9. Iron and Steels

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Whereas the fundamental properties of all metallic elements are covered systematically and comprehensively in Chap. 4, this chapter treats iron as both a base and an alloying element of metallic materials. The properties of metallic materials depend sensitively not only on their chemical composition and on the electronic and crystal structure of the phases formed, but also to a large degree on their microstructure, including the kind and distribution of lattice defects. The phase composition and microstructure of iron is strongly dependent, in turn, on the thermal and mechanical treatments, which are applied under well-controlled conditions to achieve the desired properties.

According to the complexity of the interrelations between the fundamental (intrinsic) and microstructure-dependent (extrinsic) properties of iron, this chapter provides a substantial amount of explanatory text.

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Iron is technically the most versatile and economically the most important base metal for a great variety of structural and magnetic materials, most of which are called steels. With increasing temperature, iron undergoes two structural phase transitions,

$$\alpha\ (\text{bcc}) \leftrightarrow \gamma\ (\text{fcc})\ \text{at}\ 911\,^{\circ}\text{C}$$

and

$$\gamma\ (\text{fcc}) \leftrightarrow \delta\ (\text{bcc})\ \text{at}\ 1392\,^{\circ}\text{C}\ ,$$

and a magnetic phase transition,

$$\alpha_{\text{ferromagnetic}} \leftrightarrow \alpha_{\text{paramagnetic}}\ \text{at}\ 769\,^{\circ}\text{C}\ ,$$

at ambient pressure. At elevated pressure levels, Fe forms a third structural phase ε (hcp). These phase-transitions, their variation upon alloying, and the concomitant phase transformations are the thermodynamic, structural and microstructural basis for the unique variety of iron-based alloys and of their properties [9.1–5].

The wide variety of standards for steels which have developed from national standards and efforts of international standardization are compiled in [9.6]. In the present section we are using different standard designations as provided by the sources used. In the following sections, the SAE (Society of Automotive Engineers), AISI (American Iron and Steel Institute) and UNS (unified numbering system) designations are the dominating ones.

9.1 Phase Relations and Phase Transformations

9.1.1 Iron–Carbon Alloys

The most frequent alloying element of iron is carbon. The Fe-C phase diagram (Fig. 9.1) shows the important metastable phase equilibria involving the metastable carbide Fe_3C, called cementite, in solid gray lines, whereas the stable equlibria with graphite C are shown in solid brown lines. The formation of Fe_3C predominates in most carbon and low-alloy steels because the activation energy of its nucleation is considerably lower than that of graphite. At higher carbon contents (2.5–4.0 wt% C) and in the presence of Si (1.0–3.0 wt% Si), graphite formation is favored. This is the basis of alloying and microstructure of gray cast iron (Sect. 9.7).

The Fe-C phase forms interstitial solid solutions of α- and γ-Fe. The solid solution phase of α-Fe is called ferrite, the solid solution phase based on γ-Fe is called austenite in the binary Fe-C system. These terms for the solid solutions phases of α- and γ-Fe are applied to all other Fe-based alloy systems as well. Since phase transformations induced by cooling from the austenite phase field play a major role to induce particular microstructures and properties, some resulting microstructures have also been given particular terms and form the basis of the nomenclature in steels. Cooling of Fe-C alloys from the austenite phase field can lead to three different phase transformations below the eutectoid temperature of 1009 K (736 °C). Their kinetics of formation depends on composition and cooling rate. The transformation products are:

- Pearlite, a lamellar product of ferrite and cementite. It is formed by a discontinuous (pearlitic) transformation, i. e., both phases are formed side by side in the reaction front. The lamellar spacing decreases with decreasing temperature of formation. The maximum rate of formation occurs at about 500 °C.
- Bainite, a plate- or spearhead-shaped product consisting of a ferrite matrix in which carbide particles are dispersed. The bainitic transformation mechanism depends sensitively on alloy composition and the temperature of transformation, yielding essentially two microstructural variants. A somewhat coarser transformation product formed at about 450 °C is called upper bainite and a finer transformation product formed at about 350 °C is termed lower bainite.
- Martensite, a plate-shaped product formed by a diffusionless, athermal transformation. Thermodynamically it is a metastable ferrite, designated as α' and supersatured in carbon. But by the displacive mechanism of the transformation, the distribution of the C atoms in the martensite lattice is anisotropic such that is has a body-centered tetragonal crystal structure and its c and a parameters vary with the C content accordingly (Fig. 9.2). The temperature below which martensite begins to form upon queching is termed martensite start temperature M_s and depends strongly on the C concentration (Fig. 9.3). M_f designates the temperature at which the transformation is complete. In order to pro-

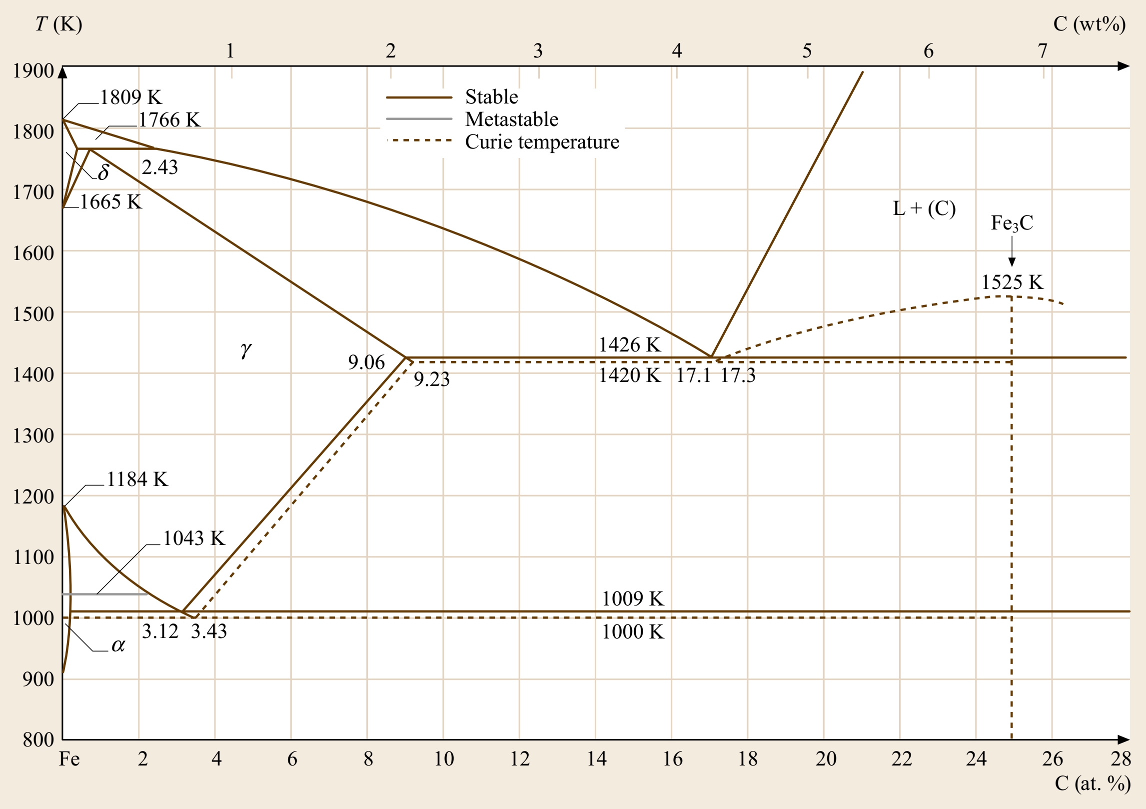

Fig. 9.1 Fe-C phase diagram. Metastable equilibria involving cementite Fe_3C are shown as *solid gray lines*, stable equilibria with graphite C are shown as *solid brown lines* (after [9.7]) (*dashed brown lines* – Curie temperature)

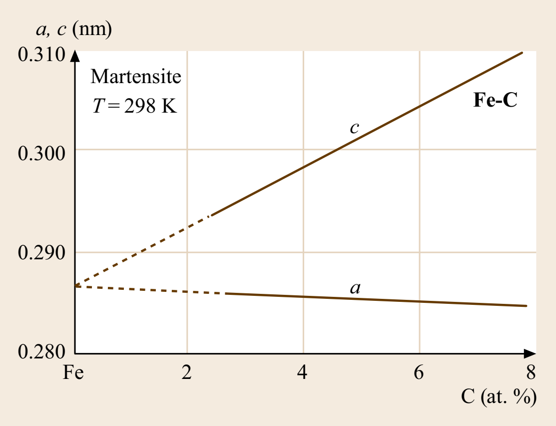

Fig. 9.2 Lattice parameters of Fe-C martensite as a function of composition (after [9.7])

mote the diffusionless martensitic transformation, the diffusion-dependent transformations to pearlite and bainite have to be suppressed by rapid cooling, usually termed quenching.

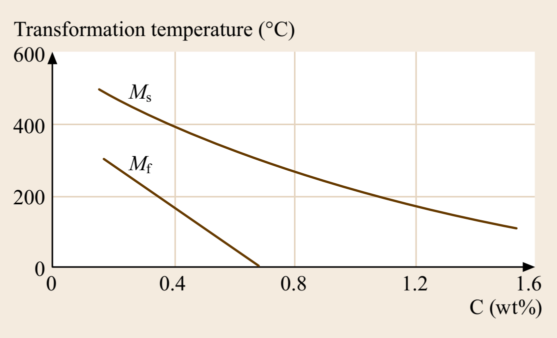

Fig. 9.3 Concentration dependence of the martensite transformation temperatures. M_s – martensite start; M_f – martensite finish, i. e., austenite is transformed completely

Since martensite formation is used as a main hardening mechanism in steels, the hardenability is a main concern of alloy design and consequence of alloy composition. The lower the rate of formation of the diffusion-dependent transformations, the higher is the fraction of martensite formed upon cooling from the austenite range, i. e., the hardenability (Sect. 9.2). The rates of pearlite and bainite formation are reduced by alloying with carbon and all substitutional alloying elements except by Co. But the decrease of M_s with increasing alloy content has, also, to be taken into account.

Subsequent heat treatment of the phases formed is termed annealing with regard to ferrite and bainite, and tempering with regard to martensite. These heat treatments play a major role in optimizing the microstructure to obtain specific properties. Upon subsequent heat treatment the transformation products listed above undergo the following reactions:

- Pearlite is coarsened by the transition of the cementite lamellae into spherical particles, thus reducing the interfacial free energy per unit volume. The process is called spheroidization and consequently the resulting microstructural constituent is termed spheroidite.
- Bainite is coarsened as well both by recovery of the ferrite plates and by coarsening of the carbide particles.
- Martensite is essentially transformed into bcc ferrite by the precipitation of carbide particles during tempering. The tempering treatment usually leads to the precipitation of metastable carbides from the martensite phase. Different metastable carbides may be formed depending on alloy composition (including substitutional alloying elements), temperature, and time of annealing. A compilation of all metastable carbides occurring in Fe-C(-X) alloys is given in Table 9.1.

9.1.2 Heat Treatments

The heat treatments referred to above need to be specified rather succinctly such that they can be correlated with the ensuing microstructures and properties. Furthermore, the specifications of heat treatments require taking the cross section and form of the part to be heat treated into account (at least if the cross sections get larger than, say, 0.5 mm). The finite thermal conductivity and the heat capacity of the material will cause any temperature change applied to the surface to occur at a decreasing rate with increasing depth in the heat-treated part. Thus, not only the time and temperature of an isothermal treatment but also the rate of cooling or the rate of heating are common parameters to be specified. Beyond those referred to above, the following treatments are widely applied to steels.

Austenitizing

Heating to and holding in the range of the austenite phase is commonly the first stage of transformation heat treatments. The higher the austenitizing temperature, the more lattice defects such as dislocations and grain boundaries are annihilated. This lowers the rate of nucleation of subsequent phase transformations.

Soft Annealing

This term is used for heat treatment of hardenable steels containing ≥ 0.4 wt% C at temperatures closely below the eutectoid temperature for a duration of ≤ 100 h. It results in a microstructure of coarse grained, ductile ferrite, and coarsened cementite.

Normalizing

This heat treatment is applied to obtain a uniform, fine-grained microstructure. The first step consists of heating the metal rapidly to, and holding it at a temperature 30–50 K above the $(\alpha+\gamma)/\gamma$ phase boundary (also referred to as the A_{c3} line) for hypo-eutectoid steels, and heating rapidly to and holding at about 50 K above the eutectoid temperature (also referred to as A_{c1} line). This step results in the formation of a fairly fine-grained austenite and ferrite structure in the hypo-eutectoid and in a fine-grained austenite with coagulated grain boundary cementite in the hyper-eutectoid compositions. Upon cooling, the austenite transforms into pearlite and this microstructural state has a favorable combination of strength, ductility, and machinability.

Table 9.1 Metastable and stable carbide phases occurring in the Fe-C(-X) alloy system (after [9.7])

Phase	Structure	Type	*a* (nm)	*b* (nm)	*c* (nm)
Fe_4C	cub		0.3878		
Fe_3C	orth	Fe_3C	0.50889	0.67433	0.452353
ε-Fe_3C	hex		0.273		0.433
$Fe_{2-3}C$	hex		0.4767		0.4354
Fe_5C_2	mon	Mn_5C_2	1.1563	0.4573 $\beta = 97.73°$	0.5058
Fe_7C_3	hex	Th_7Fe_3	0.6882		0.4540
$Fe_{20}C_9$	orth		0.9061	1.5695	0.7937

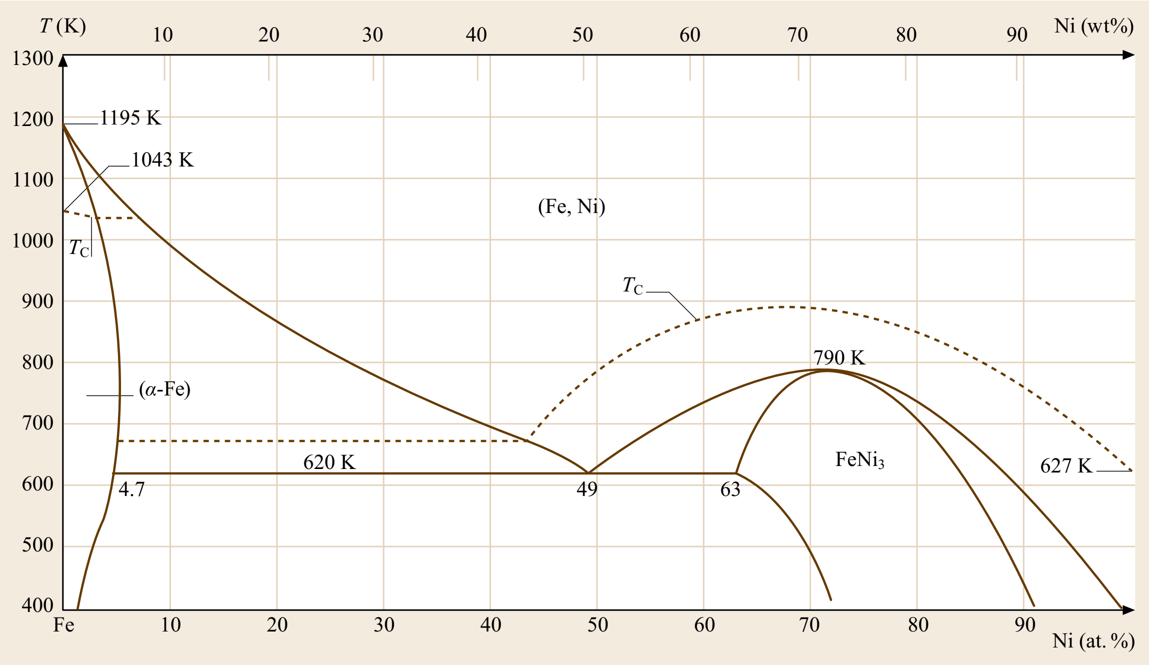

Fig. 9.4 Fe-Ni phase diagram. T_C – Curie temperature (after [9.7])

9.1.3 Substitutional Iron-Based Alloys

For the phase diagrams with substitutional alloying components shown in later sections, a major aspect pertaining to both the binary alloys shown and the steels alloyed with these components is whether the α or the γ phase of Fe is stabilized. i. e., which phase field is expanded or contracted upon alloying.

Fe-Ni

Figure 9.4 shows the Fe-Ni phase equilibria indicating that Ni stabilizes the fcc γ phase. If Fe-rich alloys are quenched from the γ phase field they transform martensitically to bcc α' martensite. The transformation temperatures are shown in Fig. 9.5. The Fe-Ni phase diagram is particularly relevant for the controlled thermal expansion and constant-modulus alloys as well as for the soft magnetic Fe-Ni based materials at higher Ni contents. These, in turn, derive their magnetic properties in part from the occurrence of the superlattice phase FeNi$_3$.

Nickel is added to Fe-C alloys to increase the hardenability and to increase the yield strength of ferrite by solid solution hardening.

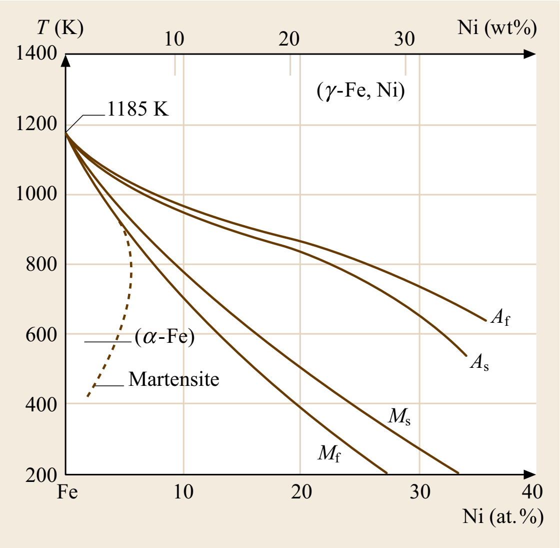

Fig. 9.5 Martensitic transformation temperatures of Fe-rich Fe-Ni alloys. The reverse transformation is characterized by the A_s (austenite start) and A_f (austenite finish) temperatures (after [9.7])

Fe-Mn

Figure 9.6 shows the Fe-Mn phase equilibria indicating that Mn is stabilizing the fcc γ phase similar to Ni. It should be noted that quenching Fe-rich alloys from the γ-phase field leads to two different martensitic transformations which may result in a bcc structure (α' martensite) or an hcp structure (ε' martensite). The transformation temperatures are shown in Fig. 9.7. The martensitic transformation can also be induced

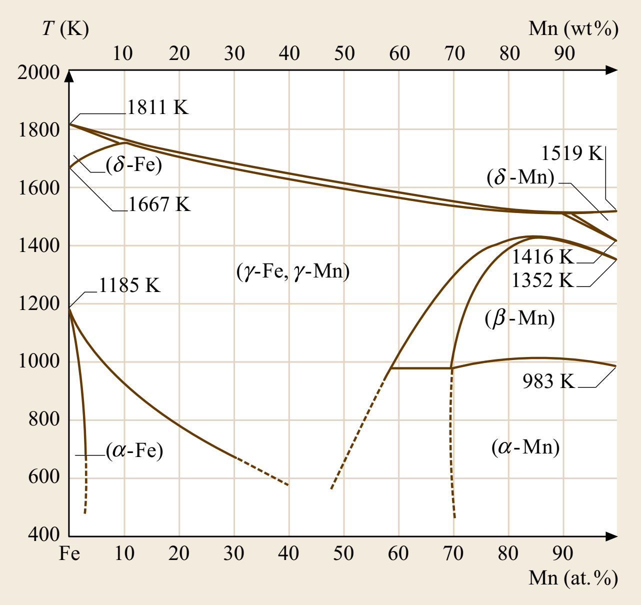

Fig. 9.6 Fe-Mn phase diagram (after [9.7])

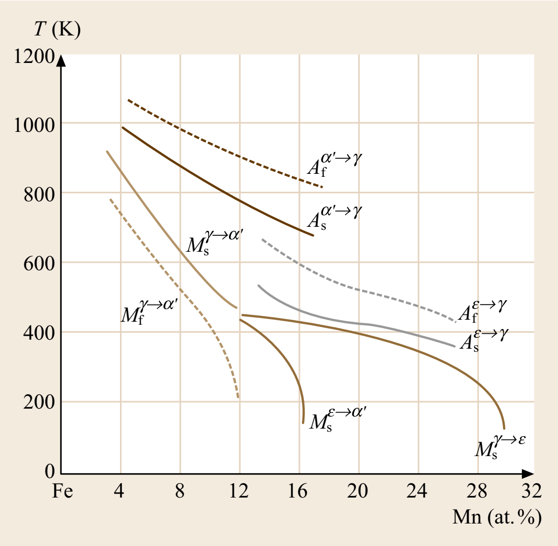

Fig. 9.7 Martensitic transformation temperatures of Fe-rich Fe-Mn alloys. The superscripts indicate the transforming phases (after [9.7])

by deformation. This property is exploited in the design of wear-resistant steels (Hatfield steel: 12 wt% Mn, 1 wt% C).

Manganese is contained in practically all commercial steels because it is used for deoxidation of the melt. Typical contents are 0.3–0.9 wt% Mn. Manganese increases the hardenability of steels and contributes moderately to the yield strength by solid solution hardening.

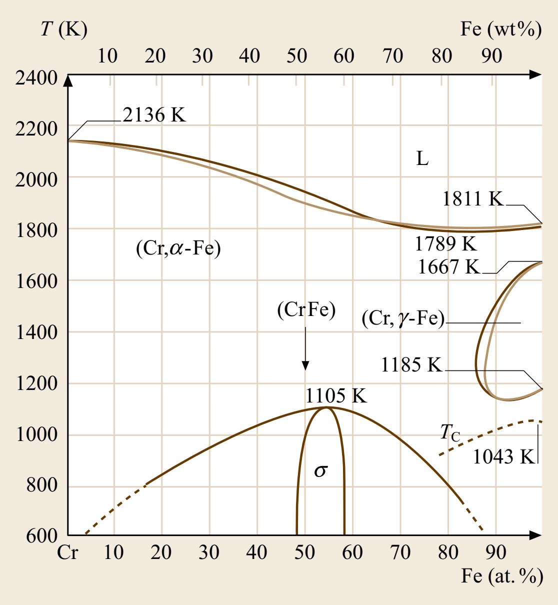

Fig. 9.8 Fe-Cr phase diagram (after [9.7])

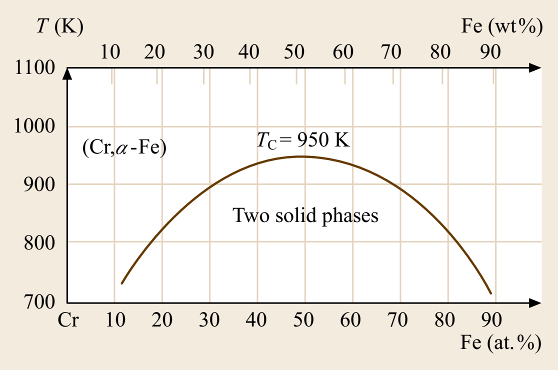

Fig. 9.9 Metastable miscibility gap in the Fe-Cr alloy system (after [9.7])

Fe-Cr

The Fe-Cr phase diagram, Fig. 9.8, is the prototype of the case of an iron-based system with an α-phase stabilizing component. Chromium is the most important alloying element of corrosion resistant, ferritic stainless steels and ferritic heat-resistant steels. If α-Fe-Cr alloys are quenched from above 1105 K and subsequently annealed, they decompose according to a metastable miscibility gap shown in Fig. 9.9. This decomposition reaction can cause severe embrittlement which is called 475 °C-*embrittlement* in ferritic chromium steels. Embrittlement can also occur upon formation of the σ phase.

