140	0.38–0.43	0.75–1.00	–	0.80–1.10	0.15–0.25	–	G41400	
4340	0.38–0.43	0.60–0.80	1.65–2.00	0.70–0.90	0.20–0.30	–	G43400	Ni–Cr–Mo steel
5120	0.17–0.22	0.70–0.90	–	0.70–0.90	–	–	G51200	Cr steel
5140	0.38–0.43	0.70–0.90	–	0.70–0.90	–	–	G51400	

N.B Significance of the digits: The first two digits represent the major alloying elements (Types) and the last two digits the carbon content to production and working techniques like quenched and tempered and thermo mechanical treatment. Line pipe steels (API 5LX) having YS up to 584 Mpa (85 ksi) are presently in use. In the recent years, line pipe material of X 120 grade has been developed specially for transport of gas [5].

2.2.4 High Alloy Steels

High alloy steels are mainly those which contain high amounts (>10%) of alloying elements. Stainless steels constitute the major material of construction among the high alloy steels in petrochemical industry.

2.2.4.1 Wrought Austenitic, Ferritic and Martensitic Stainless Steels

Stainless steels are alloys with a minimum of 10.5%Cr. In addition, these can also have nickel, and comparatively smaller amounts of molybdenum, titanium, niobium and nitrogen. It is chromium which imparts the resistance to corrosion by forming a thin ($\sim$2 nm) passive layer of chromium oxide on the surface [2]. Many metals and alloys form a thin oxide film when exposed to air, but these are not stable and get easily destroyed when exposed to corrosive environments. However, for the film to impart protection it should form easily, be stable and most importantly re-form quickly once damaged. These requirements are fulfilled by chromium when added to iron as an alloying element. A number of commercial alloys are available, having high resistance to corrosion and oxidation and improved creep rupture properties. Some alloys, in addition, also possess much higher strength. Stainless steels are classified mainly into three categories based on their crystal structure, i.e. Fe–Cr martensitic, Fe–Cr ferritic (4XX series) and Fe–Cr–Ni austenitic (3XX series). While the first two are magnetic, the latter is non-magnetic. It is important to remember that numbers 4XX and 3XX refer to stainless steels shaped by working, such as rolling, forging, etc. Both these categories of alloys were developed in early twentieth century. The credit for discovery of the corrosion resistance stainless steel goes to P. Monnartz in Germany in 1911 when the first detailed data on the corrosion of stainless steel as a function of composition were published. In 1912, Eduard Maurer at Germany's Krupp Iron Works patented the first austenitic stainless steel. In 1913, Harry Brearly of Sheffield, England, discovered and patented the first martensitic stainless steel. For these achievements, Maurer and Brearly are given the distinction as co-discoverers of the industrial usefulness of stainless steel [6].

Stainless steels can be broadly divided into four groups

- Straight chromium ferritic/martensitic stainless steels
- Austenitic Stainless Steels:
  - Chromium–nickel
  - Chromium–nickel–molybdenum
  - High performance
  - Heat resistant
- Duplex Stainless Steel
- PH steels

Of these most commonly used stainless steels in process industry are of austenitic chromium–nickel–molybdenum grades. Austenitic steels are more ductile and can be formed and welded with comparatively greater ease than the ferritic grades. They have good creep rupture strength and oxidation resistance up to 1100 °C. They are also suitable for cryogenic use up to almost 0° absolute (−270 °C). Many of the austenitic stainless steels are also available in low carbon (with suffix L) or stabilized grades (e.g. 321 and 347). Alloys meant for high temperature service wrought alloys are given a suffix of H, e.g. 304H, 347H, 316H, 321H etc., which specifies minimum carbon content of 0.04%, the amount of other elements remaining the same. Fe–Cr or Fe–Cr–Ni alloys are also used in cast form for number of services. Austenitic stainless steels of cheaper varieties are also available, where nickel has been partly or fully replaced by manganese + nitrogen to get a stable austenite phase (2XX series). This is possible because like nickel both manganese and nitrogen is austenite stabilizer. These alloys have better strength, but lower resistance to corrosion compared to Fe–Cr–Ni alloys and not very much in use as engineering material. Table 2.3 gives the nominal composition of various grades of 300 and 400 series of stainless steels [7].

Ferritic stainless steels are mainly Fe–Cr alloys with chromium content of 10.5% and above. As mentioned earlier, these are available in hardenable (martensitic) or non-hardenable (ferritic) grades. The former, with suitable heat treatment can develop high strength and hardness. The hardenable grades contain 12–15% chromium with carbon above 0.1%. Alloys containing still higher chromium are non-hardenable. In higher chromium containing alloys sometimes titanium is added in small amounts (1.5%) to improve corrosion resistance.

