

François Cardarelli

Materials Handbook

A Concise Desktop Reference



Springer

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In this book all the units of measurement used for describing physical quantities are those recommended by the Systeme International (SI). For accurate conversion factors between these units and the other non-SI units (e.g., the Imperial and US customary) please refer to Cardarelli, F., *Scientific Unit Conversion: A Practical Guide to Measurement*, 2nd Edition, Springer-Verlag, London (1999), 204 pp.

Dedication

The *Materials Concise Reference Guide* is dedicated to my father Antonio and my mother Claudine, to my sister Elsa, and to Louise Saint-Amour, for their love and support. In addition, I want to express my thanks to my two parents and my uncle Consalvo Cardarelli, who in close collaboration provided valuable help when I was teenager to contribute to my first fully equipped geological and chemical laboratory, and to my personal scientific library. This was the starting point of my strong and extensive interest in both science and technology, and gluttony for scientific and technical literature.

François Cardarelli

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(This page contains a table of contents for the book, listing chapters and their corresponding page numbers. The text is mirrored and difficult to read due to the image quality.)

Units Policy

In this book all the units of measurement used for describing physical quantities are those recommended by the *Système International d'Unités* (SI). For accurate conversion factors between these units and the other non-SI units (e.g., cgs, fps, Imperial and US customary) please refer to Cardarelli, F., *Scientific Unit Conversion: A Practical Guide to Metrication*, 2nd edition, Springer-Verlag, London (1999), 504 pp.

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Ferrous Metals Alloys

Introduction

Despite the several comprehensive series available in Material Sciences and their related fields, it is a hard task to find grouped properties of metals and alloys, ceramics, polymers, minerals, woods, and building materials in a single volume source book. Actually, the scope of this practical handbook is to provide to scientists, engineers, professors, technicians, and students working in numerous scientific and technical fields ranging from nuclear to civil engineering, easy and rapid access to the accurate physico-chemical properties of all classes of materials. Classes used to describe the materials are: (i) metals and their alloys, (ii) semiconductors, (iii) superconductors, (iv) magnetic materials, (v) miscellaneous electrical materials (e.g., dielectrics, thermocouple and industrial electrode materials), (vi) ceramics, refractories, and glasses, (vii) polymers and elastomers, (viii) minerals, ores, meteorites, and rocks, (ix) timbers and woods, and finally (x) building materials. Particular emphasis is placed on the properties of the most common industrial materials in each class. Physical and chemical properties usually listed for each material are (i) mechanical (e.g., density, elastic moduli, Poisson's ratio, yield and tensile strength, hardness, fracture toughness), (ii) thermal (e.g., melting point, thermal conductivity, specific heat capacity, coefficient of linear thermal expansion, spectral emissivities), (iii) electrical (e.g., resistivity, dielectric permittivity, loss tangent factor), (iv) magnetic (e.g., magnetic permeability, remanence, Hall constant), (v) optical (e.g., refractive indices, reflective index), (vi) electrochemical (e.g., Nernst standard electrode potential, Tafel slope, specific capacity) and (vii) miscellaneous (e.g., corrosion rate, thermal neutron cross section, natural abundances, electron work function, Richardson constant). Detailed appendices provide additional information (e.g., properties and cost of the elements, molten salts and liquid metals, crystallographic calculations), and an extensive bibliography completes this comprehensive guide. The comprehensive index and large format of the book enable the reader to locate and extract the relevant information quickly and easily. Charts and tables are all referenced and tabs are used to denote the different sections of the book. It must be emphasized that the information presented here is taken from several various scientific and technical sources, and has been meticulously checked; every care has been taken to select the most reliable data.