In carbon steels, Cr is added to increase corrosion and oxidation resistance because it promotes the for-

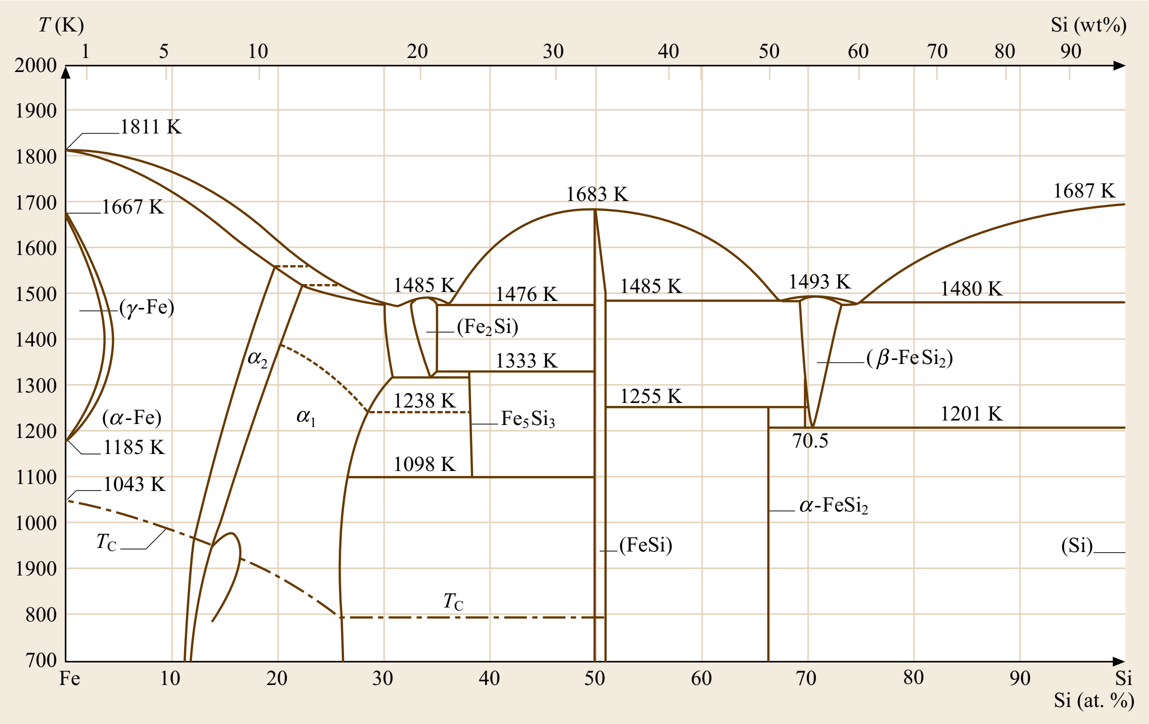

Fig. 9.10 Fe-Si phase diagram (after [9.7])

mation of stable passivating and protective oxide layers. Moreover, Cr is a strong carbide former which modifies and delays the formation of pearlite and bainite, thus increasing the hardenability. In heat-resistant steels Cr contributes to the high-temperature yield strength.

Fe-Si

The phase diagram Fe-Si, Fig. 9.10, shows that Si is a strong ferrite former. The main application of binary Fe-Si alloys is in the form of steels with ≤ 3.5 wt% Si which have an optimum combination of high magnetic moment, low magnetostriction, and low magnetocrystalline anisotropy such that they are the ideal material for high induction and low magnetic power loss applications such as power transformers. Data are given in Chap. 21.

In Fe-C steelmaking, Si is one of the principal deoxidizers. It may amount to 0.05–0.3 wt% Si in the steel depending on the deoxidizing treatment and the amount of other deoxidants used. At these levels of concentration Si contributes only moderately to the strength of ferrite and causes no significant loss of ductility.

9.2 Carbon and Low-Alloy Steels

The largest group of steels produced both by number of variants and by volume is that of carbon and low-alloy steels. It is characterized by the fact that most of the phase relations and phase transformations may be referred to the binary Fe-C phase diagram or comparatively small deviations from it. These steels are treated extensively in [9.5].

9.2.1 Compositions and Properties of Carbon Steels

According to the effect of carbon concentration on the phases formed and on their properties, Fig. 9.11 shows the variation of the effective average mechanical properties of as-rolled 25 mm bars of plain carbon steels as an approximate survey of the typical concentration dependence.

Carbon steels are defined as containing up to 1 wt% C and a total of 2 wt% alloying elements. Apart from the deoxidizing alloying elements Mn and Si, two impurity elements are always present in carbon steels: phosphorous and sulfur. Phosphorus increases strength and hardness significantly by solid solution hardening, but severely decreases ductility and toughness. Only in exceptional cases may P be added deliberately to increase machinability and corrosion resistance. Sulfur has essentially no effect on the strength properties since it is practically insoluble in ferrite. However, it decreases the ductility and fracture toughness. But S is added deliberately along with an increased Mn content to promote the formation of MnS. This compound is formed in small particles which are comparatively soft and serve as effective chip breakers in free-cutting steel grades, thus increasing machinability. On the basis of these effects of the most common alloying and impurity elements, carbon steel compositions are specified as listed in Table 9.2 and free-cutting carbon steel compositions are specified as listed in Table 9.3.

A survey of the alloying elements used and of the ranges of composition applied in carbon and low-alloy steels may be gained from the SAE-AISI system of designations for carbon and alloy steels listed in Table 9.4. Extensive cross references to other standards may be found in [9.6].

Turning to the mechanical properties, it should be emphasized that the microstructure has a decisive influence on the properties of all steels. Therefore the composition and the prior thermal, mechanical, or ther-

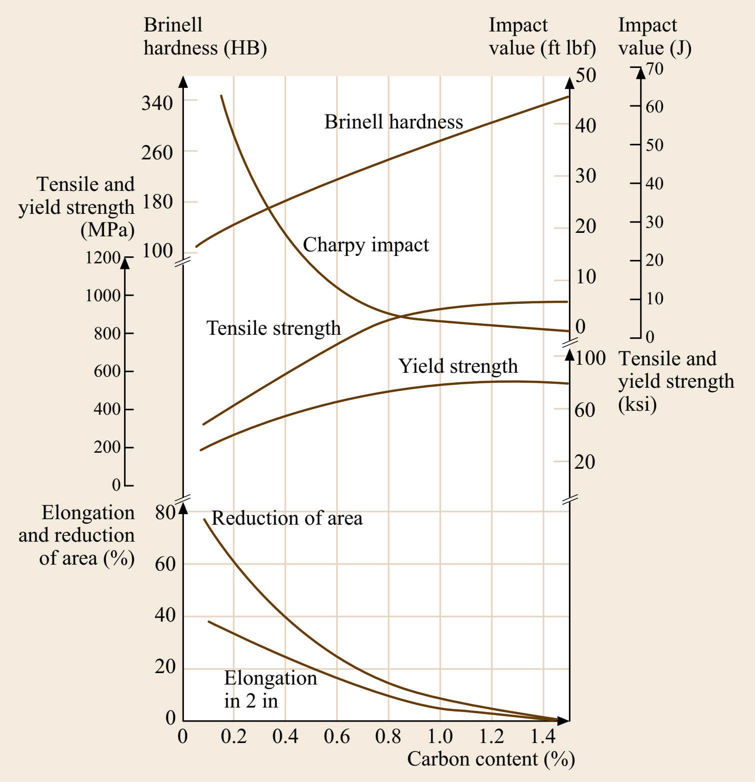

Fig. 9.11 Variations in average mechanical properties of as-rolled 25 mm diameter bars of plain carbon steels as a function of carbon content (after [9.5])

Table 9.2 Standard carbon steel compositions applicable to semi-finished products for forging, hot-rolled and cold-finished bars, wire rods, and seamless tubing (after [9.5]). Selected grades

Designation		**Cast or heat chemical ranges and limits**[a] **(wt%)**			
UN number	**SAE-AISI**	**C**	**Mn**	P_{max}	S_{max}
G10050	1005	0.06 max	0.35 max	0.040	0.050
G10100	1010	0.08–0.13	0.30–0.60	0.040	0.050
G10200	1020	0.18–0.23	0.30–0.60	0.040	0.050
G10300	1030	0.28–0.34	0.60–0.90	0.040	0.050
G10400	1040	0.37–0.44	0.60–0.90	0.040	0.050
G10500	1050	0.48–0.55	0.60–0.90	0.040	0.050
G10600	1060	0.55–0.65	0.60–0.90	0.040	0.050
G10700	1070	0.65–0.75	0.60–0.90	0.040	0.050
G10800	1080	0.75–0.88	0.60–0.90	0.040	0.050
G10900	1090	0.85–0.98	0.60–0.90	0.040	0.050

[a] When silicon ranges or limits are required for bar and semifinished products, the following ranges are commonly used: 0.10% max 0.10%–0.20%; 0.15%–0.35%; 0.20%–0.40%; or 0.30%–0.60%. For rods the following ranges are commonly used: 0.10 max; 0.07%–0.15%; 0.10%–0.20%; 0.15%–0.35%; 0.20%–0.40%; and 0.30%–0.60%. Steels listed in this table can be produced with additions of leaf or boron. Leaded steels typically contain 0.15%–0.40% Pb and are identified by inserting the letter L in the desingnation (10L45); boron steels can be expected to contain 0.0005%–0.003% B and are identified by inserting the letter B in the desingnation (10B46)

Table 9.3 Standard free-cutting (re-sulfurized) carbon steel compositions applicable to semi-finished products for forging, hot-rolled and cold-finished bars, and seamless tubing (after [9.5])

Designation		**Cast or heat chemical ranges and limits**[a] **(wt%)**			
UN number	**SAE-AISI**	**C**	**Mn**	P_{max}	S_{max}
G11080	1108	0.08–0.13	0.85–0.98	0.040	0.08–0.13
G11100	1110	0.08–0.13	0.30–0.60	0.040	0.08–0.13
G11170	1117	0.14–0.20	1.00–1.30	0.040	0.08–0.13
G11180	1118	0.14–0.20	1.30–1.60	0.040	0.08–0.13
G11370	1137	0.32–0.39	1.35–1.65	0.040	0.08–0.13
G11390	1139	0.35–0.43	1.35–1.65	0.040	0.13–0.20
G11400	1140	0.37–0.44	0.70–1.00	0.040	0.08–0.13
G11410	1141	0.37–0.45	1.35–1.65	0.040	0.08–0.13
G11440	1144	0.40–0.48	1.35–1.65	0.040	0.24–0.33
G11460	1146	0.42–0.49	0.70–1.00	0.040	0.08–0.13
G11510	1151	0.48–0.55	0.70–1.00	0.040	0.08–0.13

[a] When lead is required as an added element, a range of 0.15–0.35% is generally used. Such steel is identified by inserting the letter "L" between the 2nd and the 3rd numerals. The following ranges and limits for silicon are commonly used: up to SAE 1110 inclusive, 0.10% max; SAE 1117 and over, 0.10%, 0.10%–0.20%, or 0.15%–0.35%

momechanical treatments which determine the phase transformations and ensuing microstructural state of a steel will always have to be taken into account. Accordingly, tabulated property data will invariably be given with reference to mechanical and thermal treatments applied. The terms used and their specific definitions are outlined in Sect. 9.1.

In plain carbon steels the C content and microstructure are determining the mechanical properties. Manganese is providing moderate solid solution strengthening and increases the hardenability. The properties of plain carbon steels are also affected by the other common residual elements Si, P, and S. Furthermore, the gasses O, N, and H and their reaction products may play a role. Their content depends largely on the melting, deoxidizing and pouring practice. While Fig. 9.11 illustrates the general effect of C content on the mechanical properties if the austenite grain size and transformation microstructure are held essentially constant. Tables 9.5 and 9.6 list the mechanical properties of representative carbon and low alloy steels in specified states as a function of deformation and heat treatment.

9.2.2 Hardenability

Hardening of steels is the heat treatment consisting of heating to the range of austenite, cooling in water, oil, or air, and subsequent tempering. The term hardenabil-

Table 9.4 SAE-AISI system of designations for carbon and low-alloy steels (after [9.5])

Numerals and digits[a]	Type of steel and nominal alloy content (wt%)
Carbon steels	
10xx[a]	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 and 0.80
32xx	Ni 1.75; Cr 1.07
33xx	Ni 3.50; Cr 1.50 and 1.57
34xx	Ni 3.00; Cr 0.77
Molybdenum steels	
40xx	Mo 0.20 and 0.25
44xx	Mo 0.40 and 0.52
Chromium-molybdenum steels	
41xx	Cr 0.50, 0.80, and 0.95; Mo 0.12, 0.20, 0.25, and 0.30
Nickel-chromium-molybdenum steels	
43xx	Ni 1.82; Cr 0.50 and 0.80; Mo 0.25
43BVxx	Ni 1.82; Cr 0.50; Mo 0.12 and 0.25; V 0.03 min
47xx	Ni 1.05; Cr 0.45; Mo 0.20 and 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 0.55; Cr 0.20; Mo 0.20
98xx	Ni 1.00; Cr 0.80; Mo 0.25
Nickel-molybdenum steels	
46xx	Ni 0.85 and 1.82; Mo 0.20 and 0.25
48xx	Ni 3.50; Mo 0.25
Chromium steels	
50xx	Cr 0.27, 0.40, 0.50, and 0.65
51xx	Cr 0.80, 0.87, 0.92, 0.95, 1.00, and 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, and 0.95; V 0.10 and 0.15 min
Tungsten–chromium steels	
72xx	W 1.75; Cr 0.75
Silicon-manganese steels	
92xx	Si 1.40 and 2.00; Mn 0.65, 0.82, and 0.85; Cr 0 and 0.65
Boron steels	
xxBxx	B denotes boron steel
Leaded steels	
xxLxx	L denotes leaded steel
Vanadium steels	
xxVxx	V denotes vanadium steel

[a] The xx in the last two digits of these designations indicates that the carbon content (in hundredths of a weight percent) is to be inserted

ity refers to the suitability of a steel to be transformed partially or completely from austenite to martensite to a specified depth below the free surface of a workpiece when cooled under specified conditions. This definition reflects that the term hardenability does not only refer to the magnitude of hardness which can be attained for a particular steel, but it relates the extent of hardening achievable to the macroscopic or local cooling rate or isothermal holding time in the transformation range and, thus, to the mechanisms, kinetic phase transformations, and their effects on the mechanical properties.

The amount of martensite formed upon cooling is a function of C content and total steel composition. This behavior is due to two decisive factors of influence:

- The temperature range of transformation of austenite to martensite depends on the C content, as shown in Fig. 9.3 of Sect. 9.1.
- The diffusion-dependent transformations of austenite (to ferrite, pearlite, and bainite) compete with the martensitic transformation such that the volume fraction available for the latter will decrease as the volume transformed by the former increases. This transformation kinetics of the diffusional phase transformations is strongly dependent on alloy composition.

The lower the cooling rate may be while still permitting one to obtain a high fraction of martensite, the higher the hardenability of steel. This can best be tested by varying the cooling rate and analyzing the resulting microstructure and its hardness (and other mechanical properties). The method used most widely is an ingeniously simple testing procedure, the Jominy

Table 9.5 Mechanical properties of selected carbon and low-alloy steels in the hot-rolled, normalized, and annealed conditions (after [9.5])

AISI No.[a]	Treatment	Austenitizing temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
1015	As-rolled	–	420.6	313.7	39.0	61.0	126
	Normalized	925	424.0	324.1	37.0	69.6	121
	Annealed	870	386.1	284.4	37.0	69.7	111
1020	As-rolled	–	448.2	330.9	36.0	59.0	143
	Normalized	870	441.3	346.5	35.8	67.9	131
	Annealed	870	394.7	294.8	36.5	66.0	111
1022	As-rolled	–	503.3	358.5	35.0	67.0	149
	Normalized	925	482.6	358.5	34.0	67.5	143
	Annealed	870	429.2	317.2	35.0	63.6	137
1030	As-rolled	–	551.6	344.7	32.0	57.0	179
	Normalized	925	520.6	344.7	32.0	60.8	149
	Annealed	845	463.7	341.3	31.2	57.9	126
1040	As-rolled	–	620.5	413.7	25.0	50.0	201
	Normalized	900	589.5	374.0	28.0	54.9	170
	Annealed	790	518.8	353.4	30.2	57.2	149
1050	As-rolled	–	723.9	413.7	20.0	40.0	229
	Normalized	900	748.1	427.5	20.0	39.4	217
	Annealed	790	636.0	365.4	23.7	39.9	187
1060	As-rolled	–	813.6	482.6	17.0	34.0	241
	Normalized	900	775.7	420.6	18.0	37.2	229
	Annealed	790	625.7	372.3	22.5	38.2	179
1080	As-rolled	–	965.3	586.1	12.0	17.0	293
	Normalized	900	1010.1	524.0	11.0	20.6	293
	Annealed	790	615.4	375.8	24.7	45.0	174
1095	As-rolled	–	965.3	572.3	9.0	18.0	293
	Normalized	900	1013.5	499.9	9.5	13.5	293
	Annealed	790	656.7	379.2	13.0	20.6	192
1117	As-rolled	–	486.8	305.4	33.0	63.0	143
	Normalized	900	467.1	303.4	33.5	63.8	137
	Annealed	855	429.5	279.2	32.8	58.0	121
1118	As-rolled	–	521.2	316.5	32.0	70.0	149
	Normalized	925	477.8	319.2	33.5	65.9	143
	Annealed	790	450.2	284.8	34.5	66.8	131
1137	As-rolled	–	627.4	379.2	28.0	61.0	192
	Normalized	900	668.8	396.4	22.5	48.5	197
	Annealed	790	584.7	344.7	26.8	53.9	174
1141	As-rolled	–	675.7	358.5	22.0	38.0	192
	Normalized	900	706.7	405.4	22.7	55.5	201
	Annealed	815	598.5	353.0	25.5	49.3	163
1144	As-rolled	–	703.3	420.6	21.0	41.0	212
	Normalized	900	667.4	399.9	21.0	40.4	197
	Annealed	790	584.7	346.8	24.8	41.3	167
1340	Normalized	870	836.3	558.5	22.0	62.9	248
	Annealed	800	703.3	436.4	25.5	57.3	207
3140	Normalized	870	891.5	599.8	19.7	57.3	262
	Annealed	815	689.5	422.6	24.5	50.8	197
4130	Normalized	870	668.8	436.4	25.5	59.5	197
	Annealed	865	560.5	360.6	28.2	55.6	156
4140	Normalized	870	1020.4	655.0	17.7	46.8	302
	Annealed	815	655.0	417.1	25.7	56.9	197

Table 9.5 (continued)

AISI No.[a]	Treatment	Austenitizing temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
4150	Normalized	870	1154.9	734.3	11.7	30.8	321
	Annealed	815	729.5	379.2	20.2	40.2	197
4320	Normalized	895	792.9	464.0	20.8	50.7	235
	Annealed	850	579.2	609.5	29.0	58.4	163
4340	Normalized	870	1279.0	861.8	12.2	36.3	363
	Annealed	810	744.6	472.3	22.0	49.9	217
4620	Normalized	900	574.3	366.1	29.0	66.7	174
	Annealed	855	512.3	372.3	31.3	60.3	149
4820	Normalized	860	75.0	484.7	24.0	59.2	229
	Annealed	815	681.2	464.0	22.3	58.8	197
5140	Normalized	870	792.9	472.3	22.7	59.2	229
	Annealed	830	572.3	293.0	28.6	57.3	167
5150	Normalized	870	870.8	529.0	20.7	58.7	255
	Annealed	825	675.7	357.1	22.0	43.7	197
5160	Normalized	855	957.0	530.9	17.5	44.8	269
	Annealed	815	722.6	275.8	17.2	30.6	197
6150	Normalized	815	722.6	275.8	17.2	30.6	197
	Annealed	815	667.4	412.3	23.0	48.4	197
8620	Normalized	915	632.9	357.1	26.3	59.7	183
	Annealed	870	536.4	385.4	31.3	62.1	149
8630	Normalized	870	650.2	429.5	23.5	53.5	187
	Annealed	845	564.0	372.3	29.0	58.9	156
8650	Normalized	870	1023.9	688.1	14.0	40.4	302
	Annealed	795	715.7	386.1	22.5	46.4	212
8740	Normalized	870	929.4	606.7	16.0	47.9	269
	Annealed	815	695.0	415.8	22.2	46.4	201
9255	Normalized	900	932.9	579.2	19.7	43.4	269
	Annealed	845	774.3	486.1	21.7	41.1	229
9310	Normalized	890	906.7	570.9	18.8	58.1	269
	Annealed	845	820.5	439.9	17.3	42.1	241

[a] All grades are fine-grained except for those in the 1100 series, which are coarse-grained. Heat-treated specimens were oil quenched unless otherwise indicated

end-quench test illustrated in Fig. 9.12. The material to be tested is normalized and a test bar 100 mm long and 25 mm in diameter is machined. This specimen is austenitized and transferred to the fixture (shown in Fig. 9.12) holding it vertically 13 mm above the nozzle through which water is directed against the bottom face of the specimen. While the bottom end is quenched by water, the top end is slowly cooled in air and intermediate cooling rates occur at intermediate positions. After the test, hardness readings and microstructural analyses may be taken along the bar. They can be correlated to the pre-determined approximate cooling rate at a given temperature, as shown for a characteristic example in Fig. 9.13.

The hardenability of numerous commonly used steels has been characterised quantitatively by extensive investigations of their transformation behavior as a function of temperature and time. These investigations have been carried out in two modes of heat treatment:

- Quenching from the austenite range to a temperature in the transformation range at which the specimen is held isothermally in a salt or a lead bath for different times, and finally quenched to room temperature to be investigated regarding the transformation products by microstructural and supplementary measurements. The resulting plots of the beginning of formation of the different transformation products (sometimes including the fractional amounts and end of transformation) are termed time-temperature-transformation (TTT) diagram or isothermal transformation (IT) diagrams. An example is shown as Fig. 9.14.