Ferritic stainless steels have very good resistance to high temperature oxidation but their use is limited because of their susceptibility to 475 °C embrittlement. Thus, the use of ferritic stainless steels is limited to $\sim$300 °C.

Table 2.3 Some typical wrought austenitic and ferritic stainless steels

Designation	Type	%C max	%Cr	%Ni	% Others
AISI (UNS NO)					
304 (S30400)	Austenitic	0.08	18–20	8–12	
304L (S30403)	Austenitic	0.03	18–20	8–12	
321 (S32100)	Austenitic	0.08	17–19	9–12	Ti, 5X(C + N); 0.7 max
347 (S34700)	Austenitic	0.08	17–19	9–12	Nb, 10XC; 1.0 max
304H (S30409)	Austenitic	0.10	17–19	9–12	C-0.04 min
316 (S31600)	Austenitic	0.08	16–18	10–14	2–3 Mo
316L (S31603)	Austenitic	0.03	16–18	10–14	2–3 Mo
317 (S31700)	Austenitic	0.08	18–20	11–15	3–4 Mo
317L (S31703)	Austenitic	0.03	18–20	11–15	3–4 Mo
309 (S30900)	Austenitic	0.08	22–24	12–15	
310 (S31000)	Austenitic	0.08	24–26	19–22	
304LN (S30451)		0.03	18–20	8–12	N 0.10–0.16
316LN (S31653)		0.03	16–18	10–14	N 0.10–0.16
201(S20100)	Austenitic	0.15	16–18	3.5–5.5	Mn 5.5–7.5; N 0.25
405 (S40500)	Martensitic	0.08	11.5–14.5	–	
410S	Martensitic	0.08	11.5–13.5	–	
410 (S41008)	Martensitic	0.15	11.5–13.5		
430 (S43000)	Ferritic	0.12	16–18		
444 (S44400)	Ferritic	0.025	17.5–19.5		Mo 1.75–2.5; (Ti + Nb) [0.2 + 4(C + N)] to 0.80 max

2.2.4.2 Cast Stainless Steels

Many stainless steel components, like other metals and alloys, are available in both wrought and cast forms, such as, pumps, valves, bends, reformer tubes, etc. On the other hand, some of the alloys are available only in cast form because they cannot be worked into various shapes. However, wrought and cast alloys are designated separately even in case of those having similar composition. Cast stainless steels are usually specified on the basis of composition by using the alloy designation system established by the Alloy Casting Institute (ACI). The ACI designations of corrosion resistant castings have been adopted by ASTM International and are preferred for cast alloys over the American Iron and Steel Institute (AISI) designation for similar

Table 2.4 Some typical cast stainless steels

Designation	Type	%C max	%Cr	%Ni	% Others
[a]*ACI/UNS No.*					
CA-15 (J91150)	Ferritic	0.15	11.5–14	1 max	
CC-50 (J92615)	Ferritic	0.50	26–30	4 max	
CF-8 (J92600)	Austenitic	0.08	18–21	8–11	
CF-8M (J92999)	Austenitic	0.08	18–21	9–12	2–3 Mo
CF-8C (J92710)	Austenitic	0.08	18–21	9–12	Nb (8xC)
CH-20 (J93402)	Austenitic	0.20	22–26	12–15	
[b]*ACI/UNS No.*					
HC (J92605)	Ferritic	0.50	26–30	1 max	2.0 Si
HH (J93503)	Austenitic	0.2–0.5	24–28	11–14	2.0 Si
HI (J94003)	Austenitic	0.2–0.5	26–30	14–18	2.0 Si
HK (J92224)	Austenitic	0.2–0.6	24–28	18–22	2.0 Si
HT (J94605)	Austenitic	0.35–0.75	13–17	33–37	2.5 Si
HX	Austenitic	0.35–0.37	15–19	64–68	2.5 Si
HPJ95705	Austenitic	0.25–0.5	24–27	33–37	2.0 Si; Nb, Ti, W

[a]Cast corrosion resistant alloys
[b]Cast heat resistant alloys

wrought steels. Table 2.4 gives some of the typical cast stainless steels used for corrosive and high temperature services [8].