Contents

Introduction	xi
1 Ferrous Metals and Their Alloys	1
1.1 Iron and Steels	1
1.2 Nickel and Nickel Alloys	32
1.3 Cobalt Alloys	42
2 Common Nonferrous Metals	45
2.1 Aluminum and Aluminum Alloys	45
2.2 Copper and Copper Alloys	51
2.3 Zinc and Zinc Alloys	59
2.4 Lead and Lead Alloys	68
2.5 Tin and Tin Alloys	69
3 Less Common Nonferrous Metals	75
3.1 Alkali Metals	75
3.2 Alkaline-Earth Metals	94
3.3 Refractory and Reactive Metals (RMs)	113
3.4 Precious and Noble Metals (NM)	192
3.5 Platinum Group Metals (PGMs)	203
3.6 Rare-Earth Metals (Sc, Y, and Lanthanides)	217
3.7 Uranides (Th and U)	223
4 Semiconductors	245
4.1 Band Theory of Bonding in Crystalline Solids	245
4.2 Electrical Classification of Solids	246
4.3 Semiconductor Classes	247
4.4 Semiconductor Physical Quantities	249
4.5 Transport Properties	250
4.6 Semiconductor Physical Properties	252
4.7 Applications of Semiconductors	252
4.8 Some Common Semiconductors	252
4.9 Semiconductor Wafer Processing	260
4.10 The P-N Junction	263
5 Superconductors	265
5.1 General Description	265
5.2 Superconductor Types	266

5.3	Basic Theory	269
5.4	The Meissner–Ochsenfeld Effect	270
5.5	History	271
5.6	Industrial Uses and Applications	272
6	Magnetic Materials	275
6.1	Magnetic Physical Quantities	275
6.2	Classification of Magnetic Materials	278
6.3	Ferromagnetic Materials	281
7	Insulators and Dielectrics	291
7.1	Physical Quantities of Dielectrics	291
7.2	Insulator Physical Properties	298
7.3	Dielectric Behavior	300
7.4	Dielectric Breakdown Mechanisms	302
7.5	Electro-mechanical Coupling	303
7.6	Piezoelectricity	303
7.7	Ferroelectrics	303
7.8	Aging of Ferroelectrics	305
7.9	Industrial Dielectrics Classification	307
7.10	Selected Properties of Insulators and Dielectric Materials	308
8	Miscellaneous Electrical Materials	313
8.1	Thermocouple Materials	313
8.2	Electron-Emitting Materials	314
8.3	Photocathode Materials	315
8.4	Secondary Emission	318
8.5	Electrode Materials	319
9	Ceramics and Glasses	337
9.1	Ceramics and Refractories	337
9.2	Glasses	340
10	Polymers and Elastomers	371
10.1	Thermoplastics	371
10.2	Thermosets	377
10.3	Rubbers and Elastomers	378
10.4	Polymer Physical Properties	381
11	Minerals, Ores, and Gemstones	395
11.1	Definitions	395
11.2	Mineralogical, Physical, and Chemical Properties	396
11.3	Strunz Classification of Minerals	407
11.4	Mineral Properties Table	408
11.5	Mineral Synonyms	409
12	Rocks and Meteorites	479
12.1	Introduction	479
12.2	Types of Rocks	480
12.3	Igneous Rocks	480
12.4	Sedimentary Rocks	490
12.5	Metamorphic Rocks	495
12.6	Meteorites	499
12.7	Physical Properties of Common Rocks	506
13	Timbers and Woods	509
13.1	General Description	509

13.2	Properties of Woods	510
13.3	Applications	511
13.4	Wood Performance in Various Corrosives	511
14	Building and Construction Materials	517
14.1	Portland Cement	517
14.2	Aggregates	520
14.3	Mortars and Concrete	521
14.4	Ceramics for Construction	522
14.5	Building Stones	522
15	Appendices	527
15.1	Periodic Chart of the Elements	527
15.2	Selected Physical Properties of the Elements	528
15.3	Geochemical Classification of the Elements	528
15.4	Historical Names of the Elements	529
15.5	Cost of the Pure Elements	529
15.6	Crystallography and Crystallochemistry	529
15.7	Properties of Liquid Metals	559
15.8	Properties of Molten Salts	559
15.9	Electrochemical Galvanic Series	559
15.10	Hardness Scales	563
15.11	UNS Standard Alphabetical Designation	563
15.12	Fuel Energy Content	564
15.13	Natural Radioactivity	564
15.14	Scientific and Technical Societies	569
16	Bibliography	579
16.1	General Desk References	579
16.2	Dictionaries and Encyclopaediae	581
16.3	Comprehensive Series	582
	Index	584