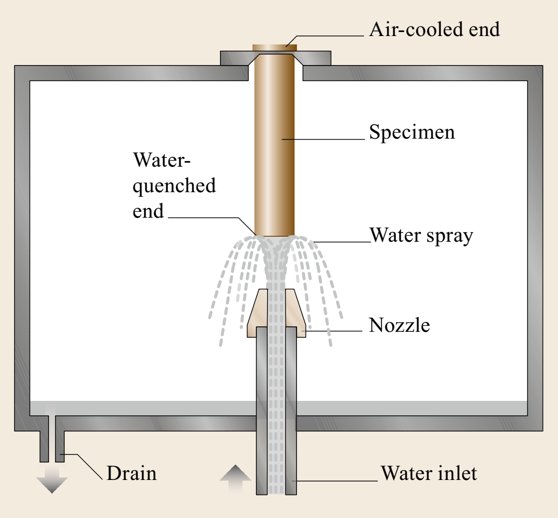

Fig. 9.12 Jominy end-quench apparatus

- Cooling from the austenite range through the transformation range at different cooling rates, and investigating the temperature of onset of transformation of the different products for different cooling rates by microstructural and supplementary measurements, e.g., dilatometry. The resulting plot is called a continuous-cooling-transformation (CCT) diagram. An example is shown in Fig. 9.15. The critical cooling rate means the lowest rate for which a fully martensitic state can be obtained.

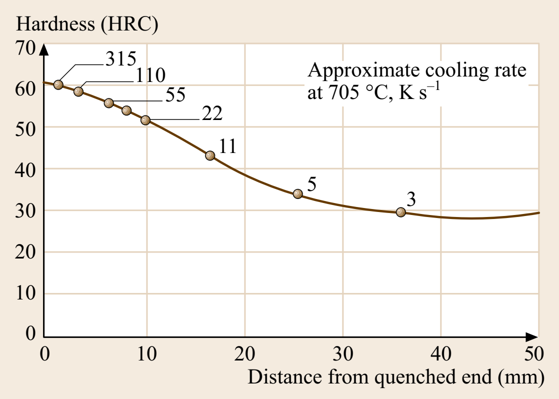

Fig. 9.13 Plot of end-quench hardenability data of an AISI 8650 steel (0.49 wt% C, 0.98 wt% Mn, 0.29 wt% Si, 0.59 wt% Ni, 0.47 wt% Cr, 0.19 wt% Mo) (after [9.5])

Apart from empirical determinations of these transformation diagrams, methods of prediction based on nucleation theory and phenomenological growth theory using the Johnson–Mehl–Avrami equation have been devised to estimate TTT diagrams [9.8].

The hardenability increases with increasing carbon and metallic alloy element concentration (with the exception of Co). The transformation kinetics and ensuing hardenability properties are documented extensively in compilations of TTT and CCT diagrams such as [9.9].

Table 9.6 Mechanical properties of selected carbon and alloy steels in the quenched-and-tempered condition, heat treated as 25 mm rounds (after [9.5])

AISI No.[a]	Tempering temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
1030[b]	205	848	648	17	47	495
	315	800	621	19	53	401
	425	731	579	23	60	302
	540	669	517	28	65	255
	650	586	441	32	70	207
1040[b]	205	896	662	16	45	514
	315	889	648	18	52	444
	425	841	634	21	57	352
	540	779	593	23	61	269
	650	669	496	28	68	201
1040	205	779	593	19	48	262
	315	779	593	20	53	255
	425	758	552	21	54	241
	540	717	490	26	57	212
	650	634	434	29	65	192
1050[b]	205	1124	807	9	27	514
	315	1089	793	13	36	444
	425	1000	758	19	48	375
	540	862	655	23	58	293
	650	717	538	28	65	235

Table 9.6 (continued)

AISI No.[a]	Tempering temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
1050	205	–	–	–	–	–
	315	979	724	14	47	321
	425	938	655	20	50	277
	540	876	579	23	53	262
	650	738	469	29	60	223
1060	205	1103	779	13	40	321
	315	1103	779	13	40	321
	425	1076	765	14	41	311
	540	965	669	17	45	277
	650	800	524	23	54	229
1080	205	1310	979	12	35	388
	315	1303	979	12	35	388
	425	1289	951	13	36	375
	540	1131	807	16	40	321
	650	889	600	21	50	255
1095[b]	205	1489	1048	10	31	601
	315	1462	1034	11	33	534
	425	1372	958	13	35	388
	540	1138	758	15	40	293
	650	841	586	20	47	235
1095	205	1289	827	10	30	401
	315	1262	813	10	30	375
	425	1213	772	12	32	363
	540	1089	676	15	37	321
	650	896	552	21	47	269
1137	205	1082	938	5	22	352
	315	986	841	10	33	285
	425	876	731	15	48	262
	540	758	607	24	62	229
	650	655	483	28	69	197
1137[b]	205	1496	1165	5	17	415
	315	1372	1124	9	25	375
	425	1103	986	14	40	311
	540	827	724	19	60	262
	650	648	531	25	69	187
1141	205	1634	1213	6	17	461
	315	1462	1282	9	32	415
	425	1165	1034	12	47	331
	540	896	765	18	57	262
	650	710	593	23	62	217
1144	205	876	627	17	36	277
	315	869	621	17	40	262
	425	848	607	18	42	248
	540	807	572	20	46	235
	650	724	503	23	55	217
1330[b]	205	1600	1455	9	39	459
	315	1427	1282	9	44	402
	425	1158	1034	15	53	335
	540	876	772	18	60	263
	650	731	572	23	63	216

Table 9.6 (continued)

AISI No.[a]	Tempering temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
1340	205	1806	1593	11	35	505
	315	1586	1420	12	43	453
	425	1262	1151	14	51	375
	540	965	827	14	58	295
	650	800	621	–	66	252
4037	205	1027	758	6	38	310
	315	951	765	14	53	295
	425	876	731	20	60	270
	540	793	655	23	63	247
	650	696	421	29	60	220
4042	205	1800	1662	12	37	516
	315	1613	1455	13	42	455
	425	1289	1172	15	51	380
	540	986	883	20	59	300
	650	793	689	28	66	238
4130[b]	205	1627	1462	10	41	467
	315	1496	1379	11	43	435
	425	1282	1193	13	49	380
	540	1034	910	17	57	315
	650	814	703	22	64	245
4140	205	1772	1641	8	38	510
	315	1551	1434	9	43	445
	425	1248	1138	13	49	370
	540	951	834	18	58	258
	650	758	655	22	63	230
4150	205	1931	1724	10	39	530
	315	1765	1593	10	40	495
	425	1517	1379	12	45	440
	540	1207	1103	15	52	370
	650	958	841	19	60	290
4340	205	1875	1675	10	38	520
	315	1724	1586	10	40	486
	425	1469	1365	10	44	430
	540	1172	1076	13	51	360
	650	965	855	19	60	280
5046	205	1744	1407	9	25	482
	315	1413	1158	10	37	401
	425	1138	931	13	50	336
	540	938	765	18	61	282
	650	786	655	24	66	235
50B46	205	–	–	–	–	560
	315	1779	1620	10	37	505
	425	1393	1248	13	47	405
	540	1082	979	17	51	322
	650	883	793	22	60	273
50B60	205	–	–	–	–	600
	315	1882	1772	8	32	525
	425	1510	1386	11	34	435
	540	1124	1000	15	38	350
	650	896	779	19	50	290

Table 9.6 (continued)

AISI No.[a]	Tempering temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
5130	205	1613	1517	10	40	475
	315	1496	1407	10	46	440
	425	1275	1207	12	51	379
	540	1034	938	15	56	305
	650	793	689	20	63	245
5140	205	1793	1641	9	38	490
	315	1579	1448	10	43	450
	425	1310	1172	13	50	365
	540	1000	862	17	58	280
	650	758	662	25	66	235
5150	205	1944	1731	5	37	525
	315	1737	1586	6	40	475
	425	1448	1310	9	47	410
	540	1124	1034	15	54	340
	650	807	814	20	60	270
5160	205	2220	1793	4	10	627
	315	1999	1772	9	30	555
	425	1606	1462	10	37	461
	540	1165	1041	12	47	341
	650	896	800	20	56	269
51B60	205	–	–	–	–	600
	315	–	–	–	–	540
	425	1634	1489	11	36	460
	540	1207	1103	15	44	355
	650	965	869	20	47	290
6150	205	1931	1689	8	38	538
	315	1724	1572	8	39	483
	425	1434	1331	10	43	420
	540	1158	1069	13	50	345
	650	945	841	17	58	282
81B45	205	2034	1724	10	33	550
	315	1765	1572	8	42	475
	425	1407	1310	11	48	405
	540	1103	1027	16	53	338
	650	896	793	20	55	280
8630	205	1641	1503	9	38	465
	315	1482	1392	10	42	430
	425	1276	1172	13	47	375
	540	1034	896	17	54	310
	650	772	689	23	63	240
8640	205	1862	1669	10	40	505
	315	1655	1517	10	41	460
	425	1379	1296	12	45	400
	540	1103	1034	16	54	340
	650	896	800	20	62	280
86B45	205	1979	1641	9	31	525
	315	1696	1551	9	40	475
	425	1379	1317	11	41	395
	540	1103	1034	15	49	335
	650	903	876	19	58	280

Table 9.6 (continued)

AISI No.[a]	Tempering temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction in area (%)	Hardness (HB)
8650	205	1937	1675	10	38	525
	315	1724	1551	10	40	490
	425	1448	1324	12	45	420
	540	1172	1055	15	51	340
	650	965	827	20	58	280
8660	205	–	–	–	–	580
	315	–	–	–	–	535
	425	1634	1551	13	37	460
	540	1310	1213	17	46	370
	650	1068	951	20	53	315
8740	205	1999	1655	10	41	578
	315	1717	1551	11	46	495
	425	1434	1358	13	50	415
	540	1207	1138	15	55	363
	650	986	903	20	60	302
9255	205	2103	2048	1	3	601
	315	1937	1793	4	10	578
	425	1606	1489	8	22	477
	540	1255	1103	15	32	352
	650	993	814	20	42	285
9260	205	–	–	–	–	600
	315	–	–	–	–	540
	425	1758	1503	8	24	470
	540	1324	1131	12	30	390
	650	979	814	20	43	295
94B30	205	1724	1551	12	46	475
	315	1600	1420	12	49	445
	425	1344	1207	13	57	382
	540	1000	931	16	65	307
	650	827	724	21	69	250

[a] All grades are fine-grained except for those in the 1100 series, which are coarse-grained. Heat-treated specimens were oil quenched unless otherwise indicated; [b] Water quenched

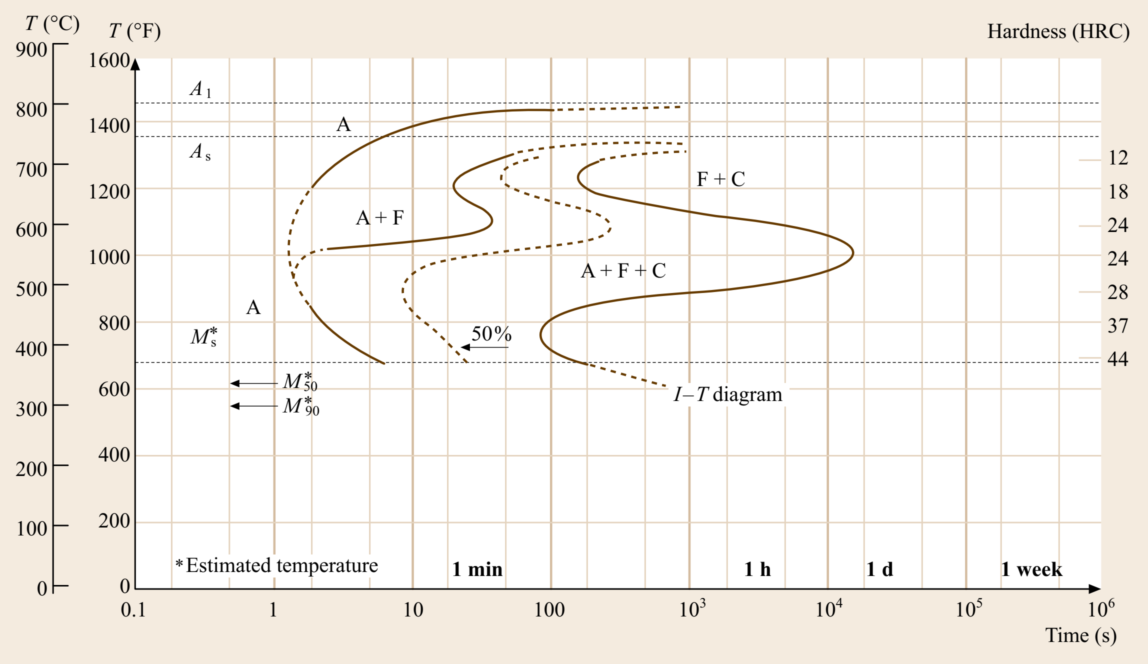

Fig. 9.14 Time-temperature-transformation (TTT) diagram of a 4130 grade low-alloy steel. A – austenite; F – ferrite; C – cementite; M – Martensite (the suffix indicates the amount of martensite formed in vol.%)

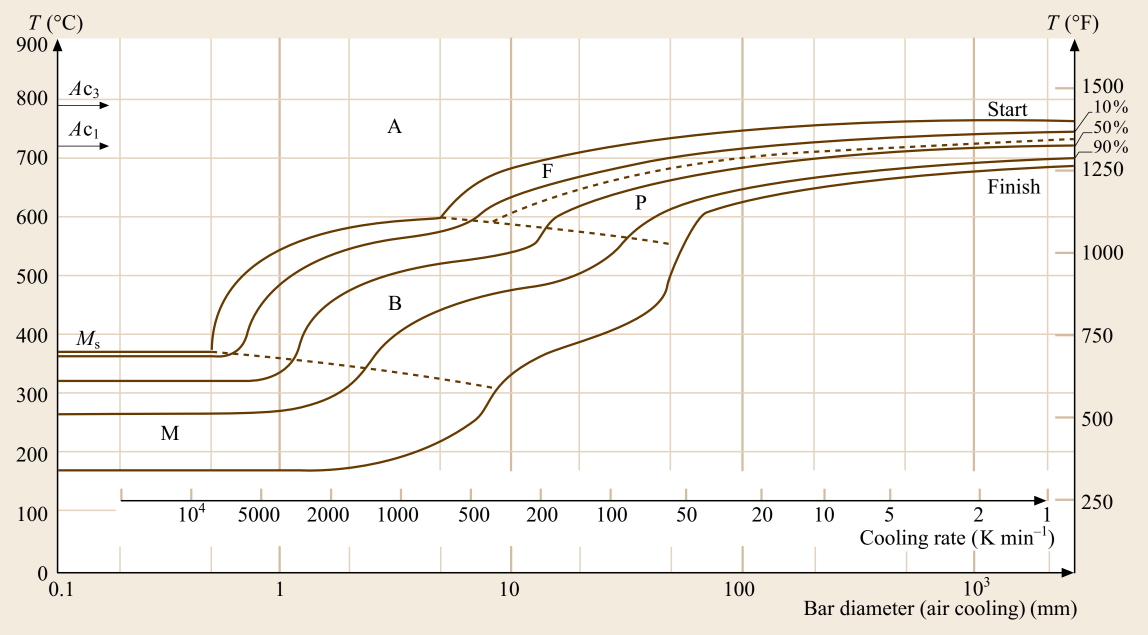

Fig. 9.15 Continuous-cooling-transformation (CCT) diagram for a 4130 grade low-alloy steel. A_{c3} and A_{c1} signify the temperatures of the $\gamma/(\gamma+\alpha)$ and eutectoid reation, respectively. A – austenite, F – ferrite, B – bainite, P – pearlite, M – martensite. The cooling rate is measured at 705 °C. The calculated critical cooling rate is 143 K s^{-1} (after [9.5])

9.3 High-Strength Low-Alloy Steels

High-strength low-alloy (HSLA) steels are designed to provide higher mechanical property values and/or higher resistance to atmospheric corrosion than conventional low-alloy steels of comparable level of alloy content. Higher yield stress is achieved by adding ≤ 0.1 wt% N, Nb, V, Ti, and/or Zr (micro-alloying) which form carbide or carbonitrite precipitates, and by special, closely-controlled processing which yields mostly fine-grained microstructures.

HSLA steels contain 0.05–0.25 wt% C, ≤ 2 wt% Mn and mainly Cr, Ni, Mo, and Cu as further alloying elements. Their yield stress is in the range ≥ 275 MPa. They are primarily hot-rolled into usual wrought product forms and commonly delivered in the as-rolled condition.

The particular processing methods of HSLA steels include [9.5]:

- *Controlled rolling* of micro-alloyed, precipitation hardening variants to obtain fine equiaxial and/or highly deformed, pancake-shaped austenite grains. During cooling these austenite grains transform into fine ferrite grains, providing an optimum combination of high yield strength and ductility.
- *Accelerated cooling* of controlled-rolled steels to enhance the formation of fine ferrite grains.
- *Quenching of steels containing* ≤ 0.08 wt% C such that acicular ferrite or low-carbon bainite is formed. This microstructural state provides an excellent combination of high yield strengths of 275–690 MPa, ductility, formability, and weldability.
- *Normalizing of V-alloyed steel*, thus increasing yield strength and ductility.
- *Intercritical annealing*, i. e., annealing in the $\gamma + \alpha$ phase field to obtain a dual-phase microstructure which, after cooling, consists of martensite islands dispersed in a ferrite matrix. This microstructure exhibits a somewhat lower yield strength but a high rate of work-hardening, providing a better combination of tensile strength, ductility, and formability than conventional HSLA steels.

HSLA steels include numerous standard and proprietary grades designed to provide specific desirable combinations of properties such as strength, ductility, weldability, and atmospheric corrosion resistance. Table 9.7 lists characteristic compositions and Table 9.8 lists mechanical properties of these characteristic variants.

In view of the multitude of compositional and processing variants of HSLA steels it is useful to have a summarizing overview as provided in Table 9.9.

Table 9.7 Compositional limits of HSLA steel grades according to ASTM standards [9.5]

ASTM specification[a]	Type or grade	UNS designation	Heat compositional limits (wt%)[b]									
			C	Mn	P	S	Si	Cr	Ni	Cu	V	Other
A 242	Type 1	K11510	0.15	1.00	0.45	0.05	–	–	–	0.20 min	–	–
A 572	Grade 42	–	0.21	1.35[c]	0.04	0.05	0.30[c]	–	–	0.20 min[d]	–	[e]
	Grade 50	–	0.23	1.35[c]	0.04	0.05	0.30[c]	–	–	0.20 min[d]	–	[e]
	Grade 60	–	0.26	1.35[c]	0.04	0.05	0.30	–	–	0.20 min[d]	–	[e]
	Grade 65	–	0.23[c]	1.65[c]	0.04	0.05	0.30	–	–	0.20 min[d]	–	[e]
A 588	Grade A	K11430	0.10–0.19	0.90–1.25	0.04	0.05	0.15–0.30	0.40–0.65	–	0.25–0.40	0.02–0.10	–
	Grade B	K12043	0.20	0.75–1.25	0.04	0.05	0.15–0.30	0.40–0.70	0.25–0.50	0.20–0.40	0.01–0.10	–
	Grade C	K11538	0.15	0.80–1.35	0.04	0.05	0.15–0.30	0.30–0.50	0.25–0.50	0.20–0.50	0.01–0.10	–
	Grade D	K11552	0.10–0.20	0.75–1.25	0.04	0.05	0.50–0.90	0.50–0.90	–	0.30	–	0.04 Nb, 0.05–0.35 Zr
	Grade K	–	0.17	0.50–1.20	0.04	0.05	0.25–0.50	0.40–0.70	0.40	0.30–0.50	–	0.10 Mo, 0.005–0.05 Nb
A 606	–	–	0.22	1.25	–	0.05	–	–	–	–	–	–
A 607	Grade 45	–	0.22	1.35	0.04	0.05	–	–	–	0.20 min[d]	–	[e]
	Grade 50	–	0.23	1.35	0.04	0.05	–	–	–	0.20 min[d]	–	[e]
	Grade 55	–	0.25	1.35	0.04	0.05	–	–	–	0.20 min[d]	–	[e]
	Grade 60	–	0.26	1.50	0.04	0.05	–	–	–	0.20 min[d]	–	[e]
	Grade 65	–	0.26	1.50	0.04	0.05	–	–	–	0.20 min[d]	–	[e]
	Grade 70	–	0.26	1.65	0.04	0.05	–	–	–	0.20 min[d]	–	[e]
A 618	Grade Ia	–	0.15	1.00	0.15	0.05	–	–	–	0.20 min	–	–
	Grade Ib	–	0.20	1.35	0.04	0.05	–	–	–	0.20 min[f]	–	–
	Grade II	K12609	0.22	0.85–1.25	0.04	0.05	0.30	–	–	–	0.02 min	–
	Grade III	K12700	0.23	1.35	0.04	0.05	0.30	–	–	–	0.02 min	0.005 Nb min[g]
A 633	Grade A	K01802	0.18	1.00–1.35	0.04	0.05	0.15–0.30	–	–	–	–	0.05 Nb
	Grade C	K12000	0.20	1.15–1.50	0.04	0.05	0.15–0.50	–	–	–	–	0.05–0.05 Nb
	Grade D	K02003	0.20	0.70–1.60[c]	0.04	0.05	0.15–0.50	0.25	0.25	0.35	–	0.08 Mo
	Grade E	K12202	0.22	1.15–1.50	0.04	0.05	0.15–0.50	–	–	–	0.04–0.11	0.01–0.05 Nb[d], 0.01–0.03 N
A 656	Type 3	–	0.18	1.65	0.025	0.035	0.60	–	–	–	0.08	0.020 N, 0.005–0.15 Nb
	Type 7	–	0.18	1.65	0.025	0.035	0.60	–	–	–	0.005–0.15	0.020 N, 0.005–0.10 Nb

Table 9.7 (continued)

ASTM specification[a]	Type or grade	UNS designation	Heat compositional limits (wt%)[b]									
			C	Mn	P	S	Si	Cr	Ni	Cu	V	Other
A 690	–	K12249	0.22	0.60–0.90	0.08–0.15	0.05	0.10	–	0.40–0.75	0.50 min	–	–
A 709	Grade 50, type 1	–	0.23	1.35	0.04	0.05	0.40	–	–	–	–	0.005–0.05 Nb
	Grade 50, type 2	–	0.23	1.35	0.04	0.05	0.40	–	–	–	0.01–0.15	–
	Grade 50, type 3	–	0.23	1.35	0.04	0.05	0.40	–	–	–	[h]	0.05 Nb max
	Grade 50, type 4	–	0.23	1.35	0.04	0.05	0.40	–	–	–	[i]	0.015 Nb max
A 715	–	–	0.15	1.65	0.025	0.035	–	–	–	–	Added as necessary	Ti, Nb added as necessary
A 808	–	–	0.12	1.65	0.04	0.05 max or 0.010 max	0.15–0.50	–	–	–	0.10	0.02–0.10 Nb, V + Nb = 0.15 max
A 812	65	–	0.23	1.40	0.035	0.04	0.15–0.50[j]	–	–	–	V + Nb = 0.02–0.15	0.05 Nb max
	80	–	0.23	1.50	0.035	0.04	0.15–0.50	0.35	–	–	V + Nb = 0.02–0.15	0.05 Nb max
A 841	–	–	0.20	[k]	0.030	0.030	0.15–0.50	0.25	0.25	0.35	0.06	0.08 Mo, 0.03 Nb, 0.02 Al total
A 871	–	–	0.20	1.50	0.04	0.05	0.90	0.90	1.25	1.00	0.10	0.25 Mo, 0.15 Zr, 0.05 Nb, 0.05 Ti

[a] For characteristics and intended uses, see Table 9.9; for mechanical properties, see Table 9.8.
[b] If a single value is shown, it is a maximum unless otherwise stated.
[c] Values may vary, or minimum value may exist, depending on product size and mill form.
[d] Optional or when specified
[e] May purchased as type 1 (0.005–0.05 Nb), type 2 (0.01–0.15 V), type 3 (0.05 Nb, max, plus 0.02–0.15 V) or type 4 (0.015 N, max, plus V ≥ 4 N).
[f] If chromium and silicon are each 0.50% min, the copper minimum does not apply.
[g] May be substituted for all or part of V.
[h] Niobium plus vanadium, 0.02 to 0.15%.
[i] Nitrogen with vanadium content of 0.015% (max) with a minimum vanadium-to-nitrogen ratio of 4:1.
[j] When silicon-killed steel is specified.
[k] For plate under 40 mm (1.5 in.), manganese contents are 0.70 to 1.35% or up to 1.60% if carbon equivalents do not exceed 0.47%. For plate thicker than 40 mm (1 to 5 in.), ASTM A 841 specifies manganese contents of 1.00 to 1.60%.