The alloys are identified by the letters and numbers assigned. The terms C and H indicate use of alloy for corrosive and heat resistant service, respectively. The second term indicates nominal Cr–Ni type as per ASTM E527 [9]. Increasing nickel content of the alloy is indicated by adding A–Z to the ACI designation. Number following this letter denotes carbon content of the alloy. In case of any additional element in the alloy, the same is indicated by adding a letter to the designation. For example Alloy CF8M would mean "cast corrosion resistant alloy containing 19Cr–9Ni (location F in the ASTM E527) containing max 0.08C with addition of Mo". Cast alloys are classified as corrosion resistant when used in corrosive and vapour environment below 650 °C and heat resistant above this temperature. Cast stainless steel is considered to have corrosion rates equivalent to wrought grade but this may also be lower because of cast structure's inhomogeneity or micro segregation [10].

2.2.4.3 Duplex Stainless Steel (DSS)

First developed and introduced in mid 1970s duplex stainless steels (DSS) ideally consist of a mixture of about equal proportion of ferrite and austenite. The mixed phase (Fig. 2.3) [11] is obtained by using a balanced composition of chromium, nickel, molybdenum and nitrogen, with nickel reduced in the range of 5–7%, depending on the chromium content. To compensate the reduction in nickel small

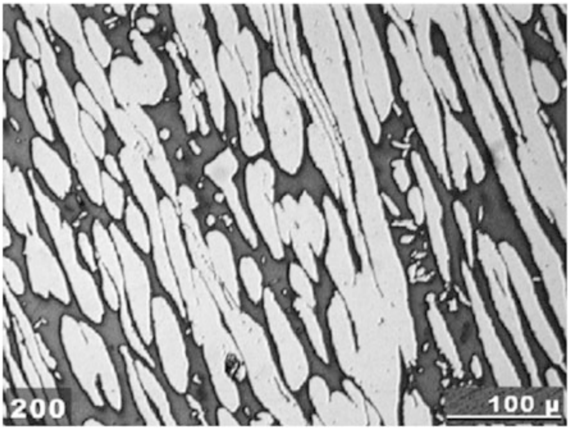

Fig. 2.3 Duplex stainless steel micro structure of austenite and ferrite [11]

amounts of nitrogen is added, which as stated earlier is an austenite stabilizer. In practice, it is not possible to get equal proportion of austenite and ferrite and variations in the same primarily affect corrosion rate (decreasing austenite) and impact energy (increasing ferrite). Optimal results are obtained in ferrite range between 35 and 60%. Though first produced in 1930s [12], use of DSS was limited. The first-generation DSS provided good performance in non-welded conditions in some service but had limited use in as-welded condition. Presence of excessive ferrite in weld and HAZ drastically affected toughness and corrosion resistance of welds. It was only in early 1970s that a new grade (18Cr grade), with good properties was added to the first-generation DSS which was accepted by the industry for its resistance to chloride SCC and used primarily for coolers and condensers where the service involved water or processing medium containing high level of chloride. Subsequently, a number of DSS alloys have been produced based on 22Cr, 23Cr and 25Cr grades [12–14] with different amounts of nickel, molybdenum and nitrogen; the 25Cr grade being called Super DSS. In addition to good corrosion resistance, these have much higher strength than the 300 series of alloys. Charles [15] has published an excellent review on the development and importance of DSS.

Considerable work is still going on in the development and studies on DSS. During the last few years DSS having high PRE of minimum 48, called Hyper DSS [16], has been developed for use under highly corrosive conditions. Of all the alloying elements in stainless steels, nickel is not only costliest but its price also fluctuates considerably. Therefore cheaper varieties of DSS, where nickel has been replaced with manganese and nitrogen, called lean DSS [17] have been developed. It is claimed to be suitable for use in place of 304L and 316L for many services. These alloys also have the advantage of higher strength and resistance to chloride stress corrosion cracking.

DSS is not as easy to weld as austenitic stainless steels but has better weldability than ferritic and martensitic stainless steels. Initial problems experienced in welding

Table 2.5 Nominal composition of major grades of duplex stainless steels (wt%)

Steel Name/UNS No.	C	Si	Mn	Cr	Ni	Mo	Cu	N
LDX 2101[a] S32101	0.03	0.6	5.0	21.5	1.5	0.3	0.3	0.22
LDX 2404™ S82441	0.02	–	3.0	24.0	3.6	1.6	–	0.27
2304[b] S32304	0.02	0.4	1.5	23.0	4.8	0.3	0.3	0.10
2205[c] S32205	0.02	0.4	1.5	22.0	5.7	3.1	0.2	0.17
2507[d] S32750	0.02	0.2	0.7	25.0	7.0	4.0	0.3	0.27
2707[e] S32707	0.03	–	–	27.0	6.5	5.0		0.4

[a]Recent development—low Ni, high Mn Lean DSS
[b]Recent development—low Ni, high Mn Conventional DSS
[c]Present-day Lean DSS
[d]Present-day DSS (conventional)
[e]Present-day DSS (Super DSS)
[f]Recent development, Hyper DSS

DSS have now been overcome. Table 2.5 gives composition of some of the typical DSS compiled from data of reputed manufacturers [13, 14, 16, 17].