common industrial materials in each class. Physical and chemical properties usually listed for each material are (i) mechanical (e.g. density, elastic modulus, tensile and yield strength, hardness, fracture toughness), (ii) thermal (e.g. melting point, thermal conductivity, specific heat capacity, coefficient of linear thermal expansion, spectral emissivities), (iii) electrical (e.g. resistivity, dielectric permittivity, loss tangent factor), (iv) magnetic (e.g. magnetic permeability, remanence, Hall constant), (v) optical (e.g. refractive indices, reflective index), (vi) electrochemical (e.g. Nernst standard electrode potential, Tafel slope, specific capacity) and (vii) miscellaneous (e.g. corrosion rate, thermal neutron cross section, natural abundances, electron work function, Richardson constant). Detailed appendices provide additional information (e.g. properties and cost of the elements, molten salts and liquid metals, crystallographic calculations), and an extensive bibliography completes this comprehensive guide. The comprehensive index and large format of the book enable the reader to locate and extract the relevant information quickly and easily. Charts and tables are well referenced and tabs are used to denote the different sections of the book. It must be emphasized that the information presented here is taken from several various scientific and technical sources, and has been meticulously checked; every care has been taken to select the most reliable data.

Ferrous Metals and Their Alloys

The ferrous metals are defined as the three upper transition metals of the group VIII B (8, 9, and 10) of Mendeleev's periodic chart, i.e., iron (Fe), cobalt (Co), and nickel (Ni).

1.1 Iron and Steels

1.1.1 Iron

1.1.1.1 General Properties and Description

Iron [7439-89-6] with the chemical symbol Fe, the atomic number 26 and the relative atomic mass of 55.845(2), is the first element of the upper transition metals of the group VIII B (8) of Mendeleev's periodic chart. Its name comes from the Anglo-Saxon, *iren*, while the symbol Fe and words such as ferrous and ferric derive from the Latin name of iron, *ferrum*. Pure iron is a soft, dense (7874 kg.m^{-3}), silvery-lustrous, magnetic metal, with a high melting point (1538°C). In addition, when highly pure, iron has both a good thermal conductivity ($78.2 \text{ W.m}^{-1}.\text{K}^{-1}$), a low coefficient of linear thermal expansion ($12.1 \mu\text{m.m}^{-1}.\text{K}^{-1}$), and is a satisfactory electric conductor ($9.71 \mu\Omega.\text{cm}$). At room temperature, highly pure iron crystallizes into a body-centered cubic (bcc) space lattice. From a mechanical point of view, pure iron exhibits a high Young's modulus of 208 GPa, with a Poisson's ratio of 0.291, but is malleable and can be easily shaped by hammering. Other mechanical properties such as yield and tensile strength strongly depend on interstitial impurity levels, and type of crystal space lattice structure. Natural iron is composed of four stable nuclides: ^{54}Fe (5.845at%), ^{56}Fe (91.754at%), ^{57}Fe (2.1191at%), and ^{58}Fe (0.2819at%), and the element has a thermal neutron cross-section of 2.6 barns. From a chemical point of view, pure iron is an active metal, and hence it rusts (i.e., oxidizes) when put in contact with moist air, forming a porous non-protective hydrated ferric oxide layer. In addition, pure iron readily dissolves in several diluted strong mineral acids such as hydrochloric and sulfuric acids with evolution of hydrogen. Various types of relatively pure or high-purity iron can be found on the market,

although only a few of them are used as structural material. Most commercial irons, except **ingot iron** and **electrolytic iron**, contain perceptible quantities of carbon, which affects their properties. Other common high-purity iron types include **reduced irons** and **carbonyl iron** (powders). Cost (1998) – pure iron metal (i.e., 99.99wt% Fe) is priced at 2.205 \$US.kg⁻¹ (1.00 \$US.lb⁻¹), while common iron (i.e. 99wt% Fe) is 9.92 €US.kg⁻¹ (4.5 €US.lb⁻¹).