Table 9.8 Tensile properties of HSLA steel grades specified in ASTM standards [9.5]

ASTM specification[a]	Type, grade or condition	Product thickness[b] (mm)	Minimum tensile strength[c] (MPa)	Minimum yield strength[c] (MPa)	Minimum elongation (%)[c] in 200 mm	in 50 mm	Bend radius[c] Longitudinal	Transverse
A242	Type 1	20	480	345	18	–	–	–
		20–40	460	315	18	21	–	–
		40–100	435	290	18	21	–	–
A572	Grade 42	150	415	290	20	24	[d]	–
	Grade 50	100	450	345	18	21	[d]	–
	Grade 60	32	520	415	16	18	[d]	–
	Grade 65	32	550	450	15	17	[d]	–
A588	Grades A–K	100	485	345	18	21	[d]	–
		100–125	460	315	–	21	[d]	–
		125–200	435	290	–	21	[d]	–
A606	Hot rolled	sheet	480	345	–	22	t	$2t-3t$
	Hot rolled and annealed or normalized	sheet	450	310	–	22	t	$2t-3t$
	Cold rolled	sheet	450	310	–	22	t	$2t-3t$
A607	Grade 45	sheet	410	310	–	22–25	t	$1.5t$
	Grade 50	sheet	450	345	–	20–22	t	$1.5t$
	Grade 55	sheet	480	380	–	18–20	$1.5t$	$2t$
	Grade 60	sheet	520	415	–	16–18	$2t$	$3t$
	Grade 65	sheet	550	450	–	15–16	$2.5t$	$3.5t$
	Grade 70	sheet	590	485	–	14	$3t$	$4t$
A618	Ia, Ib, II	19	485	345	19	22	$t-2t$	–
	Ia, Ib, II, III	19–38	460	315	18	22	$t-2t$	–
A633	A	100	430–570	290	18	23	[d]	–
	C, D	65	485–620	345	18	23	[d]	–
	C, D	65–100	450–590	315	18	23	[d]	–
	E	100	550–690	415	18	23	[d]	–
	E	100–150	515–655	380	18	23	[d]	–
A656	50	50	415	345	20	–	[d]	–
	60	40	485	415	17	–	[d]	–
	70	25	550	485	14	–	[d]	–
	80	20	620	550	12	–	[d]	–
A690	–	100	485	345	18	–	$2t$	–
A709	50	100	450	345	18	21	–	–
	50W	100	450	345	18	21	–	–
A715	Grade 50	sheet	415	345	–	22–24	0	t
	Grade 60	sheet	485	415	–	20–22	0	t
	Grade 70	sheet	550	485	–	18–20	t	$1.5t$
	Grade 80	sheet	620	550	–	16–18	t	$1.5t$
A808	–	40	450	345	18	22	–	–
		40–50	450	315	18	22	–	–
		50–65	415	290	18	22	–	–
A812	65	sheet	585	450	–	13–15	–	–
	80	sheet	690	550	–	11–13	–	–
A841	–	65	485–620	345	18	22	–	–
		65–100	450–585	310	18	22	–	–
A871	60, as-hot-rolled	5–35	520	415	16	18	–	–
	65, as-hot-rolled	5–20	550	450	15	17	–	–

[a] For characteristics and intended uses, see Table 9.9 for specified composition limits, see Table 9.7

[b] Maximum product thickness exept when a range is given. No thickness are specified for sheet products.

[c] May vary with product size and mill form

[d] Optional supplementary requierement given in ASTM A6

Table 9.9 Summary of characteristics and uses of HSLA steels according to ASTM standards [9.5]

ASTM specification[a]	**Title**	**Alloying elements**[b]	**Avalible mill forms**	**Special characteristics**	**Intended uses**
A 242	High-strength low-alloy structural steel	Cr, Cu, N,Ni, Si, Ti, V, Zr	Plate, bar, and shapes $\le$ 100 mm in thickness	Atmospheric-corrosion resistance four times of carbon steel	Structural members in welded, bolted, or riveted construction
A 572	High-strength low-alloy niobium-vanadium steel of structural quality	Nb, V, N	Plate, bar, and sheet piling $\le$ 150 mm in thickness	Yield strength of 290 to 450 MPa in six grades	Welded, bolted, or riveted structures, but many bolted or riveted bridges and buildings
A 588	High-strength low-alloy structural steel with 345 MPa minimum yield point $\le$ 100 mm in thickness	Nb, V, Cr, Ni, Mo, Cu, Si, Ti, Zr	Plate, bar, and shapes $\le$ 200 mm in thickness	Atmospheric-corrosion resistance four times of carbon steel; nine grades of similar stregth	Welded, bolted, or riveted structures, but primarily welded bridges and buildings in which weight savings or added durability is important
A 606	Steel sheet and strip hot-rolled steel and cold-rolled, high-stren low-alloy with improved corrosion resistance	Not specified	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion twice that of carbon steel (type 2) or fou times of carbon steel (type 4)	Structural and miscellaneous purposes for which weight savings or added durability is important
A 607	Steel sheet and strip hot-rolled steel and cold-rolled, high-strength low-alloy niobium and/or vanadium	Nb, V, N, Cu	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion twice that of carbon steel, but only when copper content is specified; yield strength of 310 to 485 MPa in six grades	Structural and miscellaneous purposes for which greater strength or weight savings is important
A 618	Hot formed welded and seamless high-strength low-alloy structural tubing	Nb, V, Si, Cu	Square, rectangular round and special-shape structural welded or seamless tubing	Three grades of similar yield strength; may be purchased with atmospheric-corrosion resistance twice that of carbon steel	General structural purposes include welded, bolted or riveted bridges and buildings
A 633	Normalized high-strength low-alloy structural steel	Nb, V, Cr, Ni, Mo, Cu, N, Si	Plate, bar, and shapes $\le$ 150 mm in thickness	Enhanced notch toughness; yield strength of 290 to 415 MPa in five grades	Welded, bolted, or riveted structures for service at temperatures at or above −45 °C
A 656	High strength low-alloy, hot rolled structural vanadium-aluminium-nitrogen and titanium-aluminium steels	V, Al, N, Ti, Si	Plate, normally $\le$ 16 mm in thickness	Yield strength of 552 MPa	Truck frames, brackets, crane booms, rail cars and other applications for witch weight savings is important
A 690	High-strength low-alloy steel H-piles and sheet piling	Ni, Cu, Si	Structural-quality H-pills and sheet piling	Corrosion resistance two to three times greater than that of carbon steel in the splash zone of marine marine structures	Dock walls, sea walls Bulkheads, excavations and similar structures exposed to seawater
A 709, grade 50 and 50W	Structural steel	V, Nb, N, Cr, Ni, Mo	All structural-shape groups and plate $\le$ 100 mm in thickness	Minimum yield strength of 345 MPa, Grade 50W is a weathering steel	Bridges
A 714	High-strength low-alloy welded and seamless steel pipe	V, NI, Cr, Mo, Cu, Nb	Pipe with nominal pipe size diameters of 13 to 660 mm	Minimum yield strength of $\le$ 345 MPa and corrosion resistance two or four times that of carbon steel	Piping

Table 9.9 (continued)

ASTM specification[a]	Title	Alloying elements[b]	Avalible mill forms	Special characteristics	Intended uses
A 715	Steel sheet and strip hot-rolled. high-strength low-alloy with improved formability	Nb, V, Cr, Mo, N, Ti, Zr, B	Hot-rolled sheet and strip	Improved formability[c] compared to a A 606 and A 607; yield strength of 345 to 550 MPa in four grades	Structural and miscellaneous applications for which high strength, weight savings, improved formability and good weldability are important
A 808	High-strength low-alloy steel with improved notch toughness	V, Nb	Hot-rolled plate $\leq$ 65 mm in thickness	Charpy V-notch impact energies of 40–60 J (40–60 ft lfb) at −45 °C	Railway tank cars
A 812	High-strength low-alloy steels	V, Nb	Steel sheet in coil form	Yield strength of 450–550 MPa	Welded layered pressure vesels
A 841	Plate produced by themomechanical controlled processes	V, Nb, Cr, Mo, Ni	Plates $\leq$ 100 mm in thickness	Yield strength of 310–345 MPa	Welded pressure vessels
A 847	Cold formed welded and seamless high-strength low-alloy structural rubing with improved atmospheric corrosion resistance	Cu, Cr, Ni, Si, V, Ti, Zr, Nb	Welded rubing with maximum periphery of 1625 mm and wall thickness of 16 mm or seamless tubing with maximum periphery of 810 mm and wall thickness of 13 mm	Minimum yield strength $\leq$ 345 MPa with atmosphieric-corrosion twice that of carbon steel	Round, square, or specially shaped structural tubing for welded, riveted or bolted construction of bridges and buildings
A 860	High-strength butt-welding fittings of wrought high-strength low-alloy steel	Cu, Cr, Ni, Mo, V, Nb, Ti	Normalized or quenched-and-tempered wrought fittings	Minimum yield strength $\leq$ 485 MPa	High-pressure gas and oil transmission lines
A 871	High-strength low-alloy steel with atmospheric corrosion resistance	V, Nb, Ti, Cu, Mo, Cr	As-rolled plate $\leq$ 35 mm in thickness	Atmosperic-corrosion resistance four times that of carbon structural steel	Tubular structures and poles

[a] For grades and mechanical properties, see Table 9.8.

[b] In addition to carbon, manganese, phosphorus, and sulfur. A given grade may contain one or more of the listed elements, but not necessarily all of them; for specified compositional limits, see Table 9.7.

[c] Obtained by producing killed steel, made to fine grain practice, and with microalloying elements such as niobium, vanadium titanium, and zirconium in the composition.

9.4 Stainless Steels

Stainless steels are treated extensively in [9.4]. Compared to carbon or low-alloy steels, they are characterized by an increased resistance against corrosion in aggressive media. The corrosion resistance is achieved basically by an alloy content of at least 11–12 wt% Cr. This content is required to form a dense, pore-free protective surface layer consisting mainly of chromium oxides and hydroxides. The corrosion resistance can be further increased by additional alloying with elements such as Ni, Mo, W, Mn, Si, Cu, Co, Al, or N.

Since chromium has a high affinity to carbon, the formation of chromium carbides may reduce the local concentration of Cr in solution and thus deteriorate the corrosion resistance. This can be avoided by:

- Low carbon content of the steel
- Suitable heat treatment
- Bonding of carbon by other elements with higher carbon affinity, such as Ti and Nb, so-called stabilization.

Similar effects can be attained by the formation of chromium nitrides. Thus, in addition to the chemical composition of the steel, its corrosion properties are strongly influenced by its heat treatment condition.

Depending on the intended field of application, the corrosion resistance of the steel must often be combined with other useful properties such as high strength or hardness, high temperature strength, good formability, low temperature fracture toughness, weldability or machinability. However, since optimization of one property is generally only possible at the expense of others, the property spectrum of a stainless steel is often the result of a compromise. Consequently, a large number of steel grades has been developed to meet different property requirements. Some steels have been developed just for a single application. The following section gives typical representatives of the various types of stainless steel grades.

Depending on alloy composition and cooling conditions from elevated temperature, stainless steels may occur in different types of microstructure:

- Ferritic (bcc)
- Austenitic (fcc)
- Martensitic
- Mixtures of two or all three of these phases.

The bcc structure is promoted by the ferrite forming elements Cr, Mo, W, Ti, V, Nb, Al, and Si, whereas the fcc structure is promoted by the austenite forming elements C, N, Ni, Mn, Cu, and Co. All alloying elements suppress the austenite to martensite transformation by reducing the M_s temperature, so that the steel may remain fcc at and below room temperature at a sufficiently high alloy content. For a rough estimate of the structural components of a stainless steel as a function of alloy composition, the so-called Schaeffler diagram (initially determined by M. Strauss and E. Maurer in 1920) can be used (Fig. 9.16) [9.2]. It relates the equivalent Cr and Ni content to the observed fractions of martensite, austenite, and ferrite. One of the formulas of the Ni and Cr equivalent used most frequently is that of *Schneider* [9.10] (in wt%)

$$\begin{aligned}\mathrm{Cr}_{\mathrm{equ}} &= \mathrm{Cr} + 2\,\mathrm{Si} + 1.5\,\mathrm{Mo} + 5\,\mathrm{V}\\ &\quad + 5.5\,\mathrm{Al} + 1.5\,\mathrm{Ti} + 0.7\,\mathrm{W}\,, \qquad (9.1)\\ \mathrm{Ni}_{\mathrm{equ}} &= \mathrm{Ni} + \mathrm{Co} + 0.5\,\mathrm{Mn} + 0.3\,\mathrm{Cu}\\ &\quad + 25\,\mathrm{N} + 30\,\mathrm{C}\,. \qquad (9.2)\end{aligned}$$

9.4.1 Ferritic Chromium Steels

High chromium (≥ 18 wt% Cr) and low carbon concentrations result in a fully ferritic structure of the steels at all temperatures, i. e., with a bcc delta ferrite structure and no phase transformations. Therefore these steels cannot be strengthened by quenching and tempering. The possibility to increase strength by cold deformation is limited since it decreases ductility and toughness. Steels containing < 18 wt% Cr form some austenite during heating which can be transformed into martensite by fast cooling, thus strengthening the steel. A tempering treatment just below A_{r1} results in a mixture of δ-ferrite, α-ferrite, and carbides formed from tempered martensite.

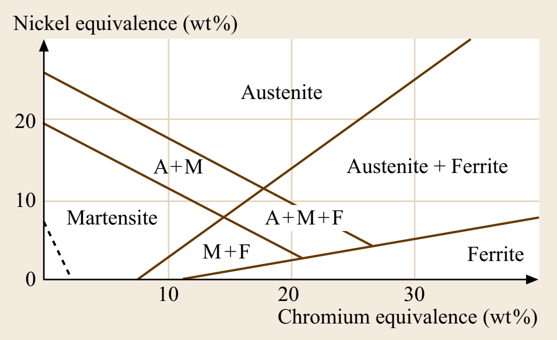

Fig. 9.16 Structure of iron-based alloys as a function of the concentrations of the chromium and nickel equivalent elements. A: austenite (fcc); F: ferrite (bcc); M: martensite (tetragonal-bcc) (after [9.2])

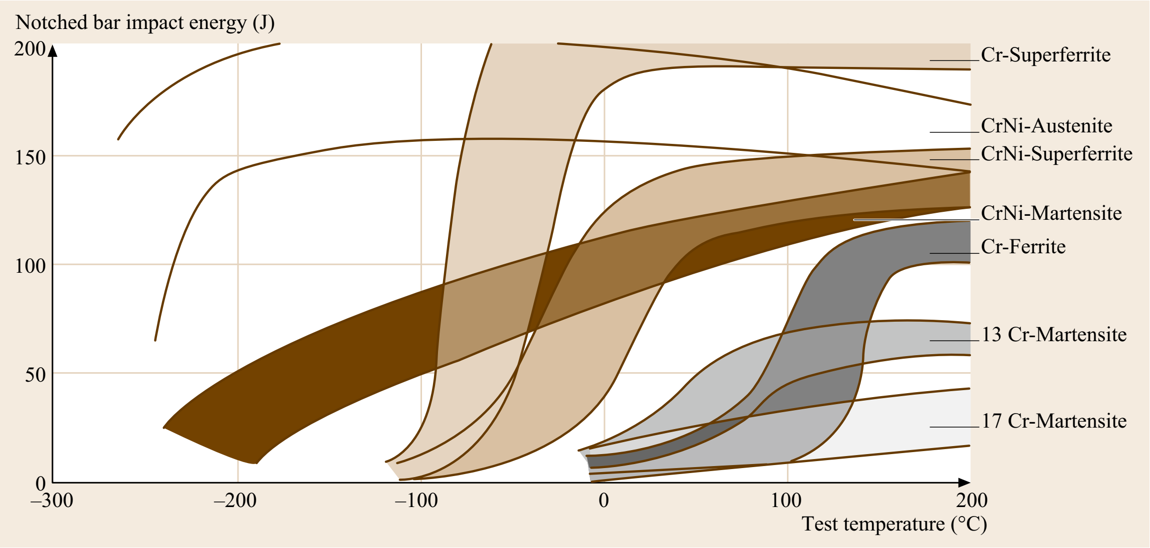

Fig. 9.17 Notched bar impact energy as a function of test temperature of various types of stainless steels (DVM samples: dimension $10 \times 10 \times 55\,\text{mm}^3$, notch depth 3 mm, notch root radius 1 mm)

In general the toughness of the conventional stainless ferritic chromium steels is not very high, the impact transition temperature often being at or above room temperature and reaching 100 °C after welding (see curve Cr-Ferrite in Fig. 9.17). This is due to (i) the tendency of the ferritic stainless steels to pronounced grain coarsing on heat treatments, leading to a relatively large grain size (which cannot be refined by phase transformation), and (ii) the precipitation of chromium carbides at the grain boundaries. Both effects render the steel rather brittle after welding. Furthermore, precipitation of chromium carbides at the grain boundaries causes susceptibility to intergranular corrosion due to the formation of zones with local chromium depletion along the grain boundaries. Some improvement can be achieved (i) by quenching or a suitable diffusion heat treatment for equilibration of the chromium distribution, and (ii) by a stabilization of the steels with small amounts of Ti and/or Nb which are added to bind the carbon and nitrogen in more stable compounds. In unstabilized steels the carbon content is generally restricted to ≤ 0.1 wt%. Up to 2 wt% Mo improves the corrosion resistance of ferritic chromium steels, especially in chloride-containing media.

In Table 9.10 the chemical composition of a number of ferritic stainless steels is given. The most common representative is the grade X6Cr17/AISI 430. Table 9.11 presents some information on hot deformation and recommended heat treatment parameters. Tables 9.12 and 9.13 show typical data of the mechanical and physical properties, respectively, and Table 9.14 reviews the weldability of these steels. With respect to their magnetic behavior, in the annealed state the ferritic stainless steels can be considered in general to be soft magnetic materials, suitable e.g., for automotive applications.

Good ductility and toughness at sub-zero temperatures can be achieved when the carbon and nitrogen content in ferritic steels is reduced to very low concentrations (below 100 ppm) (see curve Cr-superferrite in Fig. 9.17). With higher alloy concentrations in the order of 26–30 wt% Cr, up to 2 wt% Mo, and up to 4 wt% Ni, these so-called superferritic steels exhibit excellent corrosion properties, i. e., high resistance against transcrystalline stress corrosion cracking and chloride-induced pitting corrosion, as well as intercrystalline and general corrosion. However, in order to maintain the low C and N contents even after welding, an effective inert gas shielding is required during welding as it is known for welding of Ti. Obviously, the high purity requirements which have to be observed during melting, hot forming and welding, and some embrittling effects which occur in high Cr steels after lengthy high temperature exposure (475 °C embrittlement and σ-phase formation) have precluded as yet a wider application of these steels, in spite of their attractive properties. In addition to their good corrosion resistance these steels possess a higher thermal conductivity than austenitic stainless steels, which is of special interest in heat exchanger applications, and a lower rate of work hardening on cold deformation.