Another important group of stainless steels falls under the category of precipitation hardening (PH) stainless steels used primarily where wear resistance is an important requirement.

2.2.4.4 High Performance Ferritic and Austenitic Stainless Steels

Number of highly alloyed materials have been developed and are under development to meet the requirements of highly corrosive services in oil and gas, chemical, petrochemical and other industries. Under some of the conditions encountered in these services conventional stainless steels and nickel alloys fail to give satisfactory service. These alloys fall under the category of super austenitic, super ferritic, super duplex and nickel base alloys; last two having been discussed separately. While super austenitic stainless steels are used for fabrication of different equipment, ferritic stainless steels have been developed to be used primarily as heat exchanger tubing in seawater service where resistance to pitting and chloride stress corrosion cracking is an important requirement. Moreover, these have the advantage of lower cost compared to high nickel containing super austenitic stainless steels. Table 2.6 gives the composition of some of the high performance stainless steels [18].

2.2.4.5 Comparison of Different Stainless Steels

It will be apparent from the above discussion that number of alloys have been developed falling in the category of stainless steels. Table 2.7 summarizes the comparative properties of the various grades of stainless steels. These varying physical, mechanical and corrosion resistant properties enable their use under varying conditions which will be discussed in detail at appropriate sections in the book.

Table 2.6 Composition of wrought high performance ferritic and austenitic stainless steels showing major alloying elements

Name	UNS No.	C	N	Cr	Ni	Mo	Others	PRE No.
Super austenitic								
904L	N08904	0.02	–	19.0–23.0	23.0–28.0	4.0–5.0	Cu 1.0–2.0	32
Alloy 28	N08028	0.02	–	26.0–28.0	29.5–32.5	3.0–4.0	Cu 0.6–1.4	36
254 SMO	S31254	0.02	0.18–0.22	19.5–20.5	17.5–18.5	6.0–6.5	–	42
Al-6XN	N08367	0.03	0.18–0.25	20.0–22.0	23.5–25.5	6.0–7.0	0.76	43
654 SMO	S32654	0.02	0.45–0.55	24.0–28.0	21.0–23.0	7.0–8.0	Mn 2.0–4.0	54
Super ferritic								
E-BRITE 26-1	S44627	0.01	0.015	25.0–27.0	0.5	0.75–1.5	Nb	27
SEA-CURE	S44660	0.03	0.040	25.0–28.0	1.0–3.5	3.0–4.0	Ti; Nb	35
AL-29-42	S44800	0.01	0.020	28.0–30.0	2.0–2.5	3.5–4.2		40

Table 2.7 Comparison of properties of different types of stainless steels

Characteristics	Austenitic	Ferritic	Duplex
Basic composition	Cr. 18–25, Ni 8–40	Cr 10–27	Cr. 18–25; Ni 5–27
Phases	Austenite	Ferrite	50 Austenite + 50 Ferrite
Magnetic properties	Non-magnetic	Strongly magnetic	Magnetic
R.T. strength	Fair	Good	Very good
H.T. strength	Very good	Poor (>300 °C)	Poor (>300 °C)
Cryogenic property	Very good	Poor	Poor
Weldability	Very good	Poor	Fair
Corrosion/Oxidation	Very good	Fair/Good (>300 °C)	Good (>300 °C)

2.3 Non-ferrous Materials

2.3.1 Aluminium and Aluminium Alloys

Of the non-ferrous metals, tonnage-wise aluminium occupies the highest position. It is soft, has low strength and comparatively low melting point (about 660 °C). In spite of this, its lightness (about 1/3rd of that of iron), good resistance to corrosion, good electrical conductivity and comparatively lower cost make these as attractive alternative in many structural, decorative, electrical and corrosion resistance service. Aluminium and its alloys are extensively used in aerospace industry. An important property of aluminium is its ability to develop considerable strength by suitable alloying and in some cases by subsequent heat treatment, known as *age hardening*. The aluminium and its alloys on cold working retain good ductility with increase in strength and therefore, are available in various degrees of cold working, known as *tempers* that are mentioned in alloys specifications.