1.1.1.2 Natural Occurrence, Minerals, and Ores

Because nuclides of iron are particularly stable with the highest binding energy per nucleon (i.e., -8.79 MeV/nucleon for ⁵⁶Fe), its cosmic abundance is particularly high and it is thought to be the main constituent of the Earth's inner core as an iron-nickel alloy, called, after its chemical composition, *NiFe* by the Austrian geophysicist Suess. Moreover, iron is the major component of "siderite" class meteorites. The relative terrestrial abundance in the Earth's crust is about 5.63wt%, hence, it is the fourth most abundant element after oxygen, silicon, and aluminum and the second most abundant metal after aluminum. Iron, owing to its chemical reactivity, never occurs free in nature (except in meteorites) but it is present combined in a wide variety of mineral species found either in igneous, metamorphic, or sedimentary rocks and also in other geologic materials (e.g., soils). Amongst them, the most widely distributed iron-bearing minerals are oxides such as: hematite (Fe₂O₃, rhombohedral), magnetite (Fe₃O₄, cubic), and limonite (Fe₂O₃·3H₂O, orthorhombic), the carbonate siderite (FeCO₃, rhombohedral), and the two sulfides pyrite (FeS₂, cubic), and marcasite (FeS₂, cubic). Amongst these minerals, only oxides are commonly used as iron ores. Commercially profitable extraction requires iron ore deposits providing a raw ore with more than 30wt% Fe. Although certain exceptional iron ores contain as much as 66wt% Fe, usually the major commercial iron ores contain 50–60wt% Fe. In addition the quality of the iron ore is influenced by the type of inert gangue materials. In addition to iron content, the amounts of silica, phosphorus, and sulfur-bearing compounds, are also important because they strongly affect the steelmaking process. China, Brazil, Australia, Russia, and the Ukraine are the five largest world producers of iron ore, but significant amounts are also mined in India, the United States, Canada, and Kazakstan. Together, these nine countries produce 80% of the world's iron ore.

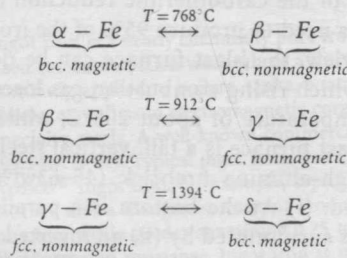
1.1.1.3 History

Iron has been known since prehistoric times and no other element has played a more important role in man's material progress. Iron beads dating from around 4000 BC were no doubt of meteoritic origin, and later samples, produced by reducing iron ore with charcoal, were not cast because adequate temperatures were not attainable without use of some form of bellows. Instead the spongy material produced by low-temperature reduction would have had to be shaped by prolonged hammering. It seems that iron was first smelted by Hittites sometime in the third millennium BC, but the value of the process was so great that its secret was carefully guarded and it was only with the fall of the Hittite empire around 1200 BC that the knowledge was dispersed and the "Iron-Age" began. In more recent times the introduction of coke as the reductant had far-reaching effects, and was one of the major factors in the initiation of the industrial revolution.

1.1.1.4 Crystallography and Critical Points

The existence of pure iron element in more than one phase, i.e., a single crystallographic form, of space lattice structure is called **allotropism**. This should not be confused with the term extended to a pure compound (e.g., molecule, alloy, etc.) which exists in several space lattice

structures and which is called **polymorphism**. The temperatures at which the changes of the crystallographic structure take place under constant pressure are called **phase transition temperatures** or **critical points**. These phase changes can be accurately determined by means of thermal analysis and dilatometry techniques. At atmospheric pressure, solid-state pure iron gives several allotropic crystallographic structures depending on temperature range. (i) Between room temperature and the critical point of 768°C , pure iron has a body-centered cubic space lattice structure (bcc, $a = 286.645 \text{ pm}$ at 25°C), and is known as **alpha-iron** ($\alpha\text{-Fe}$). Alpha-iron is soft, ductile and ferromagnetic with a density of 7874 kg.m^{-3} . (ii) When heated above its Curie temperature of 768°C , alpha-iron loses its ferromagnetic properties, but retains its body-centered cubic structure. This form of iron is called **beta-iron** ($\beta\text{-Fe}$) which is considered as a different allotropic form owing to its nonmagnetic properties. However, because no changes to the crystal lattice structure occur, it is customary to consider it as nonmagnetic alpha-iron. (iii) At about 912°C , the crystallographic structure changes to the face-centered cubic form (fcc, $a = 364.68 \text{ pm}$ at 916°C) and iron assumes the allotropic form known as **gamma-iron** ($\gamma\text{-Fe}$). At this transition temperature, a considerable absorption of heat occurs due to the endothermic reaction, and the volume of the iron unit cell contracts by 1%. Gamma-iron is nonmagnetic and has slighter greater density than low-temperature phases having a body-centered cubic structure. At a temperature of 1394°C a third transformation occurs and the face-centered cubic lattice reverts to a body-centered cubic form, which again becomes magnetic and is named **delta-iron** ($\delta\text{-Fe}$, $a = 293.22 \text{ pm}$). Finally, at the melting point of 1539°C a final pause takes place in the rise of temperature as the iron absorbs the heat required for fusion and becomes liquid (i.e., molten iron). The crystallographic phase transformations are summarized in the following reaction schemes:



