

Chapter 8

Aero Steels: Part 2—High Alloy Steels

M. Srinivas and A. Venugopal Reddy

Abstract Highly alloyed steels (total alloying element content more than 8 wt%) are generally classified as secondary hardening steels, maraging steels and precipitation hardening (stainless) steels. The effects of alloying elements on microstructure and mechanical properties are briefly described in this chapter. The manufacturing procedures and optimum processing parameters are discussed, and the heat treatment schedules and achievable properties are tabulated. Details on machining and weldability of these steels are also provided.

Keywords High alloy steels • Chemical compositions • Processing • Heat treatment • Mechanical properties

8.1 Introduction

High alloyed steels are defined as those having alloying element content more than 8 wt%. These steels are broadly categorized into three groups, namely Co + Mo secondary hardening steels, maraging steels, and precipitation hardening stainless steels. Some of these highly alloyed steels belong to the ultrahigh strength category where yield strengths are greater than 1380 MPa. Unlike low alloy steels, these ultrahigh strength high alloy steels do not have poor ductility, toughness and stress corrosion resistance.

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8.2 Secondary Hardening Steels

Secondary hardening steels belong to the quenched and tempered class of steels containing sufficient amount of carbide-forming elements (Cr, W, Mo, V). Tempering in the temperature range 500–600 °C forms fine dispersions of alloy carbides (Cr_7C_3 , W_2C , Mo_2C , VC_x) that replace the coarse cementite particles and are more stable. In the classical description of tempering, secondary hardening corresponds to the fourth stage of tempering. The replacement of coarse carbides by fine dispersions of alloy carbides occurs due to the enhanced diffusivity of carbide-forming substitutional solute atoms like Cr, Mo and V at higher tempering temperatures, and results in a hardening effect in contrast to the normal softening effect. Secondary hardening steels have a number of commercial applications such as tool steels and high strength structural applications due to their combination of ultrahigh strength and toughness.

The main alloying elements in this class of highly alloyed steels are carbon (0.2–0.5 wt%), molybdenum (0.2–2.0 wt%), chromium (0.2–1.0 wt%), cobalt (3.5–5 wt%) and nickel (7.0–10.0 wt%). International standards have classified them mainly based on their composition, which is considered to be both rational and convenient for the steel producers and users.

8.2.1 *Effects of Alloying Elements in Secondary Hardening Steels*

Increasing carbon content increases the peak hardness and strength in the secondary hardening regime, and this effect is directly related to increased volume fractions of alloy carbides [1]. An increase in strength with increasing carbon content results in a decrease in toughness. However, this effect is less marked for the high carbon grades. Increasing carbon content also decreases the ratio of notch tensile strength to yield strength, irrespective of strength level. Because of this, an optimum carbon content has to be chosen for a specific application.

Nickel increases the strength primarily by increasing the hardenability of the steel such that a lath martensite microstructure is formed. Nickel also lowers the ductile–brittle transition temperature and keeps the material ductile at room temperature even at high strength levels. The improvement of impact toughness with nickel addition is associated with enhancement of cross-slip at high strain rates and/or lower temperatures. Nickel also lowers the martensite start temperature, M_s , resulting in an increase in retained austenite. However, this increase in retained austenite content can be balanced by cobalt additions.

Cobalt addition increases the M_s temperature, refines the martensite structure and leads to retention of dislocation substructures at higher tempering temperatures, resulting in finer precipitation of dislocation-nucleated alloy carbides. Cobalt has several effects on the mechanical properties, depending on the baseline steel:

1. The effect of up to 8 wt% cobalt on tempering behaviour of carbon-free, 10 wt % Ni steel is to increase the hardness via a solid solution effect that is maintained throughout the tempering temperature range.
2. The influence of cobalt content on strength and impact toughness of a 5Ni–Cr–Mo–0.25C steel is shown in Fig. 8.1. It is seen that addition of 6 wt% Co increases the yield strength in the secondary hardening temperature range 425–540 °C. On the other hand, addition of 8 wt% Co increases the strength at all tempering temperatures, although the notch toughness decreases with increasing cobalt content particularly in the secondary hardening regime.
3. Cobalt additions to a 0.12C–10Ni steel increase the hardness and strength values at all tempering temperatures, see Fig. 8.2.

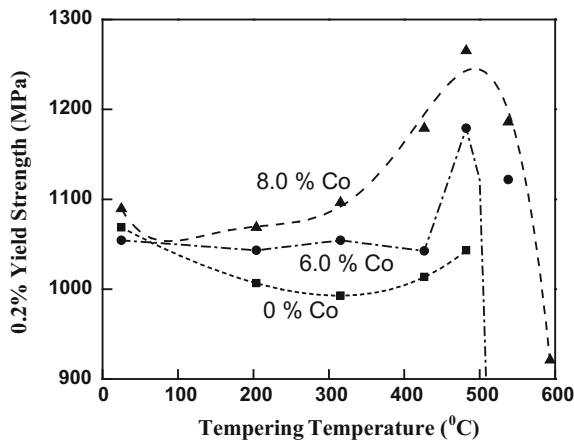


Fig. 8.1 Effect of cobalt content on tempering response of 5Ni–Cr–Mo steels [11]. Base composition: 0.25C, 0.75 Mn, 5Ni, 1.5 Cr, 0.5 Mo; austenitization: 815 °C-1 h; WQ; tempering time: 5 h