2.3.2 Copper and Copper Alloys

Copper is the second most important non-ferrous metal after aluminium. Its largest use is as electric conductor but is also extensively used in producing various alloys having good resistance to corrosion, especially in fresh and sea water service. Copper and its alloys are highly ductile and can be easily cast and worked to produce various components. The largest use of copper alloys in process industries is in tubing and piping. Where resistance to some specific corrosive media is required, the preferred method of using copper and its alloys is to use as lining over steel base for fabrication of pressure vessels, tanks, etc.

The most important copper alloys are brasses (Cu–Zn, Cu–Zn–Sn; Cu–Zn–Al), bronzes (Cu–Al, Cu–P, Cu–Zn–Si), cupronickels (Cu–Ni), etc. Some of the

Table 2.8 Composition of some copper alloys used in process industries

UNS No.	Copper	Aluminium	Nickel	Zinc	Iron	Others
C28000	59.0–63.0	–	–	Balance		
C44300	72.0	–	–	Balance		Sn 0.9–1.2; As 0.04
C44400	70.0–73.0	–	–	Balance		Sn 0.9–1.2; Sb 0.02–0.10
C44500	70.0–73.0	–	–	Balance		Sn 0.9–1.2; P 0.02–0.10
C60800	Balance	5.0–6.5	–			0.02–0.35
C68700	76.0–79.0	1.8–2.5	–	Balance		0.02–0.10
C70400	Balance	–	4.8–6.2	1.0 max	1.3–1.7	
C70600	Balance	–	9.0–11.0	1.0 max	1.0–1.8	
C71000	Balance	–	19.0–23.0	1.0 max	0.5–1.0	
C71500	Balance	–	29.0–33.0	1.0 max	0.40–1.0	
C71600	Balance		31.0		1.7–2.3	

important uses of copper alloys used in process industries are heat exchanger tubing, piping and fittings for handling sea water, fasteners and other hardware, etc. Table 2.8 lists some important copper alloys [19].

2.3.3 Nickel and Nickel Alloys

Compared to aluminium and copper, nickel is costlier but in spite of this it is extensively used both as pure nickel or mainly its alloy both for corrosion and high temperature services. Some of the important nickel base alloys are Monel® (Ni–Cu), Inconels® (Ni–Cr–Fe), Hastelloys® (Ni–Cr–Mo,). Use of nickel and its alloys is specially made where resistance to specific highly corrosive environment is needed as in strong caustic or hydrofluoric acid service. Table 2.9 lists some important nickel alloys [20].

2.3.4 Lead and Lead Alloys

Lead and its alloys as engineering material have limited but important uses. Lead alloys are used for soldering (Pb–Sn, Pb–Sn–Sb) and bearings (Pb–Sn–Sb, Cu–Pb, Cu–Sn–Pb). Pure lead and Pb–Sb (hard lead) sheets and pipes are used in specific corrosive environment, e.g. dilute sulphuric acid service. Lead has low melting point (327 °C) and low strength. Its creep resistance is poor and creep failure occurs at normal temperature under self-load. By alloying, its strength, both normal and

Table 2.9 Nominal composition of typical nickel alloys

UNS No.	Nickel	Copper	Iron	Aluminium	Chromium	Molybdenum	Others
Monel (N04400)	66.5	31.5	1.0				1.0Mn
Monel K 500 (N05500)	64.0	30.0		2.8			0.60Ti
Incoloy 600 (N06600)	75.0		8.0		15.5		0.15C
Alloy 825 (N08825)	42.0		29.5		21.5	3.0	1.3Cu; 1.0Ti
Alloy G2 (N06985)	44.0		19.5		22.0	7.0	1.5W; 2.0Cu
Hastelloy C276 (N10276)	Balance	57.0	5.5		15.0	16.0	3.8W
Hastelloy C22 (N06022)	Balance		3.0		22.0	13.0	3.0W

creep, can be increased, e.g. Pb–Sb (hard lead) has better stability as lining. Because of its low strength it is more commonly used as a lining (sheet or homogenous).

2.3.5 Titanium and Titanium Alloys

In process industry unalloyed titanium (also known as commercially pure or *CP* titanium) is commonly used. Titanium is selected for its excellent corrosion resistance properties in large varieties of environments, especially in applications where high strength is not required. However, because of high cost its use is limited to exchanger tubes using sea water as coolant and for some specific corrosive chemicals. CP grade titanium is available in four ASTM grades, i.e. 1, 2, 3 and 4 where strength of the material increases progressively from 240 MPa (35 ksi) to 640 MPa (93 ksi). The chemical composition and strength for the four CP grades are given in Table 2.10 [21]. It will be evident from the table that, the variations in mechanical properties are dependent on interstitial solid solution (oxygen, hydrogen, nitrogen) and impurity (iron) levels.