Table 9.10 Chemical composition of ferritic stainless steels

Grade no. (EN10088)	Steel designation	ASTM A 276/ AISI grade/ UNS grade	Chemical composition (wt%)							
			C	Si	Mn	S	P	Cr	Mo	Others
1.4003	X2CrNi12		≤ 0.03	≤ 1	≤ 1.5	≤ 0.015	≤ 0.040	10.5–12.5		Ni 0.3–1.0, N ≤ 0.03
1.4016	X6Cr17	430	≤ 0.08	≤ 1	≤ 1	≤ 0.03	≤ 0.040	16–18		
1.4104	X14CrMoS17	430F	0.10–0.17	≤ 1.5	≤ 1	0.15–0.35	≤ 0.06	15.5–17.5	0.2–0.6	
1.4105	X6CrMoS17		≤ 0.08	≤ 1.5	≤ 1	0.15–0.35	≤ 0.06	16–18	0.2–0.6	
1.4509	X2CrTiNb18	411,444	≤ 0.03		≤ 1			17.5–18.5		Ti 0.1–0.6, Nb3 × C + 0.3 up to 1.0
1.4510	X3CrTi17	430Ti,439	≤ 0.05	≤ 1	≤ 1	≤ 0.03	≤ 0.045	16–18		Ti 4 × (C + N) + 0.15 up to 0.8
1.4511	X3CrNb17		≤ 0.05	≤ 1	≤ 1	≤ 0.03	≤ 0.045	16–18		Nb ≤ 12 × % C, up to 1.0%
1.4113	X6CrMo17-1	434	≤ 0.08	≤ 1	≤ 1	≤ 0.03	≤ 0.045	16–18	0.9–1.4	
1.4520	X2CrTi17		≤ 0.025	≤ 0.5	≤ 0.5	≤ 0.020	≤ 0.025	16–18		Ti 0.3–0.6, N < 0.015
1.4521	X2CrMoTi18-2	444 S44400	≤ 0.025	≤ 1	≤ 1	≤ 0.03	≤ 0.04	17–20	1.8–2.5	Ti 4 × (C + N) + 0.15 up to 0.8, N ≤ 0.03
	X20Cr20	442	≤ 0.2	≤ 1	≤ 1	≤ 0.03	≤ 0.04	18–23		
1.3810	X20Cr25	446	≤ 0.25	≤ 0.5–2.0	≤ 0.5	≤ 0.03	≤ 0.04	23–27		
	X1CrMo26-1	XM27 S44627	≤ 0.01	≤ 0.4	≤ 0.4	≤ 0.02	≤ 0.02	25–28	0.75–1.5	N ≤ 0.006
	X1CrMo29-4	S44700	≤ 0.01	≤ 0.2	≤ 0.3	≤ 0.02	≤ 0.025	28–30	3.5–4.2	Ni ≤ 0.15, N ≤ 0.02
	X1CrMo29-4-2	S44800	≤ 0.01	≤ 0.2	≤ 0.3	≤ 0.02	≤ 0.025	28–30	3.5–4.2	Ni 2.0–2.5, N ≤ 0.02
[a]	X2CrMoNiTi25-4-4		0.012	0.04	0.3	0.006		25	4	Ni 4, Ti 0.4

[a] Typical values

Table 9.11 Heat treatment conditions of ferritic stainless steels

Grade no.	Rolling and forging (°C)	Soft annealing		
		Temperature (°C)	Time (min)	Cooling
1.4003	1180–1000	700–760	20–30	Air/water
1.4016	1100–800	770–830	20–30	Air/water
1.4104	1100–800	750–825	120–180	Air/furnace
1.4105	1100–800	750–825		Air/water
1.4510	1100–800	770–830	20–30	Air/water
1.4511	1050–750	790–850	20–30	Air/water
1.4113	1050–750	790–850	20–30	Air/water
1.4520	1100–800	820–880	20–30	Air/water
1.4521	1150–750	820–880		Air/water
X1CrMo26-1	1150–750	750–900		Air/water
X1CrMo29-4	1100–800	750–800	120–360	Air/furnace
X1CrMoNi29-4-2	1150–750	750–800	15–30	Air
X2CrMoNiTi25-4-4	1100–800	730–780	120–360	Air/furnace

Table 9.12 Mechanical properties of ferritic stainless steels

Grade no.	Heat treatment condition	Tensile properties of flat products $\leq$ 25 mm in thickness		
		Min. yield strength or 0.2% proof strength (MPa)	Ultimate tensile strength (MPa)	Min. fracture elongation A_5 (%)
1.4003	Annealed	260	450–550	20
1.4016	Annealed	260	430–630	20
1.4104	Annealed	300	540–740	15
1.4105	Annealed	250	430–630	20
1.4510	Annealed	240	420–600	23
1.4511	Annealed	240	420–600	23
1.4113	Annealed	280	450–630	18
1.4520	Annealed	200	380–530	24
1.4521	Annealed	300	420–620	20
X1CrMo26-1	Annealed	275	$\geq$ 450	22
X1CrMo29-4	Annealed	415	$\geq$ 550	20
X1CrMoNi29-4-2	Annealed	415	$\geq$ 550	20
X2CrMoNiTi25-4-4	Annealed	550[a]	650[a]	20[a]

[a] Typical values

Table 9.13 Physical properties of ferritic stainless steels

Grade no.	Mean thermal expansion coefficient between 20 °C and T (°C) in $10^{-6}\,\mathrm{K}^{-1}$				Density ($\mathrm{kg\,dm^{-3}}$)	Heat conductivity at 20 °C ($\mathrm{W\,m^{-1}\,K^{-1}}$)	Specific heat at 20 °C ($\mathrm{J\,g^{-1}\,K^{-1}}$)	Electrical resistivity at 20 °C ($\Omega\,\mathrm{mm^2\,m^{-1}}$)	Modulus of elasticity ($\mathrm{kN\,mm^{-2}}$)	Magne-tizable
	100	200	300	400						
1.4003	10.4	10.8	11.2	11.8	7.7	25	0.43	0.60	220	Yes
1.4016	10.0	10.0	10.5	10.5	7.7	25	0.46	0.60	220	Yes
1.4104	10.0	10.5	10.5	10.5	7.7	25	0.46	0.70	216	Yes
1.4105	10.0	10.5	10.5	10.5	7.7	25	0.46	0.70	216	Yes
1.4510	10.0	10.0	10.5	10.5	7.7	25	0.46	0.60	220	Yes
1.4511	10.0	10.0	10.5	10.5	7.7	25	0.46	0.60	220	Yes
1.4113	10.0	10.0	10.5	10.5	7.7	25	0.46	0.70	216	Yes
1.4520	10.4	10.8	11.2	11.6	7.7	20	0.43	0.70	220	Yes
1.4521	10.4	10.8	11.2	11.6	7.7	15	0.43	0.80	220	Yes
X1CrMo26-1	9.5	10.0	10.3	10.6	7.66	16.7	0.43	0.55	200	Yes
X1CrMoNi29-4-2	9.4				7.7	15.1	0.45	0.72	200	Yes

Table 9.14 Weldability of ferritic stainless steels

Grade no.	Weldable	Welding method				Preheating (°C)	After-treatment	
		SAW/MIG/ TIG welding	Arc welding	Resistance welding	Autogenous welding		Annealing	at *T* (°C)
1.4003 (Sect. 9.4.3)	Yes	+	+	+	–	–	–	–
1.4016	Yes	+	+	+	(+)	200	(+)	700
1.4104	No	–	–	–	–	–	–	–
1.4105	No	–	–	–	–	–	–	–
1.4510	Yes	+	+	+	–	200	(+)	750
1.4511	Yes	+	+	+	–	200	(+)	750
1.4113	Yes	+	+	–	–	–	+	750
1.4521	Yes	+	–	–	–	–	–	–
X2CrMoTi29-4	Yes	+	–	–	–			
X1CrMo26-1	Yes	+	–	–	–			
X1CrMo29-4	Yes	+	–	–	–			
X1CrMoNi29-4-2	Yes	+	–	–	–			

9.4.2 Martensitic and Martensitic–Ferritic Chromium Steels

Steels with 11.5–18 wt% Cr and up to 1.2 wt% C are austenitic at high temperatures and can be transformed into martensite by fast cooling. Due to the high chromium content, the hardenability of these steels is relatively high, so a fully martensitic transformation can be achieved even with relatively large cross sections and moderate cooling rates. They are normally used for applications requiring a combination of high hardness with good corrosion and wear resistance. With carbon contents below about 0.35 wt% C the steels are hypoeutectic, and some ferrite will be present after heat treatment. They can be austenitized at $\geq$ 960 °C. Steels with $\geq$ 0.40 wt% C and 13 wt% Cr are already hyper-eutectic and will contain some undissolved primary carbides after quenching. To dissolve more carbon, these steels are usually quenched from a higher austenitization temperature around 1050 °C. The steels cannot be hardened if the carbon concentration is below 0.12 wt% C and the chromium content $\geq$ 16 wt% Cr.

In some grades a small content of 0.5–1 wt% Mo (and sometimes some W, V, or Nb) is used to increase the tempering resistance, i. e., to retain higher hardness on tempering by means of precipitation reactions. Increased S contents or Se additions improve the machinability of the steels. About 1–2.5 wt% Ni together with reduced carbon content is applied if hardenabilty of higher cross sections and an improved weldability are required.

The hardness after quenching depends on the carbon content, as illustrated in Fig. 9.18 for a 12 wt% Cr steel [9.2]. In the as-quenched state the steels are hard but very brittle. Thus a tempering treatment is necessary to adjust toughness and strength to the level required for a specific application. For high hardness, annealing temperatures of about 100–300 °C are applied, whereas increases in ductility and toughness require tempering at or above 650 °C.

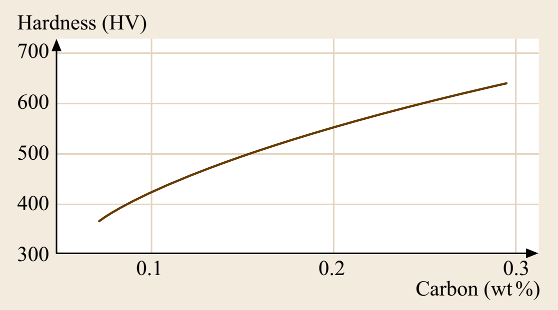

Fig. 9.18 As-quenched hardness as a function of the carbon content of a martensitic 12 wt% Cr steel

The chemical composition for a number of martensitic Cr steels is given in Table 9.15. Tables 9.16–9.19 review data on recommended heat treatment conditions, mechanical properties, physical properties, and weldability, respectively.

It should be noted that a different way to produce stainless steels with high hardness is by precipitation hardening. Such steels have a low carbon content and contain in addition to chromium a few wt% of Ni and Cu. The hardening is caused by Cu precipitates. Others use precipitation hardening by intermetallic phases such as NiTi, TiAl, or NiAl.

Table 9.15 Chemical composition of martensitic and martensitic-ferritic chromium steels

Grade no. (EN10088)	Steel designation	ASTM A 276/AISI grade	Chemical composition (wt%)							
			C	Si	Mn	P	S	Cr	Mo	Ni
1.4006	X12Cr13	410	0.08–0.15	≤ 1.0	≤ 15	≤ 0.040	≤ 0.015	11.5–13.5		≤ 0.75
1.4005	X12CrS13	416	0.06–0.15	≤ 1.0	≤ 1.5	0.040	0.15–0.35	12.0–14.0	≤ 0.6	
1.4021	X20Cr13	420	0.16–0.25	≤ 1.0	≤ 1.5	≤ 0.040	≤ 0.015	12.0–14.0		
1.4028	X30Cr13	420	0.26–0.35	≤ 1.0	≤ 1.5	≤ 0.040	≤ 0.015	12.0–14.0		
1.4104	X14CrMoS17-2	430F	0.10–0.17	≤ 1.0	≤ 1.5	≤ 0.040	0.15–0.35	15.5–17.5	0.2–0.6	
1.4057	X17CrNi16-2	431	0.12–0.22	≤ 1.0	≤ 15	≤ 0.040	≤ 0.015	15–17		1.50–2.50
1.4109	X70CrMo15	440A	0.60–0.75	≤ 0.7	≤ 1.0	≤ 0.040	≤ 0.015	14.0–16.0	0.40–0.80	
1.4125	X105CrMo17	440C	0.95–1.20	≤ 1.0	≤ 1.0	≤ 0.040	≤ 0.015	16.0–18.0	0.40–0.80	

Table 9.16 Heat treatment conditions of martensitic and martensitic-ferritic chromium steels

Grade no.	Rolling and forging	Soft annealing			Quenching			Annealing
	T (°C)	*T* (°C)	Time (min)	Cooling	*T* (°C)	Medium	Hardness HRC ca.	*T* (°C)
1.4006	1100–800	750–810	120–360	Air/furnace	950–1010	Air/oil	31	700–780
1.4005	1150–750	745–825	15–30	Air	980–1000	Air/oil	31	680–780
1.4021	1100–800	745–825	120–360	Air/furnace	950–1050	Air/oil	47	620–780
1.4028	1100–800	730–790		Air/furnace	950–1050	Air/oil		650–730
1.4104	1100–800	750–850	120–180	Air/furnace	950–1070	Air/oil	27	550–650
1.4057	1100–800	680–800	180–240	Air/furnace	950–1050	Air/oil	47	600–720
1.4109	1100–900	790–830	120–360	Furnace	1000–1100	Oil	59	150–200
1.4125	1100–900	780–840	160–240	Furnace	950–1050	Oil	61	560–640

Table 9.17 Mechanical properties of martensitic and martensitic-ferritic chromium steels

Grade no.	Heat treatment condition	Tensile properties of flat products ≤ 25 mm thickness			CVN impact energy at room temperature (J) longitudinal/transversal	Min. yield strength or 0.2% proof strength at *T* (°C) in MPa			
		Min. yield strength or 0.2% proof strength (MPa)	Ultimate tensile strength (MPa)	Fracture elongation A_5 (%) long./trans.		100	200	300	400
1.4006	Annealed	250	≤ 730	20/15	–/–	235	225	220	195
	Quenched and tempered	450	650–850	16/12	≥ 25/–	420	400	365	305
1.4005	Quenched and tempered	450	650–850	12/–	–/–	–	–	–	–
1.4021	Annealed	–	≤ 760	–	–/–				
	Quenched	500	750–850	15/11	25/–	420	400	365	305
	Tempered	600	800–950	13/10	20/–				
1.4028	Annealed	–	≤ 740	≥ 15	–/–				
	Quenched and tempered	650	850–1000	≥ 10	11/–				
1.4104	Annealed	300	540–740	–	–/–				
	Quenched and tempered	550	650–850	≥ 12	–/–				
1.4057	Annealed	–	≤ 950	–	–				
	Quenched and tempered	600	800–950	14/12	25/20	495	460	430	345

Table 9.18 Physical properties of martensitic and martensitic-ferritic chromium steels

Grade no.	Mean thermal expansion coefficient between 20 °C and T (°C) in $10^{-6}\,K^{-1}$				Density (kg dm^{-3})	Heat conductivity at 20 °C (W m^{-1} K^{-1})	Specific heat at 20 °C (J g^{-1} K^{-1})	Electrical resistivity at 20 °C (Ω mm^2 m^{-1})	Modulus of elasticity (kN/mm^2)	Magnetizable
	100	200	300	400						
1.4006	10.5	11.0	11.5	12.0	7.7	30	0.46	0.60	215	Yes
1.4005	10.5	11.0	11.5	12.0	7.7	30	0.46	0.60	215	Yes
1.4021	10.5	11.0	11.5	12.0	7.7	30	0.46	0.60	215	Yes
1.4028	10.5	11.0	11.5	12.0	7.7	30	0.46	0.65	215	Yes
1.4104	10.0	10.5	10.5	10.5	7.7	25	0.46	0.70	215	Yes
1.4057	10.0	10.5	10.5	10.5	7.7	25	0.46	0.70	215	Yes
1.4109	10.5	11.0	11.0	11.5	7.7	30	0.46	0.65	210	Yes
1.4125	10.4	10.8	11.2	11.6	7.7	15	0.43	0.80	220	Yes

Table 9.19 Weldability of martensitic and martensitic-ferritic chromium steels

Grade no.	Weldable	Welding method				Pre-heating	After-treatment		
		SAW/MIG/TIG welding	Arc welding	Resistance welding	Autogenous welding	T (°C)	Annealing	at T (°C)	Q + T anew
1.4006	Yes	+	+	+	(+)	100–300	+	650	–
1.4005	Yes	+	+	+	–	300	–	–	–
1.4021	Condit.	+	+	–	–	100–300	+	650	(+)
1.4028	Yes	–	+	–	–	300–400	+	720–750	–
1.4104	No	–	–	–	–	–	–	–	–
1.4057	Condit.	+	+	–	–	100–300	+	700	(+)
1.4109	No	–	–	–	–	–	–	–	–
1.4125	No	–	–	–	–	–	–	–	–

9.4.3 Austenitic Stainless Steels

By adding of austenite forming elements, mainly Ni, the range of stability of the fcc phase is extended down to and below room temperature. The favorable combinations of ductility, toughness, hot and cold formability, weldability, and corrosion resistance have made the austenitic CrNi steels by far the most important and popular stainless steels. The most widespread representatives are the steel grades AISI 304 (X5CrNi18-10, 1.4301) and AISI 316 (X5CrNiMo17-12-2, 1.4401). The austenitic steels are applied in the solution-annealed (at 1000–1100 °C) and fast-cooled state which yields a microstructure that is free of carbide precipitates and has a homogeneous distribution of the alloying elements necessary for good corrosion resistance.

Compared to the bcc ferrite phase the fcc austenite phase is characterized by a higher solubility but a lower diffusivity of almost all alloying elements. The first fact allows the production of single phase fcc alloys with a broad composition spectrum. This permits adjustment of the properties of the steel to specific requirements of corrosion and oxidation resistance, cold and hot strength etc. The low diffusivity makes precipitation processes rather sluggish.

The austenite of the quenched steels can be unstable and can transform into martensite as a result of cold deformation or cooling to sub-zero temperatures, especially if these steels are relatively weakly-alloyed. This transformation leads to increased strength and reduced ductility. Martensite can be detected by magnetization measurements because the austenite is paramagnetic whereas the martensite is ferromagnetic. Since the fcc austenitic steels do not exhibit the ductile-brittle transition characteristic of ferritic alloys, the austenitic steels stay sufficiently ductile even at liquid He temperature (4.2 K) and are thus preferred materials for cryogenic applications. Their yield strength of 200–250 MPa is lower than that of the ferritic steels, but due to their pronounced work hardening by cold deformation (making extensive cold-forming operations difficult and often requiring intermediate soft annealing heat treatments), they have a higher tensile strength and fracture elongation. A pronounced solid solution strengthening is possible, especially by higher concentrations of nitrogen (up to about 0.4 wt% N). The nitrogen-alloyed CrNi steels are characterized by particularly favorable combinations of mechanical and corrosion properties.

As mentioned above, after fast cooling from $\geq 1000\,°C$, the austenitic stainless steels are free of carbide precipitates. But since steels with ≥ 0.05 wt% C

Table 9.20 Heat treatment conditions of austenitic stainless steels

Grade no.	Rolling and forging T (°C)	Cooling	Quenching T (°C)	Cooling
1.4310	1180–900	Air	1010–1090	Air, water
1.4541 1.4401 1.4402 1.4406 1.4436 1.4571 1.4580	1150–750	Air	1030–1110	Air, > 2 mm water
1.4301 1.4303 1.4305 1.4306 1.4311	1150–850	Air	1000–1100	Air, > 2 mm water
1.4550	1150–750	Air	1020–1120	Air, > 2 mm water
1.4429 1.4438 1.4439	1150–750	Air	1030–1150	Air, > 2 mm water
1.4435	1150–750	Air, below 600 °C, furnace	1030–1110	Air, > 2 mm water

are already carbon-supersaturated at temperatures below 900 °C, holding the material at temperatures between about 400 and 900 °C will lead to preciptation of chromium carbides (mainly $M_{23}C_6$ type), preferentially at the grain boundaries. This will result in an increased susceptibility to intergranular corrosion due to local chromium depletion. The means to avoid this undesirable effect are the same as for the ferritic steels: bonding of the carbon (and nitrogen) atoms by an overstoichiometric alloying with Nb, Ta, or Ti (so-called stabilization of the steels), or the reduction of the carbon content to below 0.03 wt% C resulting in the development of the extra low carbon (ELC) steels. However, in strongly oxidative media (such as concentrated nitric acid) even steels that have been sufficiently stabilized by Ti may exhibit intergranular corrosion due to selective dissolution of the TiC. Under less severe corrosion conditions, the Ti stabilized steels are as stable as the Nb stabilized grades but at somewhat lower costs.

Chemical compositions, heat treatment conditions, physical properties, and hints to weldability of austenitic stainless steels are presented in Tables 9.20–9.24. The austenitic stainless steels are often considered to be nonmagnetic or nonmagnetisable. However, in fact they are paramagnetic with a relative permeability of less than about 1.6 (often less than 1.1). Small volume fractions of residual δ-ferrite or martensite which can be formed on deep cooling or cold deformation or of magnetisable precipitates may lead to some small ferromagnetic behavior. The steels are the less prone to martensite formation on deep cooling or cold deformation the higher the alloy content is.