1.1.1.5 Mining and Mineral Dressing

Most iron ores are extracted by common open pit mining. Some underground mines exist, but, wherever possible, surface mining is preferred because it is less expensive. After mining, depending on the quality of the raw iron ore, two routes can be used to prepare the concentrated ore. For certain rich iron ore deposits the raw ore (above 66wt% Fe) is crushed to reduce the maximum particle size, and sorted into various fractions by passing it over sieves through which lump or rubble ore (i.e., 5 to 25 mm) is separated from the fines (i.e., less than 5 mm). Due to the high iron content, the lumps can be charged directly in the blast furnace without any further processing. Fines, however, must first be agglomerated, which means reforming them into lumps of suitable size by a process called **sintering**. In this agglomeration process, fines are heated in order to achieve partial melting during which ore particles fuse together. For this purpose, the elevated heat required is generated by burning of fine coke known as coke breeze. After cooling, the sinter is broken up and screened to yield blast-furnace feed and an undersize fraction that is recycled.

Common ore is crushed and ground in order to release the ore minerals from the inert gangue materials (e.g., silica). Gangue minerals are separated from iron ore particles by common ore refinement processes in order to decrease silica content to less than 9wt%. Most concentration processes use froth flotation, and gravity separation based on density differences

to separate light minerals from heavier iron ores. Electromagnetic separation techniques are also used but hematite is not sufficiently ferromagnetic to be easily recovered. After refinement, the ore concentrate is in a powdered form unsuitable for direct use in the blast furnace. It has a much smaller particle size than ore fines and cannot be agglomerated by sintering. Instead, concentrates must be agglomerated by **pelletizing** (a process originated in Sweden and Germany in 1911, and optimized in the 1940s). In this process, first, humidified concentrates are fired in a rotary kiln, in which the tumbling action produces soft, spherical agglomerates. These agglomerates are then dried and hardened by firing in air at a temperature ranging between 1250°C to 1340°C, yielding spherical pellets with about 1 cm diameter.

1.1.1.6 Iron Making

Highly pure iron is prepared on a small scale by the reduction of the pure oxide or hydroxide with the hydrogen, or by the carbonyl process in which iron is heated with carbon monoxide under pressure and the $\text{Fe}(\text{CO})_5$ so formed decomposed at 250°C to give off the powdered metal. By contrast, in industrial scale production of steel the first stage in the conversion of iron ore into steel is the blast furnace, which accounts for the largest tonnage of any metal produced by man.

Iron making produces iron metal from iron chemically combined with oxygen. The blast furnace process, which consists of the carbothermic reduction of iron oxides, is industrially the most efficient process, and is used to produce 95% of the iron made in the world. From a chemical engineering point of view, the **blast furnace** can be described as a countercurrent heat and oxygen exchanger in which rising combustion gas loses most of its heat on the way up, leaving the furnace at a temperature of about 200°C, while descending iron oxides are reduced to metallic iron. The blast furnace is a tall, vertical steel reactor lined internally with refractory ceramics such as high-alumina firebrick (45–63wt% Al_2O_3) and graphite. Five sections can be clearly identified: (i) At the bottom is a parallel-sided hearth where liquid metal and slag collect, and this is surmounted by (ii) an inverted truncated cone known as the **bosh**. Air is blown into the furnace through (iii) **tuyeres** (water-cooled copper nozzles), mounted at the top of the hearth close to its junction with the bosh. (iv) A short vertical section called the **bosh parallel**, or the **barrel**, connects the bosh to the truncated upright cone that is the **stack**. Finally, the fifth and top section, through which the charge is fed into the furnace, is the **throat**. The lining in the bosh and hearth, where the highest temperatures occur, is usually made of carbon bricks, which are manufactured by pressing and baking a mixture of coke, anthracite, and pitch. Actually, carbon exhibits excellent corrosion resistance to the molten iron and slag in comparison with aluminosilicate firebricks used for the remainder of the lining.