Titanium is light compared to iron (about 50%) and therefore it has the advantages of having lower weight to strength ratio. Ti6 Al–4V alloy is widely used titanium alloy where strength and toughness are required.

Table 2.10 Variations in composition (by wt%) and strength of unalloyed titanium

ASTM B265/UNS	Fe max	O max	N max	C max	H max	Elongation %	Y.S. MPa	UTS MPa
Gr. 1/R50250	0.2	0.18	0.3	0.1	0.015	24.0	170–310	240
Gr. 2/R50400	0.3	0.25	0.3	0.1	0.015	20.0	275–450	345–480
Gr. 3/R50550	0.25	0.3	0.5	0.1	0.015	18.0	360–480	480–700
Gr. 4/R50700	0.5	0.4	0.5	0.1	0.015	15.0	500–530	600–680

2.3.6 *Other Non-ferrous Metals*

The other non-ferrous metals have either no utility in process industries (zinc, silver, tin, etc.) or have limited use under special conditions (tantalum, zirconium, magnesium, cobalt, etc.). Others like silicon, antimony, barium, etc., are used in small quantities as minor or micro-alloying elements. For example, magnesium is used for handling hydrofluoric acid, zirconium for its resistance to carbamate solution, tantalum for its resistance to many highly corrosive solutions.

2.4 Unified Numbering System

Originally alloys were classified independently by producers and users of metals and alloys and societies and trade associations concerned for identification. Ferrous materials in USA were classified by AISI, SAE, and Foundry Societies, etc. With increasing number of alloys being developed, numerous uncoordinated designation systems created a lot of confusion. To overcome this, the Unified Numbering System (UNS) was developed in 1977 [22] jointly by Society of Automotive Engineering (SAE) and ASTM to unify the different systems in vogue over the years. In this system, the metals and alloys are divided into 18 series with designations starting with a letter followed by five numbers. The letter identifies the family of material such as, S for stainless steels, C for copper alloys G for carbon and alloy steels. The following five numbers represent as far as possible the commonly designated user friendly numbers. For example, stainless steel type 316 would be designated as S31600 and carbon steel containing 0.2%C as G10200. Thus, it also provides the uniformity necessary for efficient indexing, record keeping, data storage and retrieval and cross referencing. Some of the important items of UNS system are listed in Table 2.11.

Two important aspects of UNS are that (1) arbitrary assignment of UNS numbers derived unofficially from former members is avoided and proper trade association contacted and (2) a UNS number is not a specification in itself but is only for identifying metals and alloys specified elsewhere. A UNS number therefore should not be considered as a specification as it does not set any requirements but identifies groups of metals and alloys whose controlling limits have been established in specifications published elsewhere. The UNS numbers identify metals and alloys that are generally in regular production and use. According to ASTM E 527, UNS number will not ordinarily be issued for a material that has just been conceived or that is still in only experimental trial.

Table 2.11 Unified alloying number system (UNS)

Ferrous metals and alloys			
D00001–D99999	Specified mechanical properties steels		
F00001–F99999	Cast irons and cast steels		
G0000–G99999	AISI and SAE carbon and alloy steels		
H00001–H99999	AISI H steels		
K00001–K99999	Miscellaneous steels and ferrous alloys		
S00001–S99999	Heat and corrosion resistance stainless steels		
T00001–T99999	Tool steels		
Non-ferrous metals and alloys			
A00001–A99999	Aluminium and aluminium alloys		
L00001–L99999	Low melting metals and alloys		
M00001–M99999	Miscellaneous non-ferrous metals and alloys		
N00001–N99999	Nickel and nickel alloys		
P00001–P99999	Precious metals and alloys		
T00001–T99999	Reactive and refractory metals and alloys		
Examples			
Alloy description	Former designation	System No.	UNS designation No.
Al–1.2Mn	AA	3003	A93006
Copper electrolytic (Tough Pitch)	CDA	110	C11000
Carbon steel (0.2%C)	AISI	1020	G10200
Stainless steel (18Cr–8Ni)	AISI	304	S30400

2.5 Material Specification

2.5.1 Material Standard

It is a document that contains a technical specification or other precise criteria designed to be used consistently as a rule, guideline or definition and thus increase reliability and the effectiveness of many goods and services. Standards are created by bringing together the experience and expertise of all interested parties such as the producers, sellers, buyers, users and regulators of a particular material, product, process or service. Standards are designed for voluntary use and do not impose any regulations. However, laws and regulations may refer to certain standards and make compliance with them mandatory.