Table 9.21 Chemical composition of austenitic stainless steels

Grade no. (EN 10088)	Steel designation	ASTM A 276/ AISI grade	Chemical composition (wt%)								
			C	Si	Mn	P	S	Cr	Ni	Mo	Others
1.4310	X10CrNi18-8	301	0.05–0.15	≤ 2.0	≤ 2.0	≤ 0.045	≤ 0.015	17.0–19.5	6.0–9.5	≤ 0.8	$N \le 0.11$
1.4301	X5CrNi18-10	304	≤ 0.07	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.0–19.5	8.0–10.5		
1.4303	X4CrNi18-12	305, 308	≤ 0.06	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.0–19.0	11.0–13.0	≤ 0.5	$Cu \le 1.0$, $N \le 0.11$
1.4305	X8CrNiS18-9	303	≤ 0.10	≤ 1.0	≤ 2.0	≤ 0.045	0.15–0.35	17.0–19.0	8.0–10.0		$Cu \le 1.0$, $N \le 0.11$
1.4306	X2CrNi19-11	304L	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	18.0–20.0	10.0–12.0		$N \le 0.11$
1.4311	X2CrNiN18-10	304LN	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.5–19.5	8.5–11.5		N 0.12–0.22
1.4541	X6CrNiTi18-10	321	≤ 0.08	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.0–19.0	9.0–12.0		$Ti\ 5 \times \%\,C \le 0.70$
1.4550	X6CrNiNb18-10	347	≤ 0.08	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.0–19.0	9.0–12.0		$Nb\ 10 \times \%\,C \le 1.0$
1.4401	X5CrNiMo17-12-2	316	≤ 0.07	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	10.0–13.0	2.0–2.5	
1.4404	X2CrNiMo17-12-2	316L	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	10.0–13.0	2.0–2.5	$N \le 0.11$
1.4406	X2CrNiMoN17-12-2	316LN	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	10.5–12.5	2.0–2.5	N 0.12–0.22
1.4571	X6CrNiMoTi17-12-2	316Ti	≤ 0.08	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.030	16.5–18.5	10.5–13.5	2.0–2.5	$Ti\ 5 \times \%, C \le 0.80$
1.4580	X6CrNiMoNb17-12-2	316Cb	≤ 0.08	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	10.5–13.5	2.0–2.5	$Nb\ 10 \times \%\,C \le 1.0$
1.4429	X2CrNiMoN17-13-3	316LN	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	11.0–14.0	2.5–3.0	N 0.12–0.22
1.4435	X2CrNiMo18-14-3	316L, 317L	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.0–19.0	12.5–15.0	2.5–3.0	$N \le 0.11$
1.4436	X3CrNiMo17-13-3	316	≤ 0.05	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	10.5–13.0	2.5–3.0	$N \le 0.11$
1.4438	X2CrNiMo18-15-4	317L	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	17.5–19.5	13.0–16.0	3.0–4.0	
1.4439	X2CrNiMoN17-13-5	317 LMN	≤ 0.03	≤ 1.0	≤ 2.0	≤ 0.045	≤ 0.015	16.5–18.5	12.5–14.5	4.0–5.0	N 0.12–0.22
1.4372	X12CrMnNiN17-7-5	201	≤ 0.15	≤ 1.0	5.5–7.5	≤ 0.045	≤ 0.015	16.0–18.0	3.5–5.5		N 0.05–0.25
1.4373	X12CrMnNiN18-9-5	202	≤ 0.15	≤ 1.0	7.5–10.0	≤ 0.045	≤ 0.015	17.0–19.0	4.0–6.0		N 0.05–0.25
1.4828	X15CrNiSi20-12	309	≤ 0.20	1.5–2.5	≤ 2.0	≤ 0.045	≤ 0.03	19.0–21.0	11.0–13.0		$N \le 0.11$
1.4845	X8CrNi25-21	310S	≤ 0.10	≤ 1.5	≤ 2.0	≤ 0.045	≤ 0.015	24.0–26.0	19.0–22.0		$N \le 0.11$

Table 9.22 Mechanical properties of austenitic stainless steels (hot rolled, solution annealed)

Grade no.	Tensile properties flat products $\leq$ 25 mm thickness			Min. CVN impact energy at room temperature (J)	Min. yield strength or 0.2% proof strength at T (°C) in MPa				
	Min. yield strength or 0.2% proof strength (MPa)	Ultimate tensile strength (MPa)	Min. fracture elongation A_5 (%)		100	200	300	400	500
1.4310	250	600–950	40	105	210	190	180		
1.4301	210	520–720	45	100	157	127	110	98	92
1.4303	190	500–700	45	100	162	134	117	105	99
1.4305	190	500–700	35						
1.4306	200	520–700	45	100	147	118	100	89	81
1.4311	270	550–750	40	100	205	157	136	125	119
1.4541	200	520–720	40	100	176	157	136	125	119
1.4550	200	520–720	40	100	177	157	136	125	119
1.4401	220	530–680	40	100	177	147	127	115	110
1.4404	220	530–680	40	100	166	137	118	108	100
1.4406	280	580–780	40	100	211	167	145	135	129
1.4571	220	540–690	40	100	185	167	145	135	129
1.4580	220	520–720	40	100	186	167	145	135	129
1.4429	280	580–780	35	100	225	178	155	145	138
1.4435	220	550–700	40	100	166	137	118	108	100
1.4436	220	550–700	40	100	177	147	127	115	110
1.4438	220	550–700	35	100	172	147	127	115	110
1.4439	270	580–780	35	100	225	185	165	150	
1.4372	330	750–950	45	100					
1.4373	320	680–880	45	100					
1.4828	230	550–750	28	30					
1.4845	210	500–700	33	30					

Table 9.23 Physical properties of austenitic stainless steels

Grade no.	Mean thermal expansion coefficient between 20 °C and T (°C) in $10^{-6}\,K^{-1}$								Density (kg dm^{-3})	Thermal conductivity at 20 °C (W m^{-1} K^{-1})	Specific heat at 20 °C (J g^{-1} K^{-1})	Electrical resistivity at 20 °C (Ω mm^2 m^{-1})	Modulus of elasticity at 20 °C (kN mm^{-2})
	100	200	300	400	500	600	700	800					
1.4310	16.0	16.5	17.0	17.5	18.0	18.5	18.5	19.0	7.9	15	0.50	0.73	200
1.4301													
1.4303													
1.4305													
1.4306													
1.4311													
1.4541													
1.4550													
1.4401	16.5	17.5	17.5	18.5	18.5	19.0	19.5	19.5	8.0	15	0.50	0.75	200
1.4404													
1.4406													
1.4435													
1.4436													
1.4571													
1.4580													
1.4429													
1.4438	16.5	17.5	18.0	18.5	19.0	19.0	19.5	19.5	8.0	14	0.50	0.85	200
1.4439													
1.4372		15.7		17.5					7.8	15	0.50	0.70	200
1.4373		17.5		18.4					7.8	15	0.50	0.70	200
1.4828		16.5		17.5					7.9	15	0.50	0.85	200
1.4845		15.5		17.0					7.9	15	0.50	0.85	200

Table 9.24 Weldability of austenitic stainless steels (welding methods not in parantheses are to be preferred)

Grade no.	Weldable	Welding method SAW/MIG/TIG welding	Arc welding	Resistance welding	Autogenous welding	Pre-heating T (°C)	After-treatment
1.4310	Yes	+	+	+	+	–	–
1.4301 1.4303 1.4306 1.4438 1.4541 1.4550 1.4401 1.4404 1.4406 1.4571 1.4580	Yes	+	+	+	(+)	–	–
1.4305	No	–	–	–	–	–	–
1.4311 1.4429 1.4435 1.4436 1.4439	Yes	+	+	+	–	–	–

9.4.4 Duplex Stainless Steels

In recent years, duplex steels are a class of stainless steels that have found increased interest and are becoming more common [9.11] due to lower alloying cost and attractive properties. They have a mixed structure with nearly equal volume fractions of 50% ferrite and 50% austenite (the practical range of the ferrite content is between 30 and 60 vol.%). According to their chemical composition, mechanical and corrosion properties they are often subdivided into lean, standard, super, and hyper duplex steels, respectively Typical examples are presented in Table 9.25. The lean duplex steels contain about 22 wt% Cr and low concentrations of Ni (≈ 2 wt%) and Mo (< 0.5 wt%). The super and hyper duplex steels are characterized by higher concentrations of 25–32 wt% Cr, 6–9 wt% Ni, 3–5 wt% Mo and up to 0.5 wt% N. Higher contents of Mn and N allow to further reduce the Ni content and thus to reduce alloying cost.

The duplex steels solidify as δ-ferrite which will partly transform into austenite upon cooling. Thus, the phase fractions of ferrite and austenite depend not only on the concentrations of ferrite and austenite forming elements, but also on the annealing and cooling conditions which have to be controlled within narrow limits. The influence of annealing temperature and cooling conditions on the ferrite content of a steel with 0.05 wt% C, 25 wt% Cr, 8 wt% Ni, 2.5 wt% Mo and 1.5 wt% Cu is illustrated in Table 9.26 [9.3]. During the partial phase transformation of ferrite into austenite below 1350 °C, a redistribution of the alloying elements occurs with the ferrite-forming elements Cr, Mo, and Ti enriched in the α-phase and the austenite-forming elements C, N, Ni, and Mn enriched in the γ-phase. The reduced C content in the α-phase delays the formation of chromium carbides. The relatively high Mo and N contents ensure good resistance against pitting corrosion.

The advantages of the duplex steels compared to austenitic steels are a substantially higher yield and tensile strength (Table 9.27) and a better resistance against chloride-induced stress corrosion cracking and pitting corrosion. A few data on heat treatment conditions and physical properties are given in Tables 9.28 and 9.29, respectively. In comparison with ferritic stainless steels, the duplex steels have a better weldability, a higher low temperature toughness down to −50 °C or even −80 °C, and a lower susceptibility to general and intergranular corrosion. With respect to optimum toughness, the δ-ferrite content should not surpass 60 vol.%. The volume fraction of ferrite determines also the soft magnetic properties of the duplex stainless steels.

Brittle Cr-rich phases can deteriorate ductility, toughness, and corrosion resistance of duplex steels due to the formation of σ-phase at slow cooling through the temperature range of 1000–500 °C and of the α' phase when the steel is exposed for a longer time to temperatures between 350 and 525 °C (so-called 475 °C *embrittlement*). Therefore, duplex steels are usually water-quenched from a solution treatment at 1000–1150 °C, and service temperatures are restricted to less than 250–300 °C. These problems are the more pronounced the higher the alloy content is.

Table 9.25 Chemical composition of duplex stainless steels

Grade no. (EN 10088)	Steel designation	UNS No.	Notation	Chemical composition (wt%)								
				C	Si	Mn	S	P	Cr	Ni	Mo	Others
1.4062	X2CrNiN22-2	S32202	Lean duplex	≤ 0.03	≤ 1	≤ 2	≤ 0.03	≤ 0.04	21.5–24	1.0–2.8	0.45	N 0.18–0.26
1.4162	X2CrMnNiN21-5-1	S32101	Lean duplex	≤ 0.04	≤ 1	4–6	≤ 0.03	≤ 0.04	21–22	1.35–1.7	0.1–0.8	N 0.20–0.25 Cu 0.1–0.8
1.4482	X2CrMnNiMoN21-5-3	S32001	Lean duplex	≤ 0.03	≤ 1	4–6	≤ 0.015	≤ 0.035	19.5–21.5	1.0–3.0	0.6	Cu 1.0 N≤ 0.17
1.4362	X2CrNiN23-4	S32304	Lean duplex	≤ 0.03	≤ 1	≤ 2.5	≤ 0.015	≤ 0.035	22–24	3.5–5.5	0.1–0.6	Cu 0.1–0.5, N 0.05–0.20
1.4460	X4CrNiMoN27-5-2	S32900	Duplex	≤ 0.05	≤ 1	≤ 2	≤ 0.015	≤ 0.035	23–28	4.5–6.5	1.3–2.0	N 0.05–0.20
1.4462	X2CrNiMoN22-5-3	S31803 S32205	Duplex	≤ 0.03	≤ 1	≤ 2	≤ 0.015	≤ 0.035	21–23	4.5–6.5	2.5–3.5	N 0.08–0.22
1.4410	X2CrNiMoN25-7-4	S32750	Super duplex	≤ 0.03	≤ 1	≤ 2	≤ 0.015	≤ 0.035	24–26	6.0–8.0	3.0–4.5	N 0.24–0.35 Cu 0.5
1.4501	X2CrNiMoCuWN25-7-4	S32760	Super duplex	≤ 0.03	≤ 1	≤ 1	≤ 0.015	≤ 0.035	24–26	6.0–8.0	3.0–4.0	N 0.2–0.3 Cu 0.5–1.0 W 0.5–1.0
	X2CrNiMoN32-7-3.5-0.5	S32207	Hyper duplex	≤ 0.03	≤ 1	≤ 1.5	≤ 0.015	≤ 0.035	29–33	6.0–9.0	3.0–5.0	N 0.4–0.6 Cu 1.0

Table 9.26 Influence of annealing temperature and cooling conditions on the ferrite content of a steel with 0.05 wt% C, 25 wt% Cr, 8 wt% Ni, 2.5 wt% Mo and 1.5 wt% Cu [9.11]

Annealing temperature (°C) (holding time 15 min)	Ferrite content (vol.%) after	
	Water quenching	Air cooling
1350	93.0	78.8
1300	70.2	61.8
1250	43.5	37.5
1150	35.7	34.2
1050	24.0	23.7
1000	7.6	7.6

Table 9.27 Mechanical properties of duplex stainless steels

Grade no.	Heat treatment condition	Tensile properties of flat products $\leq$ 25 mm thickness			Min. long. CVN impact energy at room temperature (J)
		Min. yield strength or 0.2% proof strength (MPa)	Ultimate tensile strength (MPa)	Min. fracture elongation A_5 (%)	
1.4062	Annealed	$\geq$ 460	640–840	25	100
1.4162	Annealed	$\geq$ 450	$\geq$ 650	30	100
1.4482	Annealed	$\geq$ 460	650–850	25	100
1.4362	Annealed	$\geq$ 400	630–820	25	100
1.4460	Annealed	$\geq$ 485	620–800	20	100
1.4462	Annealed	$\geq$ 500	$\geq$ 700	20	100
1.4410	Annealed	$\geq$ 530	730–930	20	100
1.4501	Annealed	$\geq$ 530	730–930	25	100
S33207	Annealed	$\geq$ 550	800–1000	25	120

Table 9.28 Heat treatment conditions of duplex stainless steels

Grade no.	Rolling and forging T (°C)	Cooling	Quenching	
			T (°C)	Cooling
1.4062	1150–950	Air, water	980–1080	Water, air
1.4162	1150–950	Air, water	950–1050	Water, air
1.4482	1150–950	Air, water	950–1050	Water, air
1.4362	1150–950	Air, water	950–1050	Water, air
1.4460	1150–900	Air, water	1020–1100	Water, air
1.4462	1230–950	Air, water	1020–1100	Water, air
1.4410	1230–1025	Air, water	1025–1125	Water, air
1.4501	1230–1000	Air, water	$\geq$ 1100	Water, air
S33207			1040–1140	Water, air

Table 9.29 Physical properties of duplex stainless steels

Grade no.	Mean thermal expansion coefficient between 20 °C and T (°C) in $10^{-6}\,\mathrm{K}^{-1}$					Density ($\mathrm{kg\,dm^{-3}}$)	Heat conductivity at 20 °C ($\mathrm{W\,m^{-1}\,K^{-1}}$)	Specific heat at 20 °C ($\mathrm{J\,g^{-1}\,K}$)	Electrical resistivity at 20 °C ($\Omega\,\mathrm{mm^2\,m^{-1}}$)	Modulus of elasticity at 20 °C ($\mathrm{kN\,mm^{-2}}$)	Magnetizable
	100	200	300	400	500						
1.4062	10.5	11.5	12.0			7.8	15	0.48	0.70	200	Yes
1.4162	13.0	13.5	14.0			7.8	15	0.50	0.80	200	Yes
1.4482	13.0	13.5	14.0			7.8	15	0.50	0.80	200	Yes
1.4362	13.0	13.5	14.0	14.5	15.0	7.75	15	0.48	0.80	200	Yes
1.4460	10.8	11.0	11.6	12.1	12.3	7.7	15	0.46	0.80	200	Yes
1.4462	13.0	13.5	14.0	14.5	15.0	7.8	15	0.48	0.80	200	Yes
1.4410	13.0	13.5	14.0	14.5	15.0	7.85	15	0.48	0.80	205	Yes
1.4501	13.0	13.5	14.0			7.84	15	0.50	0.85	190	Yes
S33207	13.5	13.5	14.0	14.5		7.7	13	0.48	0.87	200	Yes

The duplex stainless steels can be welded with all common welding processes except oxyacetylene welding. Recommended welding details are given in [9.11]. Preheating and post-weld stress relief heating are not necessary. The susceptibility to hot cracking of the weld seam is very low due to the ferrite component, but the formation of too much ferrite and of embrittling phases in the heat affected zone requires special attention, e.g., with respect to heat input and interpass temperature.

9.5 Heat-Resistant Steels

Heat-resistant steels are treated extensively in [9.1], creep data are compiled in [9.12]. Steels are considered heat-resistant if they possess – in addition to good mechanical properties at ambient temperature – special resistance against short or long term exposure to hot gases, combustion products and melts of metals or salts at temperatures above about 550 °C where non- or low-alloyed steels are no longer applicable due to extensive scaling and creep.

Thus, heat-resistant steels are characterized by a combination of good high temperature strength, scaling resistance, a sufficient hot and cold formabilty, and weldability. They are sufficiently stable against embrittling processes at the high application temperatures. The resistance against scaling and hot gas corrosion is affected by the formation of a protective dense, pore-free, and tightly adherent oxide layer at the surface. The main alloying elements leading to such an oxide layer are Cr, Al, and Si. The oxidation and scaling resistance increases with increasing Cr content between about 6 and 25 wt% Cr. Higher Cr concentrations do not lead to further improvement. Additions of up to 2 wt% Al and up to 3 wt% Si enhance the effect of Cr. Small additions of rare earth metals, e.g., of Ce, can improve the adherence and the ductility of the oxide layer. In order to keep the protective oxide layer intact during temperature changes, the steels should exhibit low volume changes and, if possible, no phase transformations during heating and cooling. Consequently, there are two main groups of heat resistant steels: ferritic and austenitic steels, both showing no phase transformations.

The *ferritic* Cr (or Cr-Al-Si) steels are less expensive but have a lower creep strength above 800 °C. They may suffer from three embrittling mechanisms:

- The 475 °C *embrittlement* due to decomposition in the metastable miscibility gap of the Fe-Cr solid solution, occuring between about 350 and 550 °C at Cr contents above 15 wt% Cr (Fig. 9.9)
- The formation of the brittle intermetallic FeCr σ-phase at temperatures between about 550 and 900 °C (Sect. 9.1, Fig. 9.8)
- Grain coarsening at temperatures above about 900 °C.

However, these embrittling mechanisms will not impair the behavior at high operating temperatures if taken into account properly, but will deteriorate the toughness after cooling to room temperature. Heating to temperatures above the range of occurrence of the embrittling phases followed by sufficiently fast cooling will suppress the embrittling effects.

The Cr and Ni alloyed *austenitic* steels possess a higher temperature strength and better ductility, toughness, and weldability. The susceptibility to embrittling effects is considerably lower. At Ni contents above 30 wt% Ni, they are outside the stability region of the brittle σ-phase.

The properties of the *ferritic-austenitic* steels lie between those of the ferritic and austenitic steels. They are characterized by a higher fracture toughness, cold formability, high temperature strength, and weldability than the fully ferritic grades, and by a higher chemical resistance in sulphurous gases than the austenitic grades.

It is obvious that the scaling resistance of the heat-resisting steels will be detrimentally influenced by any other corrosion mechanism which may be destroying the oxide layer, e.g., by chemical reactions with other metal oxides, chlorine, or chlorides. Thus in general, the heat resistance cannot be characterized by a single test method or measuring parameter but will depend on the specific environmental conditions.

In Table 9.30 chemical compositions of the most important grades of heat resistant steels are presented [9.13]. Table 9.31 contains some information about recommended temperature ranges for heat treatment and hot forming. In Tables 9.32 and 9.33 the mechanical properties at room temperature and at high temperatures are listed, respectively. Table 9.34 shows some physical properties. The ferritic and ferritic-austenitic steels are magnetisable while the austenitic grades are nonmagnetic. Qualitative data on the high temperature behavior in special gas atmospheres are given in Table 9.35. In carburizing atmospheres car-

Table 9.30 Chemical composition of heat-resisting steels

Grade[a]	Steel designation	ASTM/AISI grade	Chemical composition (wt%)								
			C	Si	Mn	P	S	Al	Cr	Ni	Others
Ferritic steels											
1.4713	X10CrAlSi7	–	≤ 0.12	0.5–1.0	≤ 1	≤ 0.04	≤ 0.03	0.5–1.0	6.0–8.0	–	–
1.4720	X7CrTi12	–	≤ 0.08	≤ 1.0	≤ 1	≤ 0.04	≤ 0.03	–	10.5–12.5	–	Ti $\ge 6 \times$ % C up to 1.0
1.4724	X10CrAlSi13	405	≤ 0.12	0.7–1.4	≤ 1	≤ 0.04	≤ 0.03	0.7–1.2	12.0–14.0	–	–
1.4742	X10CrAlSi18	430	≤ 0.12	0.7–1.4	≤ 1	≤ 0.04	≤ 0.03	0.7–1.2	17.0–19.0	–	–
1.4762	X10CrAlSi25	446	≤ 0.12	0.7–1.4	≤ 1	≤ 0.04	≤ 0.03	1.2–1.7	23.0–26.0	–	–
Ferritic-austenitic steels											
1.4821	X15CrNiSi25-4	327	0.10–0.20	0.8–1.5	2.0	≤ 0.04	≤ 0.03	–	24.0–27.0	3.5–5.5	–
Austenitic steels											
1.4878	X10CrNiTi18-10	321	≤ 0.12	≤ 1	≤ 2.0	≤ 0.045	≤ 0.03	–	17.0–19.0	9.0–12.0	Ti $\ge 4\times$ % C up to 0.8
1.4828	X15CrNiSi20-12	309	≤ 0.20	1.5–2.5	≤ 2.0	≤ 0.045	≤ 0.03	–	19.0–21.0	11.0–13.0	–
1.4833	X12CrNi23-12	309S	≤ 0.08	≤ 1	≤ 2.0	≤ 0.045	≤ 0.03	–	21.0–23.0	12.0–15.0	–
1.4845	X8CrNi25-21	310S	≤ 0.15	≤ 0.75	≤ 2.0	≤ 0.045	≤ 0.03	–	24.0–26.0	19.0–22.0	–
1.4841	X15CrNiSi25-20	310, 314	≤ 0.20	1.5–2.5	≤ 2.0	≤ 0.045	≤ 0.03	–	24.0–26.0	19.0–22.0	
1.4864	X12NiCrSi36-18	330	≤ 0.15	1.0–2.0	≤ 2.0	≤ 0.030	≤ 0.02	–	15.0–17.0	33.0–37.0	–
1.4876	X10NiCrAlTi32-21	B163	≤ 0.12	≤ 1	≤ 2.0	≤ 0.030	≤ 0.02	0.15–0.6	19.0–23.0	30.0–34.0	Ti 0.15–0.6

[a] According to SEW 470 [9.11]

Table 9.31 Recommended conditions for heat treatment and hot forming of heat-resisting steels

Grade[a]	Hot forming temperature (°C)	Soft annealing (°C) Cooling in air (water)	Quenching T (°C) Cooling in water (air)	Limiting scaling temperature in air (°C)
Ferritic steels				
1.4713	1100–750	750–800	–	620
1.4720	1050–750	750–850	–	800
1.4724	1100–750	800–850	–	850
1.4742	1100–750	800–850	–	1000
1.4762	1100–750	800–850	–	1150
Ferritic-austenitic steels				
1.4821	1150–800	–	1000–1050	1100
Austenitic steels				
1.4878	1150–800	–	1020–1070	850
1.4828	1150–800	–	1050–1100	1000
1.4833	1150–900	–	1050–1100	1000
1.4845	1150–800	–	1050–1100	1050
1.4841	1150–800	–	1050–1100	1150
1.4864	1150–800	–	1050–1100	1100
1.4876	1150–800	900–980 (Recrystallization annealing)	1100–1150 (Solution annealing)	1100

[a] According to SEW 470 [9.11]

Table 9.32 Mechanical properties of heat-resisting steels at 20 °C

Grade no.[a]	Heat treatment condition	Hardness HB max.	Min. 0.2% proof stress (MPa)	Ultimate tensile strength (MPa)	Min. elongation $L_0 = 5d_0$ (%) Longit.	Transv.
Ferritic steels						
1.4713	Annealed	192	220	420-620	20	15
1.4720	Annealed	179	210	400-600	25	20
1.4724	Annealed	192	250	450-650	15	11
1.4742	Annealed	212	270	500-700	12	9
1.4762	Annealed	223	280	520-720	10	7
Ferritic-austenitic steels						
1.4821	Quenched	235	400	600–850	16	12
Austenitic steels						
1.4878	Quenched	192	210	500–750	40	30
1.4828	Quenched	223	230	500–750	30	22
1.4833	Quenched	192	210	500–750	35	26
1.4845	Quenched	192	210	500–750	35	26
1.4841	Quenched	223	230	550–800	30	22
1.4864	Quenched	223	230	550–800	30	22
1.4876	Recryst. annealed	192	210	500–750	30	22
	Solution annealed	192	170	450–700	30	22

[a] According to SEW 470 [9.11]

Table 9.33 Long-term mechanical properties of heat-resistant steels at high temperatures: average values of scatter bands