During the blast furnace process, the solid charge (mixture of iron ore, limestone, and coke) is loaded either by operated skips or by conveyor belts at the top of the furnace at a temperature ranging from 150°C to 200°C, while preheated air (900 to 1350°C) in hot-blast stoves, sometimes enriched up to 25vol% oxygen, is blown into the furnace through the tuyeres. During the process, the coke serves both as fuel and reducing agent, and a fraction combines with iron. The limestone acts as a fluxing agent, i.e., it reacts with both silica gangue materials and traces of sulfur to form a slag; sometimes fluorspar is also used as fluxing agent. During the carbothermic reduction operations, the ascending carbon monoxide, resulting from the exothermic combustion of coke at the tuyere entrance, begins to react with the descending charge, partially reducing the ore to ferrous oxide. At the same time the carbon monoxide is cooled by the descending charge and it reacts forming carbon dioxide and carbon black (soot). This soot dissolves in the iron forming a eutectic and hence decreases the melting temperature. At this stage the temperature is sufficiently high to decompose the limestone into lime and carbon

dioxide. Carbon dioxide reacts with the coke to give off carbon monoxide, and the free lime combines with silica gangue to form a molten silicate slag floating upon molten iron. Slag is removed from the furnace by the same taphole as the iron, and it exhibits the following chemical composition: 30–40wt% SiO₂, 5–15wt% Al₂O₃, 35–45wt% CaO, and 5–15wt% MgO. As the partially reduced ore descends, it encounters both increasing high temperature and high concentration of carbon monoxide which accelerates the reactions. At this stage the reduction of ferrous oxide into iron is completed and the main product, called molten pig iron (i.e., hot metal or blast-furnace iron), is tapped from the bottom of the furnace at regular intervals. The gas exiting at the top of the furnace is composed mainly of 23vol% CO, 22vol% CO₂, 3vol% water, and 49vol% N₂, and after the dust particles have been removed using dust collectors, it is mixed with coke oven gas and burned in hot-blast stoves to heat the air blown in through the tuyeres. It is important to note that during the process, traces of aluminum, manganese, and silicon from the gangue are oxidized and are recovered into the slag, while phosphorus and sulfur dissolves in the molten iron.

1.1.1.7 Pure Iron Grades

Table 1.1 Pure iron grades

Pure iron grade	Purity (wt% Fe)	Description
Ingot iron	99.8–99.9	Ingot iron is a nearly chemically pure iron type (i.e., 99.8 to 99.9wt% Fe) that is used for construction work where a ductile, rust resistant metal is required. It is mainly applied to boilers, tanks, enameled ware, and galvanized culvert sheets, as well as to electromagnetic cores and as a raw material for producing specialty steels. A well-known commercial type is Armco [®] ingot iron (99.94wt% Fe). Typical ingot irons have as low as 0.02wt% carbon or less. The Armco [®] ingot iron, for example, typically has carbon concentrations of 0.013% and a manganese content around 0.017wt%. Ingot iron may also be obtained in grades containing 0.25 to 0.30wt% copper, which increases the corrosion resistance. Ingot iron is made by the basic open-hearth process and highly refined, remaining in the furnace 1 to 4 h longer than the normal time, and maintained at a temperature of 1600 to 1700°C.
Electrolytic iron	99.9	Electrolytic iron is a chemically pure iron (i.e., 99.9wt% Fe) produced by the cathodic deposition of iron in an electrochemical refining process. Bars of cast iron are used as soluble anodes and dissolved in an electrolyte bath containing iron (II) chloride (FeCl ₂). The cathodic reduction of ferrous cations gives pure iron on the cathodes, which are often hollow steel cylinders. The deposited iron tube is removed by hydraulic pressure or by splitting, and then annealed and rolled into plates. The product is used for magnetic cores and, in general, applications where both high ductility and purity are required.
Reduced iron	99.9	Reduced iron is a fine gray amorphous powder made by reducing crushed iron ore by heating in hydrogen atmosphere. It is used for special chemical purposes.
Carbonyl iron	99.99	Carbonyl iron or carbonyl iron powder is metallic iron of extreme purity, produced as microscopic spherical particles by the reaction of carbon monoxide on iron ore. This reaction gives a liquid, called iron carbonyl Fe(CO) ₅ , which is vaporized and deposited as a powder. Carbonyl iron is mainly used for magnetic cores for high-frequency equipment and for pharmaceutical application of iron.
Wrought iron	99	Wrought iron, which is no longer commercially produced, is a relatively pure iron containing nonmetallic slag inclusions produced by the blast furnace. Modern wrought iron products are actually made of low-carbon steel.