2.5.2 Purpose of Specification

In the previous sections, the classification of metallic materials on the basis of composition, e.g. C-steel, C–0.5Mo, 2.25Cr–1.0Mo, 18Cr–8Ni, 90Cu–10Ni, 70Ni–30Cu, etc. has been briefly presented. Composition forms the first step in the selection of material under certain conditions. However, during design or procurement simply mentioning the general composition does not suffice because metals and alloys of the same composition may be required to have different shapes to fulfil some specific purpose, which in turn can depend on purpose, requiring different

1. Manufacturing processes
2. Working and shaping of metals
3. Heat treatment
4. Mechanical properties
5. Workability, ductility and toughness
6. Weldability

To facilitate and ensure the right material having required properties, there is need to have some definite guidelines which can be used by both the users and manufacturers. The need for this has resulted in the development of material standards. Almost all countries have National Standards and follow the same or internationally well-recognized standards for metallic materials and codes like ASTM, ASME and API, of USA. Other important standards such as BS of U.K., DIN of Germany, JIS of Japan and GOST of Russia. International Standard Organization (ISO) and European standards (EN) are also slowly getting accepted. Presently all EU nations have adopted the EN Standard.

For familiarity with original designations and trade names these, instead of UNS numbers, have been mostly used in this book. Readers can get the equivalent UNS number by referring to relevant ASTM/ASME standards.

2.5.3 Preparation of Standards

Preparation for standards involves various steps, such as (a) repeatability of composition and property data submitted by the manufacturer (b) existence of any standards of similar material in other accepted standards (c) and extensive trial and its feedback from fabricators, designers and actual users. Standards do not include products having company trade names but only requirements of a particular material, which any manufacturer is free to produce and market under the relevant specifications. All data submitted/collected are reviewed by a panel of experts and, if the result is found to be satisfactory, the standard is prepared and issued. Some of the organizations bring out an interim specification and make it a permanent one only after the performance is found to be satisfactory. If not, the standard is either withdrawn or modified.

When a new alloy is developed, the manufacturers are required to submit room, low or high temperature properties, depending on the proposed service, welding procedure and weldability, feedback on field performance and other necessary details. Once the committee is convinced that the material will meet the requirements of safe pressurized components, then only it is accepted. ASME first publishes these as Code Cases and then subsequently issued as standard. It may be mentioned that such standards exist not only for metals and alloys but also for all products, including various testing and analytical procedures.

2.5.3.1 Broad Coverage Under Specifications

Standards are prepared with a view to specifying minimum requirements for the material to be certified as usable. It is natural that the specification cannot include special requirements under all types of uses. For example, all pressure vessel quality carbon steels can be used up to sub-zero temperatures of −29 °C as per ASME. For use at still lower temperatures, additional requirement of impact test is included only in those specifications of carbon steels, where the design/operating temperatures are in the sub-zero range of −29 to −46 °C. In addition, there are some service-related specific requirements, which are not covered in specifications. For example, many ferrous and non-ferrous metals and alloys used in sour service (in oil and gas production/refineries) fail if the composition, strength and or hardness are not controlled within required limits. In such cases, it is the responsibility of the users to specify these, where necessary, as an additional requirement.

For metallic material of interest to the process industry, separate specifications cover the different forms in which the material of the same group, such as, low and medium alloy Cr–Mo steel, stainless steels, etc., are produced. These are

- Plates
- Tubes/Pipes
- Forgings
- Casting, etc.

In addition, some specifications are also made for specific services. For example, there are separate specifications for superheater tubes, high temperature castings, steel plates for use at medium and low temperatures, and so on. It may be mentioned that, unless specially required, the standards give only room temperature mechanical properties, which form the basis for both production and acceptance of a material.

Some of the important contents of material specifications are:

Shaping Process

The metals and alloys come in various forms like plates, pipe, tube, wire, valve, etc. The methods used are rolling, extrusion, drawing, forgoing, casting, etc. While composition may be the same, properties may vary depending on the process need. Thus for each of these processes there are different specifications.

Manufacturing Process

The material properties will also vary with the presence of small amounts of additional elements, which may be deliberately added or present as impurities. The various grades of carbon and low alloy ferritic steel can be produced in rimmed, semi-killed and killed conditions which form part of a specification. Each of these have advantages and disadvantage and the user has to decide under what condition the material will meet his requirements.