Grade[a]	Temperature (°C)	1% creep limit (MPa) at $t =$ 1000 h	10 000 h	Creep rupture strength (MPa) at $t =$ 1000 h	10 000 h	100 000 h
Ferritic and ferritic-austenitic steels						
1.4713	500	80	50	160	100	55
1.4720	600	27.5	17.5	55	35	20
1.4724	700	8.5	4.7	17	9.5	5
1.4742	800	3.7	2.1	7.5	4.3	2.3
1.4762	900	1.8	1.0	3.6	1.9	1.0
1.4821						
Austenitic steels						
1.4878	600	110	85	185	115	65
	700	45	30	80	45	22
	800	15	10	35	20	10
1.4828	600	120	80	190	120	65
1.4833	700	50	25	75	36	16
	800	20	10	35	18	7.5
	900	8	4	15	8.5	3.0
1.4845	600	150	105	230	160	80
1.4841	700	53	37	80	40	18
	800	23	12	35	18	7
	900	10	5.7	15	8.5	3.0
1.4864	600	105	80	180	125	75
	700	50	35	75	45	25
	800	25	15	35	20	7
	900	12	5	15	8	3
1.4876	600	130	90	200	152	114
(Solution annealed)	700	70	40	90	68	47
	800	30	15	45	30	19
	900	13	5	20	11	4

[a] According to SEW 470 [9.11]

Table 9.34 Physical properties of heat-resisting steels

Grade[a]	Density at 20 °C ($g\,cm^{-3}$)	Mean coefficient of thermal expansion between 20 °C and T (°C) (in $10^{-6}\,K^{-1}$)						Thermal conductivity at T (°C) ($W\,m^{-1}\,K^{-1}$)		Specific heat at 20 °C ($J\,g^{-1}\,K^{-1}$)	Specific electrical resistivity at 20 °C ($\Omega\,mm^2\,m^{-1}$)
		200	400	600	800	1000	1200	20	500		
Ferritic steels											
1.4713	7.7	11.5	12.0	12.5	13.0	–	–	23	25	0.45	0.70
1.4720	7.7	11.0	12.0	12.5	13.0	–	–	25	28	0.45	0.60
1.4724	7.7	11.0	11.5	12.0	12.5	13.5	–	21	23	0.45	0.90
1.4742	7.7	10.5	11.5	12.0	12.5	13.5	–	19	25	0.45	0.95
1.4762	7.7	10.5	11.5	12.0	12.5	13.5	15.0	17	23	0.45	1.10
Ferritic-austenitic steels											
1.4821	7.7	13.0	13.5	14.0	14.5	15.0	15.5	17	23	0.50	0.90
Austenitic steels											
1.4878	7.9	17.0	18.0	18.5	19.0	–	–	15	21	0.50	0.75
1.4828	7.9	16.5	17.5	18.0	18.5	19.5	–	15	21	0.50	0.85
1.4833	7.9	16.0	17.5	18.0	18.5	19.5	–	15	19	0.50	0.80
1.4845	7.9	15.5	17.0	17.5	18.0	19.0	–	14	19	0.50	0.85
1.4841	7.9	15.5	17.0	17.5	18.0	19.0	19.5	15	19	0.50	0.90
1.4864	8.0	15.0	16.0	17.0	17.5	18.5	–	13	19	0.50	1.00
1.4876	8.0	15.0	16.0	17.0	17.5	18.5	–	12	19	0.50	1.00

[a] According to SEW 470 [9.11]

Table 9.35 Resistance of heat-resisting steels in various media

Grade[a]	Resistance to Carburization	Sulfurous gases Oxidizing	Reducing	Nitrogenous and low-oxygen gases	Maximum operating temperature in air (°C)
Ferritic steels					
1.4713	Medium	Very high	Medium	Low	800
1.4762	Medium	Very high	High	Low	1150
Ferritic-austenitic steels					
1.4821	Medium	High	Medium	Medium	1100
Austenitic steels					
1.4878	Low	Medium	Low	High	850
1.4828	Low	Medium	Low	High	1000
1.4841	Low	Medium	Low	High	1150
1.4864	High	Medium	Low	High	1100

[a] According to SEW 470 [9.11]

bon can diffuse into the steel, reacting with the chromium to form chromium carbides which can lead to embrittlement and reduced scaling resistance due to chromium depletion in the matrix. Higher Ni and Si contents reduce the carburization susceptibility. In sulfur-containing atmospheres, which contain the sulfur mostly in the form of SO_2 or H_2S, the formation of sulfides at the surface may inhibit the formation of the protecting oxide layer. Under oxidizing conditions this process will proceed rather slowly, but under reducing conditions the pick-up of sulfur occurs very fast. This is especially true with Ni-alloyed steels due to the formation at about 650 °C of a low-melting Ni/NiS eutectic. Thus under such conditions the ferritic steels are more stable than the austenitic grades. In sulfur-containing atmospheres the maximum service temperatures will be about 100–200 °C lower than in air.

The heat-resistant steels are weldable by the usual processes, with arc welding preferred over gas fusion welding. For the ferritic steels, the tendency to grain coarsening in the heat affected zone has to be kept in mind. The application of austenitic filler metals will lead to better mechanical properties of the weld connection than those of the base metal (however, with respect to the scaling resistance, different thermal expansions of the ferritic and austenitic materials may be a problem). Filler materials should be at least as highly alloyed as the base metal. In sulfurizing atmospheres it is advisable to use ferritic electrodes for the cap passes only in order to ensure a tough weld. Post-weld heat treatments are generally not necessary.

9.6 Tool Steels

Tool steels are the largest group of materials used to make tools for cutting, forming, or otherwise shaping a material into a part or component. An extensive account is given in [9.14]. Other major groups of tool materials are cemented carbides (Sect. 9.6) and ceramics including diamond (Chap. 6).

The most commonly used materials are wrought tool steels, which are either carbon, alloy, or high-speed steels capable of being hardened by quenching and tempering to hardness levels $\leq 70\,\mathrm{HRC}$. High-speed tool steels are so named because of their suitability to machine materials at high cutting speed. Other steels used for metalworking applications include steels produced by powder metallurgy, medium-carbon alloy steels, high-carbon martensitic stainless steels, and maraging steels.

Wrought tool steels are essentially hardenable alloy steels with relatively high contents of the carbide forming elements Cr, Mo, W, and V. If the steels are quenched and tempered, the dependence of their hardness on tempering temperature indicates the level of hardening achieved as well as its temperature stability, (Fig. 9.19). The rate of effective softening at tempering temperatures up to about 300 °C is mainly due to the competing effects of recovery and the precipitation of iron carbides (Table 9.1). The hardening at higher

Table 9.36 Alloy carbides occurring in tool steels

Type of carbide	Prototype	Lattice type	Occurrence, composition[a]
M_7C_3	Cr_7C_3	Hexagonal	In Cr alloy steels M = **Cr**
$M_{23}C_6$	$Cr_{23}C_6$	fcc	In high-Cr steels M = **Cr**, Fe, W, Mo
M_6C	W_6C	fcc	M = **W**, **Mo**, Cr, V, Co
M_2C	W_2C	Hexagonal	M = **W**, **Mo**, Cr
MC	VC	fcc	VC

[a] Bold letters indicate major components

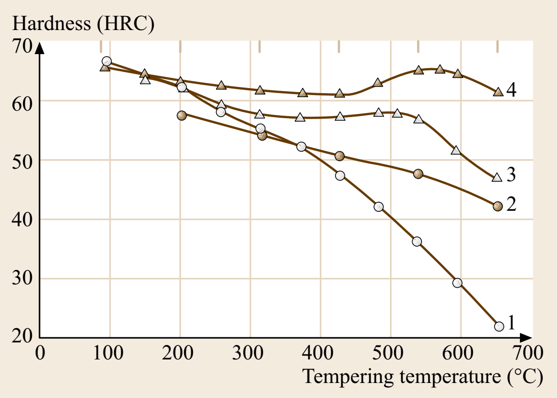

Fig. 9.19 Isothermal (1 h) tempering curves of 4 typical tool steels. *Curves 1* and *2*: softening of AISI grade W (water-hardening) and O (oil-hardening) steels; *Curves 3* and *4*: softening and secondary hardening of AISI grade A2 (air-hardening medium alloy) and M2 (Mo high-speed) steels (after [9.14])

temperatures is associated with the precipitation of alloy carbides which can form at elevated temperatures only because of their high melting points and transformation kinetics. They give rise to a second maximum on isothermal tempering curves, as curves 3 and 4 in Fig. 9.19, which is referred to as secondary hardening.

The alloy carbide phases which precipitate and give rise to secondary hardening are listed in Table 9.36. Co is an alloying element which raises the high temperature stability of tool steels by raising their melting temperature. Figure 9.20 shows this effect by a comparison of the hardness versus temperature data for non-Co-based and Co-based high-speed tool steels.

Table 9.37 gives composition ranges for the tool steels most commonly used. According to the AISI classification, each group of similar composition and properties is given a capital letter, somewhat related to the major alloying element. Thus, high-speed steels are classified by M for molybdenum and T for tungsten. Within each group individual types are assigned code numbers.

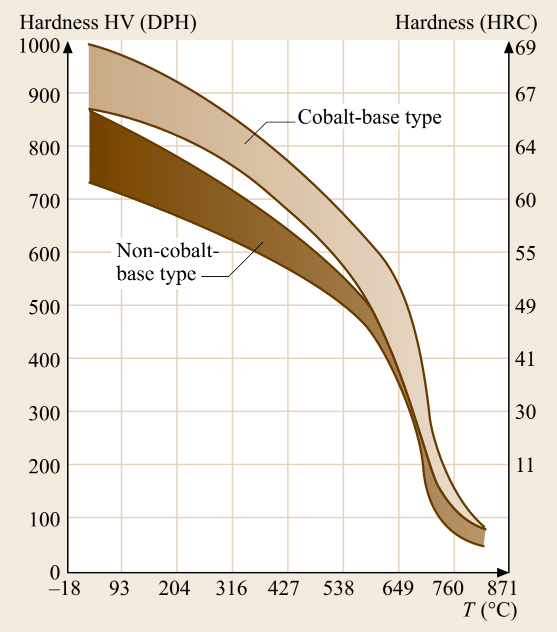

Fig. 9.20 Comparison of the hot hardness of Co-bearing versus non-Co bearing high-speed tool steels (after [9.14])

The basic properties of tool steels that determine their performance in service are hardness, wear resistance, ductility and fracture toughness, and in many applications stability against softening at elevated temperatures. Characteristic mechanical properties at room temperature as a function of hardening treatment are listed for group L and group S steels in Table 9.38.

Table 9.37 Composition ranges of principle types of tool steels according to AISI and UNS classifications. All steels except group W contain 0.25 max wt% Cu, 0.03 max wt% P, and 0.03 max wt% S; group W steels contain 0.20 max wt% Cu, 0.025 max wt% P, and 0.025 max wt% S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group A, D, H, M and T steels. (after [9.14])

Designation		Composition (wt%)								
AISI	UNS No.	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Molybdenum high-speed steels										
M1	T11301	0.78–0.88	0.15–0.40	0.20–0.50	3.50–4.00	0.30 max	8.20–9.20	1.40–2.10	1.00–1.35	–
M2	T11302	0.78–0.88; 0.95–1.05	0.15–0.40	0.20–0.45	3.75–4.50	0.30 max	4.50–5.50	5.50–6.75	1.75–2.20	–
M3, class 1	T11313	1.00–1.10	0.15–0.40	0.20–0.45	3.75–4.50	0.30 max	4.75–6.50	5.00–6.75	2.25–2.75	–
M3, class 2	T11323	1.15–1.25	0.15–0.40	0.20–0.45	3.75–4.50	0.30 max	4.75–6.50	5.00–6.75	2.75–3.75	–
M4	T11304	1.25–1.40	0.15–0.40	0.20–0.45	3.75–4.75	0.30 max	4.25–5.50	5.25–6.50	3.75–4.50	–
M7	T11307	0.97–1.05	0.15–0.40	0.20–0.55	3.50–4.00	0.30 max	8.20–9.20	1.40–2.10	1.75–2.25	–
M10	T11310	0.84–0.94; 0.95–1.05	0.10–0.40	0.20–0.45	3.75–4.50	0.30 max	7.75–8.50	–	1.80–2.20	–
M30	T11330	0.75–0.85	0.15–0.40	0.20–0.45	3.50–4.25	0.30 max	7.75–9.00	1.30–2.30	1.00–1.40	4.50–5.50
M33	T11333	0.85–0.92	0.15–0.40	0.15–0.50	3.50–4.00	0.30 max	9.00–10.00	1.30–2.10	1.00–1.35	7.75–8.75
M34	T11334	0.85–0.92	0.15–0.40	0.20–0.45	3.50–4.00	0.30 max	7.75–9.20	1.40–2.10	1.90–2.30	7.75–8.75
M35	T11335	0.82–0.88	0.15–0.40	0.20–0.45	3.75–4.50	0.30 max	4.50–5.50	5.50–6.75	1.75–2.20	4.50–5.50
M36	T11336	0.80–0.90	0.15–0.40	0.20–0.45	3.75–4.50	0.30 max	4.50–5.50	5.50–6.50	1.75–2.25	7.75–8.75
M41	T11341	1.05–1.15	0.20–0.60	0.15–0.50	3.75–4.50	0.30 max	3.25–4.25	6.25–7.00	1.75–2.25	4.75–5.75
M42	T11342	1.05–1.15	0.15–0.40	0.15–0.65	3.50–4.25	0.30 max	9.00–10.00	1.15–1.85	0.95–1.35	7.75–8.75
M43	T11343	1.15–1.25	0.20–0.40	0.15–0.65	3.50–4.25	0.30 max	7.50–8.50	2.25–3.00	1.50–1.75	7.75–8.75
M44	T11344	1.10–1.20	0.20–0.40	0.30–0.55	4.00–4.75	0.30 max	6.00–7.00	5.00–5.75	1.85–2.20	11.00–12.25
M46	T11346	1.22–1.30	0.20–0.40	0.40–0.65	3.70–4.20	0.30 max	8.00–8.50	1.90–2.20	3.00–3.30	7.80–8.80
M47	T11347	1.05–1.15	0.15–0.40	0.20–0.45	3.50–4.00	0.30 max	9.25–10.00	1.30–1.80	1.15–1.35	4.75–5.25
M48	T11348	1.42–1.52	0.15–0.40	0.15–0.40	3.50–4.00	0.30 max	4.75–5.50	9.50–10.50	2.75–3.25	8.00–10.00
M62	T11362	1.25–1.35	0.15–0.40	0.15–0.40	3.50–4.00	0.30 max	10.00–11.00	5.75–6.50	1.80–2.10	–
Tungsten high-speed steels										
T1	T12001	0.65–0.80	0.10–0.40	0.20–0.40	3.75–4.50	0.30 max	–	17.25–18.75	0.90–1.30	–
T2	T12002	0.80–0.90	0.20–0.40	0.20–0.40	3.75–4.50	0.30 max	1.0 max	17.50–19.00	1.80–2.40	–
T4	T12004	0.70–0.80	0.10–0.40	0.20–0.40	3.75–4.50	0.30 max	0.40–1.00	17.50–19.00	0.80–1.20	4.25–5.75
T5	T12005	0.75–0.85	0.20–0.40	0.20–0.40	3.75–5.00	0.30 max	0.50–1.25	17.50–19.00	1.80–2.40	7.00–9.50
T6	T12006	0.75–0.85	0.20–0.40	0.20–0.40	4.00–4.75	0.30 max	0.40–1.00	18.50–21.00	1.50–2.10	11.00–13.00
T8	T12008	0.75–0.85	0.20–0.40	0.20–0.40	3.75–4.50	0.30 max	0.40–1.00	13.25–14.75	1.80–2.40	4.25–5.75
T15	T12015	1.50–1.60	0.15–0.40	0.15–0.40	3.75–5.00	0.30 max	1.00 max	11.75–13.00	4.50–5.25	4.75–5.25

Table 9.37 (continued)

Designation		Composition (wt%)								
AISI	UNS No.	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Intermediate high-speed steels										
M50	T11350	0.78–0.88	0.15–0.45	0.20–0.60	3.75–4.50	0.30 max	3.90–4.75	–	0.80–1.25	–
M52	T11352	0.85–0.95	0.15–0.45	0.20–0.60	3.50–4.30	0.30 max	4.00–4.90	0.75–1.50	1.65–2.25	–
Chromium hot-worked steels										
H10	T20810	0.35–0.45	0.25–0.70	0.80–1.20	3.00–3.75	0.30 max	2.00–3.00	–	0.25–0.75	–
H11	T20811	0.33–0.43	0.20–0.50	0.80–1.20	4.75–5.50	0.30 max	1.10–1.60	–	0.30–0.60	–
H12	T20812	0.30–0.40	0.20–0.50	0.80–1.20	4.75–5.50	0.30 max	1.25–1.75	1.00–1.70	0.50 max	–
H13	T20813	0.32–0.45	0.20–0.50	0.80–1.20	4.75–5.50	0.30 max	1.10–1.75	–	0.80–1.20	–
H14	T20814	0.35–0.45	0.20–0.50	0.80–1.20	4.75–5.50	0.30 max	–	4.00–5.25	–	–
H19	T20819	0.32–0.45	0.20–0.50	0.20–0.50	4.00–4.75	0.30 max	0.30–0.55	3.75–4.50	1.75–2.20	4.00–4.50
Tungsten hot-worked steels										
H21	T20821	0.26–0.36	0.15–0.40	0.15–0.50	3.00–3.75	0.30 max	–	8.50–10.00	0.30–0.60	–
H22	T20822	0.30–0.40	0.15–0.40	0.15–0.40	1.75–3.75	0.30 max	–	10.00–11.75	0.25–0.50	–
H23	T20823	0.25–0.45	0.15–0.40	0.15–0.60	11.00–12.75	0.30 max	–	11.00–12.75	0.75–1.25	–
H24	T20824	0.42–0.53	0.15–0.40	0.15–0.40	2.50–3.50	0.30 max	–	14.00–16.00	0.40–0.60	–
H25	T20825	0.22–0.32	0.15–0.40	0.15–0.40	3.75–4.50	0.30 max	–	14.00–16.00	0.40–0.60	–
H26	T20826	0.45–0.55[a]	0.15–0.40	0.15–0.40	3.75–4.50	0.30 max	–	17.25–19.00	0.75–1.25	–
Molybdenum hot-worked steels										
H42	T20842	0.55–0.70[a]	0.15–0.40	–	3.75–4.50	0.30 max	4.50–5.50	5.50–6.75	1.75–2.20	–
Air-hardening, medium-alloy, cold-worked steels										
A2	T30102	0.95–1.05	1.00 max	0.50 max	4.75–5.50	0.30 max	0.90–1.40	–	0.15–0.50	–
A3	T30103	1.20–1.30	0.40–0.60	0.50 max	4.75–5.50	0.30 max	0.90–1.40	–	0.80–1.40	–
A4	T30104	0.95–1.05	1.80–2.20	0.50 max	0.90–2.20	0.30 max	0.90–1.40	–	–	–
A6	T30106	0.65–0.75	1.80–2.50	0.50 max	0.90–1.20	0.30 max	0.90–1.40	–	–	–
A7	T30107	2.00–2.85	0.80 max	0.50 max	5.00–5.75	0.30 max	0.90–1.40	0.50–1.50	3.90–5.15	–
A8	T30108	0.50–0.60	0.50 max	0.75–1.10	4.75–5.50	0.30 max	1.15–1.65	1.00–1.50	–	–
A9	T30109	0.45–0.55	0.50 max	0.95–1.15	4.75–5.50	1.25–1.75	1.30–1.80	–	0.80–1.40	–
A10	T30110	1.25–1.50[a]	1.60–2.10	1.00–1.50	–	1.55–2.05	1.25–1.75	–	–	–
High-carbon, high-chromium, cold-worked steels										
D2	T30402	1.40–1.60	0.60 max	0.60 max	11.00–13.00	0.30 max	0.70–1.20	–	1.10 max	–
D3	T30403	2.00–2.35	0.60 max	0.60 max	11.00–13.50	0.30 max	–	1.00 max	1.00 max	–
D4	T30404	2.05–2.40	0.60 max	0.60 max	11.00–13.00	0.30 max	0.70–1.20	–	1.00 max	–
D5	T30405	1.40–1.60	0.60 max	0.60 max	11.00–13.00	0.30 max	0.70–1.20	–	1.00 max	2.50–3.50
D7	T30407	2.15–2.50	0.60 max	0.60 max	11.50–13.50	0.30 max	0.70–1.20	–	3.80–4.40	–

Table 9.37 (continued)

Designation		Composition (wt%)								
AISI	UNS No.	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Oil-hardening cold-worked steels										
O1	T31501	0.85–1.00	1.00–1.40	0.50 max	0.40–0.60	0.30 max	–	0.40–0.60	0.30 max	–
O2	T31502	0.85–0.95	1.40–1.80	0.50 max	0.50 max	0.30 max	0.30 max	–	0.30 max	–
O6	T31506	1.25–1.55[b]	0.30–1.10	0.55–1.50	0.30 max	0.30 max	0.20–0.30	–	–	–
O7	T31507	1.10–1.30	1.00 max	0.60 max	0.35–0.85	0.30 max	0.30 max	1.00–2.00	0.40 max	–
Shock-resisting steels										
S1	T41901	0.40–0.55	0.10–0.40	0.15–1.20	1.00–1.80	0.30 max	0.50 max	1.50–3.00	0.15–0.30	–
S2	T41902	0.40–0.55	0.30–0.50	0.90–1.20	–	0.30 max	0.30–0.60	–	0.50 max	–
S5	T41905	0.50–0.65	0.60–1.00	1.75–2.25	0.50 max	–	0.20–1.35	–	0.35 max	–
S6	T41906	0.40–0.50	1.20–1.50	2.00–2.50	1.20–1.50	–	0.30–0.50	–	0.20–0.40	–
S7	T41907	0.45–0.55	0.20–0.90	0.20–1.00	3.00–3.50	–	1.30–1.80	–	0.20–0.30[c]	–
Low-alloy special-purpose tool steels										
L2	T61202	0.45–1.00[a]	0.10–0.90	0.50 max	0.70–1.20	–	0.25 max	–	0.10–0.30	–
L6	T61206	0.65–0.75	0.25–0.80	0.50 max	0.60–1.20	1.25–2.00	0.50 max	–	0.20–0.30[c]	–
Low-carbon mold steels										
P2	T51602	0.10 max	0.10–0.40	0.10–0.40	0.75–1.25	0.10–0.50	0.15–0.40	–	–	–
P3	T51603	0.10 max	0.20–0.60	0.40 max	0.40–0.75	1.00–1.50	–	–	–	–
P4	T51604	0.12 max	0.20–0.60	0.10–0.40	4.00–5.25	–	0.40–1.00	–	–	–
P5	T51605	0.10 max	0.20–0.60	0.40 max	2.00–2.50	0.35 max	–	–	–	–
P6	T51606	0.05–0.15	0.35–0.70	0.10–0.40	1.25–1.75	3.25–3.75	–	–	–	–
P20	T51620	0.28–0.40	0.60–1.00	0.20–0.80	1.40–2.00	–	0.30–0.55	–	–	–
P21	T51621	0.18–0.22	0.20–0.40	0.20–0.40	0.50 max	3.90–4.25	–	–	0.15–0.25	1.05–1.25Al
Water-hardening tool steels										
W1	T72301	0.70–1.50[d]	0.10–0.40	0.10–0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	–
W2	T72302	0.85–1.50[d]	0.10–0.40	0.10–0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.15–0.35	–
W3	T72303	1.05–1.15	0.10–0.40	0.10–0.40	0.40–0.60	0.20 max	0.10 max	0.15 max	0.10 max	–

[a] Available in several carbon ranges.
[b] Contains free graphite in the microstructure.
[c] Optional.
[d] Specified carbon ranges are designated by suffix numbers.