1.1.1.8 The Major Carbon-Iron Phases

Plain carbon steel is an alloy of iron and carbon. Other alloying elements may be added to produce steels for special purposes. As a general rule, the structure of steel is determined by the amounts and nature of alloying materials, and by the rate of cooling from the molten state. Carbon is a strongly reactive element which induces stabilization of the gamma-iron phase. Indeed, carbon is always present owing to its use during the steelmaking process. First of all, it is necessary to describe the structural phases occurring in the structural Fe-C diagram.

Ferrite alpha (ferrite α , bcc) is a solid solution of an insertion of carbon in alpha-iron. For instance, maximum solubility of carbon in alpha-iron is 0.01wt% at room temperature (RT) and 0.02wt% at 727°C. Therefore, a solid solution of which alpha iron is the solvent is called ferrite. Because of the extremely small amount of carbon which it can contain in solid solution, ferrite in a steel that contains only iron and carbon may be considered substantially pure iron, and it is sometimes called pure iron in some textbooks. Because the ferrite of an alloy steel may contain in solid solution appreciable amounts of other elements, however, it is better to use the term only in its exact meaning: a solid solution of any elements in alpha-iron.

Ferrite delta (ferrite δ , bcc) is a solid solution of an insertion of carbon in delta-iron. For instance, maximum solubility of carbon in delta-iron is 0.1wt% at 1487°C.

Cementite (Fe_3C) which is a hard, brittle, and ferromagnetic compound at RT is a chemical combination of excess carbon as iron carbide with 6.68wt% of C. Actually, at RT under conditions of equilibrium, any carbon present in excess of that small amount must exist in a form other than that of a solute in a solid solution.

Austenite gamma (austenite γ , fcc), is a solid insertion solution of carbon in gamma-iron which represents the solvent. The solute consists of iron carbide only, or of any number of other elements. It is definitively established that the carbon atoms in austenite occupy interstitial positions in the fcc space lattice causing the lattice parameter to increase progressively with the carbon content.

Table 1.2 Stabilizing elements

Effect	Alloying elements or impurities
Ferrite stabilizers	C, Cr, Mo, Ti, W, V, Nb, and Si
Austenite stabilizers	Ni, Mn

The various temperatures at which pauses occur in the rise or fall of temperature when steel is heated from room temperature or cooled from the molten state are called **arrest points**. These are identical with the critical or transformation points in the pure iron phase diagram. The arrest points obtained on heating are designated A_c and those obtained on cooling are designated A_r . The suffixes c and r are respectively named after the French words *chauffage* (meaning heating) and *refroidissement* (meaning cooling).

1.1.2 Cast Irons

Cast irons contain much higher carbon and silicon levels than steels, theoretically higher than 1.8wt%, but typically 3–5wt% Fe and 1–3wt% Si. These form another category of ferrous materials, which are intended to be cast from the liquid state to the final desired shape. Various types of cast iron are widely used in industry, especially for valves, pumps, pipes, filters and certain mechanical parts, including:

- Gray cast iron
- White cast iron