Chemical Composition

Any metal or alloy does not have a fixed composition because it is never possible to ensure the same for all the heats (molten metal/alloy) during manufacturing. In other words, there will always be some range within which different elements can vary without affecting the basic characteristic of the alloy. In addition, there is likely to be other elements, either added or present as impurities. For example, in any iron base alloys there is presence of manganese and silicon, which are to be added during production. On the other hand, sulphur and phosphorous are always present as impurities. Thus it is necessary that the composition remains within limits to be designated as a particular metal or alloy. Normally the maximum content of each element is specified, except in some cases where the range is mentioned.

Mechanical Properties

Mechanical properties like, strength, elongations, toughness, etc., are very important parameters to judge the suitability of an alloy for a particular service. Again the mechanical properties will depend on heat treatment to which the material is subjected. So the specification also states the heat treatments to be used. For example, the properties of carbon steel will vary with heat treatments like annealing or normalizing and tempering. Thus heat treatment becomes an important step for both manufacturer and users. For example, the user can ask for the product to be provided in normalized and tempered condition to have optimum properties. On the other hand, the manufacturer can attain the desired properties by adjusting the composition (mainly carbon and manganese) and heat treatment.

Specification gives the minimum mechanical properties like UTS, Y.S (0.2% Proof stress), % elongation, and reduction in area (% RA). The minimum value is given because while manufacturing one can never attain repeatedly the some preset fixed properties. So within a reasonable range, changes in mechanical properties, as in case of chemical analysis, are permitted. If the user asks for say carbon steel plates of Gr. 60 (min UTS of 410 MPa (60 ksi)), the manufacturer guarantees that it would meet the minimum requirement of all properties specified. However, the actual properties of plates supplied may be more and vary from plate to plate but in no case it will be less than the minimum specified values.

Quality

The quality of the finished material is also important. Presence of inclusions or lamination will have an adverse effect on performance. In case of cladding, only limited amount of disbonded area can be permitted to avoid in-service failure. Similarly, dimensional variations of any product or component should be within limits. For example, tolerance limits in plate thickness and size, inner diameter and outer diameter of tubes/pipes, flanges, rods, etc., are to be set. All these requirements are covered under specification. Thus in the use of material, it is always essential to procure the material based on recognized specifications along with any requirements specially required for a particular service.

2.5.4 Dual Certification

Presently available in market are stainless steel products which have dual or multiple certifications, often involving both standard and low carbon variants of the grade being certified together. Dual or multiple certifications means the issue of two separate inspection certificate for the same inspected/tested or delivered batch of steel. Since 1980s, it has become a practice and acceptable by stainless steel supplier to provide dual certificate for the same batch of steel. According to the British Steel Association, [23, 24] to reduce inventory the suppliers certify together if the chemical composition and mechanical properties match the grades, such as, 304/304L or 316/316L or 304/304H. Full compliance with all the requirements of the first (primary) standard is assured and for the others only the cast chemical composition and room temperature mechanical properties of the products are certified, Dual certification can be used for other materials also provided they meet all the requirements of the identified material specification and grade [25]. For example, steel plates of SA-516 come in five grades, that is, 55, 60, 65 and 70 with composition and mechanical properties (tensile and yield stress) as given in Table 2.12.

If we examine the table above, we find that a material with maximum carbon of 0.18%, manganese content of 0.9%, having a tensile strength of 476 MPa (70 ksi) and a yield strength of 239 MPa (35 ksi) will satisfy for all four grades of SA-516. In that case, it can be dual stamped for all four grades provided it also meets other requirements stipulated in the specification. The designer can therefore consider its use for any of the four grades.

Once the material is selected and the specification decided, the equipment is to be designed and fabricated using applicable Codes. Codes are systematically arranged comprehensive collection of laws or procedure to attain desired objective of safety. However, unlike specifications, Codes have got statutory status binding on parties concerned.

Table 2.12 Chemical and mechanical properties of A-516 plate with respect to different grades

Requirement	Gr. 55	Gr. 60	Gr. 65	Gr. 70
Carbon max—≤ ½ in.	0.18%	0.21%	0.24%	0.27%
Manganese—≤ ½ in.	0.60–0.90%	0.60–0.90%	0.85–1.20%	0.85–1.20%
Tensile strength—ksi	55–75	60–80	65–85	70–90
Yield strength, min—ksi	30	32	35	38

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