Table 9.38 Mechanical properties of group L and group S tool steels at room temperature as a function of hardening treatment (after [9.14])

Type	Condition	Tensile strength (MPa)	0.2% yield strength (MPa)	Elongation in 50 mm (%)	Reduction in area (%)	Hardness (HRC)
L2	Annealed	710	510	25	50	96 HRB
	Oil quenched from 855 °C and single tempered at:					
	205 °C	2000	1790	5	15	54
	315 °C	1790	1655	10	30	52
	425 °C	1550	1380	12	35	47
	540 °C	1275	1170	15	45	41
	650 °C	930	760	25	55	30
L6	Annealed	655	380	25	55	93 HRB
	Oil quenched from 845 °C and single tempered at:					
	315 °C	2000	1790	4	9	54
	425 °C	1585	1380	8	20	46
	540 °C	1345	1100	12	30	42
	650 °C	965	830	20	48	32
S1	Annealed	690	415	24	52	96 HRB
	Oil quenched from 925 °C and single tempered at:					
	205 °C	2070	1895	–	–	57.5
	315 °C	2025	1860	4	12	54
	425 °C	1790	1690	5	17	50.5
	540 °C	1680	1525	9	23	47.5
	650 °C	1345	1240	12	37	42
S5	Annealed	725	440	25	50	96 HRB
	Oil quenched from 870 °C and single tempered at:					
	205 °C	2345	1930	5	20	59
	315 °C	2240	1860	7	24	58
	425 °C	1895	1690	9	28	52
	540 °C	1515	1380	10	30	48
	650 °C	1035	1170	15	40	37
S7	Annealed	640	380	25	55	95 HRB
	Oil quenched from 940 °C and single tempered at:					
	205 °C	2170	1450	7	20	58
	315 °C	1965	1585	9	25	55
	425 °C	1895	1410	10	29	53
	540 °C	1820	1380	10	33	51
	650 °C	1240	1035	14	45	39

9.7 Cast Irons

The term cast iron pertains to a large family of multicomponent Fe-C-Si alloys which solidify according to the eutectic of the Fe-C system (Sect. 9.1; Fig. 9.1). They are treated extensively in [9.15]. Their comparatively high C and Si contents lead to solidification either according to the metastable equilibria involving Fe_3C or according to the stable equilibria involving graphite, depending, also, on the content of further alloying elements, melt treatment, and rate of cooling. Since, in addition, the metallic phases can be alloyed and their microstructures varied by annealing and transformation treatments as in other ferrous alloys, a multitude of microstructural states and associated properties result.

9.7.1 Classification

The C rich phases determine the basic classification of cast irons. According to the color of their facture surfaces, Fe_3C-containing grades are called white, graphite-containing grades are called gray, and alloys which solidify in mixed states are called mottled. In addition, the shape of the graphite phase particles and the microstructure of the metallic matrix phases are taken into account since they are also characterizing the mechanical properties.

Shape of Graphite Phase Particles

Lamellar (flake) graphite (FG) is characteristic of cast irons with near-zero ductility; spheroidal (nodular) graphite (SG) is characteristic of ductile cast iron; compacted (vermicular) graphite (CG) is a transition form between flake and nodule shape; temper graphite (TG) results from a tempering treatment and consists of small clusters of branched graphite lamellae.

Microstructure of Metallic Matrix Phases

Ferritic, pearlitic, austenitic, bainitic (austempered). More details are presented in Fig. 9.21 and Table 9.39.

9.7.2 Iron-Carbon-Silicon Equilibria and Carbon Equivalent

Since C and Si are the alloying elements which dominate the solidification behavior and the resulting microstructures of cast irons, their phase equilibria need to be taken into account. Figure 9.22 shows a section through the metastable ternary Fe-C-Si diagram at 2 wt% Si which approximates the Si content of many cast irons. Compared to the binary Fe-C system, the addition of Si decreases the stability of Fe_3C and increases the stability of ferrite, as indicated by the expansion of the α-phase field. With increasing Si concentration, the C concentrations of the eutectic and the eutectoid equilibria decrease while their temperatures increase.

These relations are the basis for correlating the C and Si concentrations with the ranges of formation of steels and of the main groups of cast irons as shown in Fig. 9.23. The relations are expressed in terms of the carbon equivalent (CE) $\mathrm{CE} = (\mathrm{wt\%\,C}) + (1/3)(\mathrm{wt\%\,Si})$. The concentration of the eutectic (upper dashed line) is given by $\mathrm{CE_e} = 4.3$. Accordingly, alloys with $\mathrm{CE} < 4.3$ are hypoeutectic and alloys with $\mathrm{CE} > 4.3$ are hypereutectic. In P-containing cast irons the relation is $\mathrm{CE} = (\mathrm{wt\%\,C}) + (1/3)(\mathrm{wt\%\,Si} + \mathrm{wt\%\,P})$. In addition, shows the limit of solubility of C in austen-

Table 9.39 Classification of cast irons according to commercial designation, microstructure and color of fracture surface (after [9.15])

Commercial designation	Carbon-rich phase	Matrix[a]	Fracture	Final structure after
Gray iron	Lamellar graphite	P	Gray	Solidification
Ductile iron	Spheroidal graphite	F, P, A	Silver-gray	Solidification or heat treatment
Compacted graphite iron	Compacted (vermicular) graphite	F, P	Gray	Solidification
White iron	Fe_3C	P, M	White	Solidification and heat treatment[b]
Mortled iron	Lamellar graphite + Fe_3C	P	Mottled	Solidification
Malleable iron	Temper graphite	F, P	Silver-gray	Heat treatment
Austempered ductile iron	Spheroidal graphite	At	Silver-gray	Heat treatment

[a] F: ferrite; P: pearlite; A: austenite; M: martensite; At: austempered (bainite)
[b] White irons are not usually heat treated, exept for stress relief and to continue austenite transformation

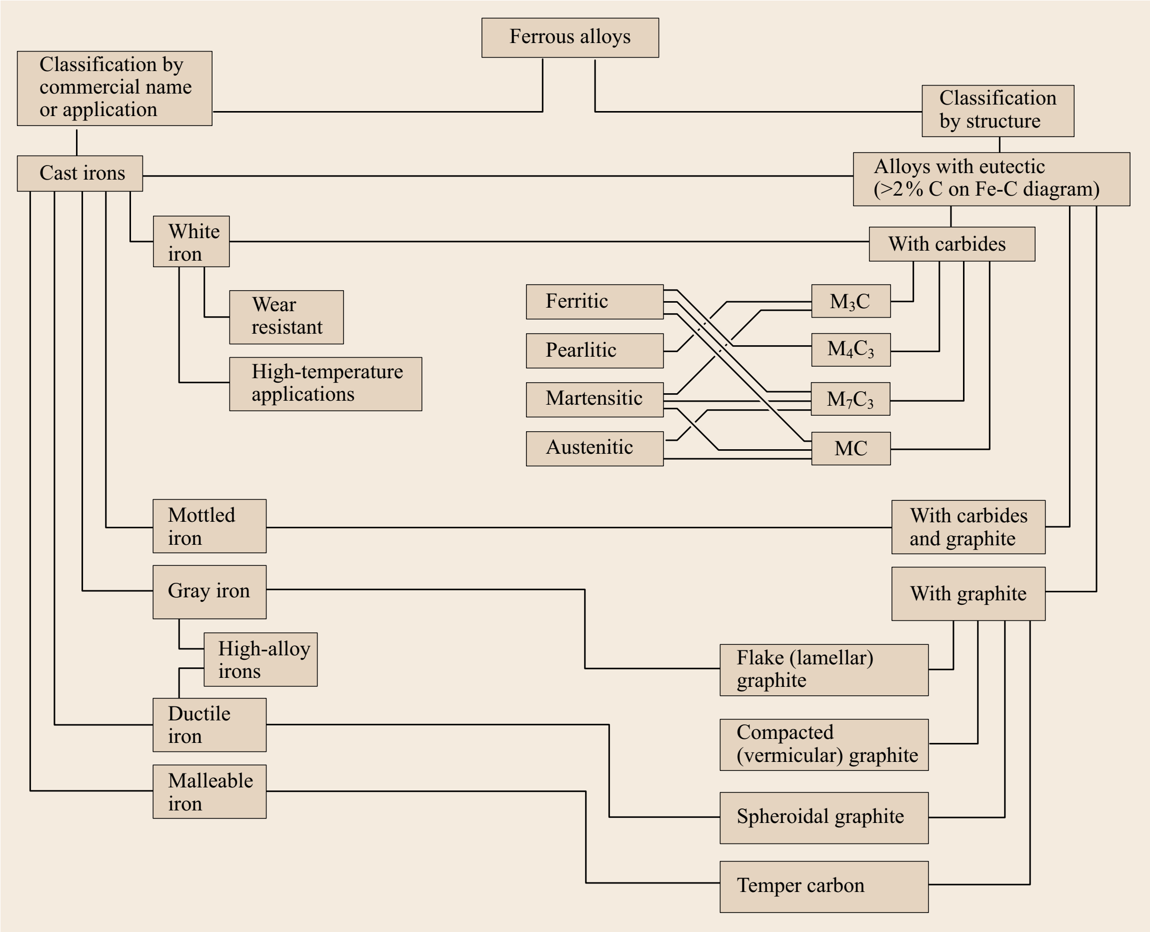

Fig. 9.21 Classification of cast irons (after [9.15])

ite (lower dashed line), which is the upper limit of the range of steels. It is given by $\mathrm{CE}_{\gamma_{\max}} = 2.1 = (\mathrm{wt\%\,C}) + (1/6)(\mathrm{wt\%\,Si})$.

9.7.3 Grades of Cast Irons

Table 9.40 lists the composition ranges of typical unalloyed cast irons, indicating that they are classified mainly by the type of carbon-rich phase formed and by the basic mechanical behavior.

Gray Iron

This most common type of cast iron is characterised by flake graphite and requires a high CE to ensure a sufficient graphitization potential which is also increased by Al addition. Gray irons may be moderately

Table 9.40 Range of composition, microstructural and mechanical characteristics of typical unalloyed cast irons (after [9.15])

Type	Carbon phase	Concentration range (wt%)				
		C	Si	Mn	P	S
Gray	FG	2.5–4.0	1.0–3.0	0.2–1.0	0.002–1.0	0.02–0.25
Compacted graphite	CG	2.5–4.0	1.0–3.0	0.2–1.0	0.01–0.1	0.01–0.03
Ductile	SG	3.0–4.0	1.8–2.8	0.1–1.0	0.01–0.1	0.01–0.03
White	Fe_3C	1.8–3.6	0.5–1.9	0.25–0.8	0.06–0.2	0.06–0.2
Malleable	Fe_3C/TG	2.2–2.9	0.9–1.9	0.15–1.2	0.02–0.2	0.02–0.2

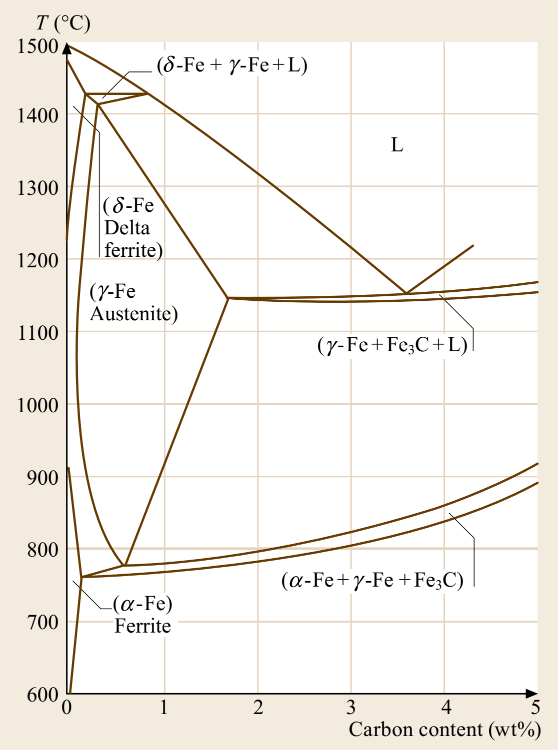

Fig. 9.22 Section through the metastable Fe-C-Si phase diagram at 2 wt% Si (after [9.15])

alloyed, e.g., by 0.2–0.6 wt% Cr, 0.2–1 wt% Mo, and 0.1–0.2 wt% V which promote the formation of alloy carbides and pearlite. Upon plastic deformation the flake form of graphite promotes early internal crack formation and, thus, causes the low ductility of gray iron.

Ductile Iron

This cast iron is characterized by the spheroidal graphite phase (SG) in its microstructure. Spheroidal graphite is formed during solidification if the melt has been treated by the addition of a component which promotes the particular nucleation and growth behavior of graphite in the form of nodules. The most common alloying component added to nucleate spheroidal graphite is Mg, but Ca, Ce, La, and Y have also been found to favour spheroidal graphite formation. Basically this microstructural modification leads to higher yield strength and higher ductility because the plastic deformation of the metallic matrix phases can be extended to higher strains than in gray iron before fracture sets in.

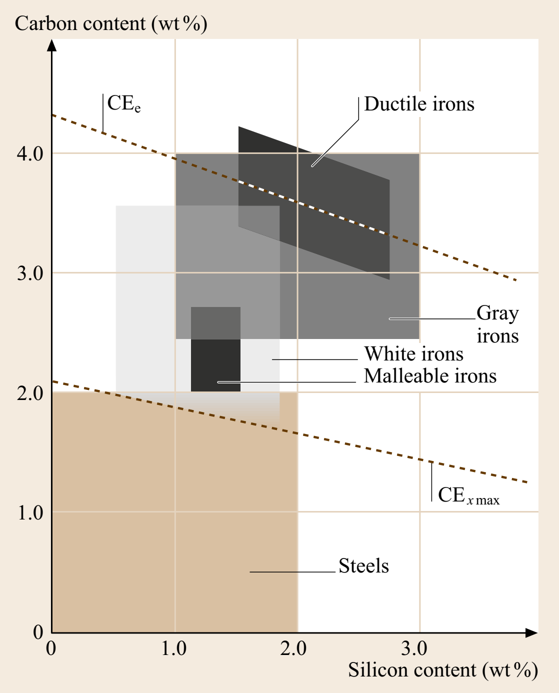

Fig. 9.23 Approximate C and Si concentrations for the composition ranges of steels and different grades of cast irons (after [9.15])

Malleable Irons

The melt treatment of malleable cast irons involves Mg, Ca, Bi, or Te additions. But malleable irons have an as-cast structure consisting of Fe_3C in a pearlitic matrix. By heat treatment in the range of 800–970 °C the cementite phase is transformed into graphite (TG). The cooling is controlled in such a way as to promote pearlite formation, ferrite formation, or a mixture of the two.

Alloy Cast Irons

Alloying elements beyond the levels mentioned above are added to cast irons almost exclusively to enhance resistance to abrasive wear or chemical corrosion, or to extend their stability for application at elevated temperature. The function of the alloying elements is essentially the same as in steels. Table 9.41 lists the groups of grades with typical compositions and the microstructural constituents present in the as-cast state.

Table 9.41 Ranges of alloy content of typical alloy cast irons (after [9.15]). Where a single value is given rather than a range, that value is a maximum limit

Description	**Composition (wt%)**[a]									**Matrix structure as-cast**[c]
	TC[b]	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**	**Cu**	
Abrasion-resistant white irons										
Low-carbon white iron[d]	2.2–2.8	0.2–0.6	0.15	0.15	1.0–1.6	1.5	1.0	0.5	[e]	CP
High-carbon, low-silicon white iron	2.8–3.6	0.3–2.0	0.30	0.15	0.3–1.0	2.5	3.0	1.0	[e]	CP
Martensitic nickel-chromium iron	2.5–3.7	1.3	0.30	0.15	0.8	2.7–5.0	1.1–4.0	1.0	–	M, A
Martensitic nickel, high-chromium iron	2.5–3.6	1.3	0.10	0.15	1.0–2.2	5.0–7.0	7.0–11.0	1.0	–	M, A
Martensitic chromium-molybdenum iron	2.0–3.6	0.5–1.5	0.10	0.06	1.0	1.5	11.0–23.0	0.5–3.5	1.2	M, A
High-chromium iron	2.3–3.0	0.5–1.5	0.10	0.06	1.0	1.5	23.0–28.0	1.5	1.2	M
Corrosion-resistant irons										
High-silicon iron[f]	0.4–1.1	1.5	0.15	0.15	14.0–17.0	–	5.0	1.0	0.5	F
High-chromium iron	1.2–4.0	0.3–1.5	0.15	0.15	0.5–3.0	5.0	12.0–35.0	4.0	3.0	M, A
Nickel-chromium gray iron[g]	3.0	0.5–1.5	0.08	0.12	1.0–2.8	13.5–36.0	1.5–6.0	1.0	7.5	A
Nickel-chromium ductile iron[h]	3.0	0.7–4.5	0.08	0.12	1.0–3.0	18.0–36.0	1.0–5.5	1.0	–	A
High-resistant gray iron										
Medium-silicon iron[i]	1.6–2.5	0.4–0.8	0.30	0.10	4.0–7.0	–	–	–	–	F
Nickel-chromium iron[g]	1.8–3.0	0.4–1.5	0.15	0.15	1.0–2.75	13.5–36.0	1.8–6.0	1.0	7.5	A
Nickel-chromium-silicon iron[j]	1.8–2.6	0.4–1.0	0.10	0.10	5.0–6.0	13.0–43.0	1.8–5.5	1.0	10.0	A
High-aluminium iron	1.3–2.0	0.4–1.0	0.15	0.15	1.3–6.0	–	20.0–25.0 Al	–	–	F
Heat resistant ductile irons										
Medium-silicon ductile iron	2.8–3.8	0.2–0.6	0.08	0.12	2.5–6.0	1.5	–	2.0	–	F
Nickel-chromium ductile iron[h]	3.0	0.7–2.4	0.08	0.12	1.75–5.5	18.0–36.0	1.75–3.5	1.0	–	A
Heat-resistant white irons										
Ferritic grade	1.0–2.5	0.3–1.5	–	–	0.5–2.5	–	30.0–35.0	–	–	F
Austenitic grade	1.0–2.0	0.3–1.5	–	–	0.5–2.5	10.0–15.0	15.0–30.0	–	–	A

[a] Where a single value is given rather than a range, that value is a maximum limit

[b] Total carbon; [c] CP: coarse pearlite; M: martensite; A: austenite; F: ferrite

[d] Can be produced from a malleable-iron base composition

[e] Copper can replace all or part of the nickel

[f] Such as Durion, Durichlor 51, Superchlor

[g] Such as Ni-resist austenitic iron (ASTM A 436)

[h] Such as Ni-resist austenitic ductile iron (ASTM A 439)

[i] Such as Silal

[j] Such as Nicrosilal

9.7.4 Mechanical Properties of Cast Irons

Due to the multitude of as-cast structures as a function of alloy composition, melt treatment, cooling rate (as influenced by the cooling conditions and the cross section of the work piece), and subsequent heat treatment, there is a wide range of mechanical properties which can be achieved according to the requirements of the application. Table 9.42 gives a survey in terms of characteristic examples.

Table 9.42 Mechanical properties of cast irons

Material	**$R_{p0.2}$ (N mm^{-2}), minimum**	**R_m (N mm^{-2}), minimum**	**A_5 (%), minimum**	**Matrix microstructure, unspecified**	**Material number**[a]	**Short code**[a]
Gray cast irons (FG) DIN 1691		100[b]		Mainly ferritic	0.6010	GG-10
		200[b]			0.6020	GG-20
		350[b]			0.6035	GG-35
Ductile cast irons (SG) DIN 1693	250[c]	390[c]	15[d]	Pearlitic-ferritic	0.7040	GGG-40
	360[c]	600[c]	2[d]	Mainly pearlitic	0.7060	GGG-60
	400[c]	700[c]	2[d]	Wide variation permissable	0.7070	GGG-70
White malleable irons (TG)		350[d]	4	Core: granular pearlite	0.8035	GTW-35-04
DIN 1692	260[b]	450[d]	7	Core: lamellar to granular pearlite	0.8045	GTW-45-07
	220[b]	400[d]	5	Ferrite	0.8040	GTW-40-05
Black malleable irons (TG) DIN 1692	200[c]	350[d]	10	Pearlite, ferrite	0.8135	GTS-35-10
	270[c]	450[d]	6	Pearlite	0.8145	GTS-45-06
	430[c]	650[d]	2	Hardened	0.8165	GTS-65-02
	530[c]	700[d]	2		0.8170	GTS-70-02
Austenitic alloy cast irons (FG) DIN 1694		140/220	–		0.6652	GGL-NiMn13-7
		190/240	12		0.6661	GGL NiCr20-3
		170/240	–		0.6680	GGL-NiSiCr30-5-5
Austenitic cast iron (SG) DIN 1694	210	390	15[d]		0.7652	GGG-NiMn13-7
	210	390	7[d]		0.7661	GGG NiCr20-3
	240	390	–		0.7680	GGG-NiSiCr30-5-5
	210	370	7[d]		0.7685	GGG-NiCr35-3

[a] According to German Materials Standard

[b] The values refer to a cylindrical test specimen of 30 mm in diameter corresponding to a wall thickness of 15 mm. The tensile strength values to be expected depend on the wall thickness. Example: GG-20.

Wall thickness (mm)	2.5–5.5	5.5–10	10–20	20–40	40–80	80–150
R_m (N mm^{-2})	230	205	180	155	130	115

[c] Diameter of the test rod: 12 or 15 mm. For cast parts with a thickness < 6 mm tensile test specimens.

[d] For a cylindrical test specimen of 12 mm in diameter. The mechanical properties depend on the diameter of the test specimen. Example: GTW-45-07

Diameter of the test rod (mm)	9	12	15
R_m (N mm^{-2})	400	450	480
$R_{p0.2}$ (N mm^{-2})	230	260	280

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