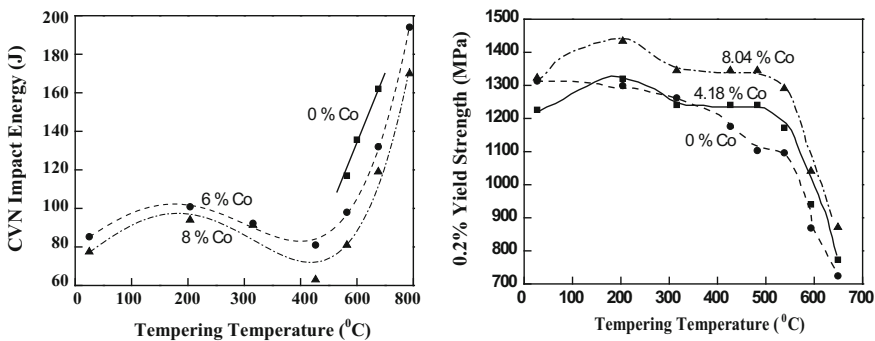


Fig. 8.2 Effect of cobalt content on the tempering response of 0.12C–10Ni–2Cr–1Mo steels [1, 11]. Austenitization: 815 °C-1 h; WQ; tempering time: 5 h

It is evident from Figs. 8.1 and 8.2 that the increased yield strength at the secondary hardening peak is higher in 10Ni–Co–Cr–Mo steels than in 5Ni–Cr–Mo steels. In addition, in 10Ni–Co–Cr–Mo steels the toughness is lower at lower tempering temperatures than those resulting in the peak yield strength. In other words, the toughness increases with increase in yield strength in the temperature range where the yield strength peak appears.

Manganese behaves in a similar manner to nickel. However, the manganese content is limited to 0.35 wt%, since further amounts do not contribute to the toughness.

Silicon additions increase the strength and decrease the toughness of the steels. In addition, silicon shifts the temper embrittlement regime from 260 °C to 425–480 °C. Hence special melting practices must be employed to keep silicon content as low as possible.

Effect of carbide-forming elements: Increasing the amount of carbide formers such as molybdenum and chromium also leads to higher peak hardness and strength [1]. The increase in hardness and strength can be attributed to the increase in alloy carbide content. Chromium in the presence of molybdenum goes into solution in the Mo_2C and results in a hardness increase. These carbide-forming elements are kept at minimum levels in medium carbon steels when high toughness is required. However, in low-carbon-containing steels these elements do not have a detrimental effect on toughness and hence they help in increased strength, weldability, temper resistance and elevated temperature properties [2].

Vanadium addition in low concentrations acts as a grain refiner and reduces the reaction rates of the pearlite and bainite transformations in HP 9-4-X steels.

Fracture in ultrahigh strength high-toughness steels occurs by microvoid nucleation, growth and coalescence. Therefore the well-known decrease in toughness with increased strength depends on factors that influence the microvoid coalescence. Microvoid nucleation occurs at inclusions and alloy carbides, with decohesion first occurring at large inclusions. The inclusion content can be minimized by adopting advanced melting practices. By increasing the size and spacing between inclusions for the same volume fraction, it is possible to achieve increased toughness. When the inclusion content is maintained constant, refining the size of the alloy carbides leads to a significant improvement in toughness. This is because more energy must be expended to nucleate microvoids at smaller carbides, such that they can then link up with the larger microvoids already nucleated at inclusions [1].

8.2.2 Processing and Thermal Treatments

Secondary hardening steels are produced by electric arc melting (EAM)/vacuum induction melting (VIM) followed by consumable-electrode vacuum arc remelting (VAR), depending on the stringency requirements. The optimum combinations of properties are obtained using vacuum arc remelting plus carbon deoxidation. The

hot working processes are similar to those used for AISI 4340 or similar medium carbon low alloy steels.

The maximum soaking temperature has been set at 1120 °C for carbon deoxidized material, to prevent grain coarsening in the absence of significant amounts of aluminium. Forging of VAR + carbon deoxidized steel ingots of HP 9-4-45 and HP 9-4-25 has to be carried out to 75 % of maximum reduction and a maximum finish temperature of 1040–1065 °C.

8.2.3 HP 9-4-X Steels

The chemical compositions of HP 9-4-X steels are given in Table 8.1. Heat treatments and mechanical properties given in Tables 8.2, 8.3, and 8.4 are discussed after these tables.

The HP 9-4-X steels, where X represents carbon contents over the approximate range 0.2–0.5C, can be through-thickness hardened up to diameters of 10–30 cm, respectively, using water quenching. The strongest grade HP 9-4-45 can give very high strength, but a refrigeration step should be included to transform retained austenite. Higher toughness is obtained from a bainitic treatment, which results in slightly lower yield strength. For the HP 9-4-30, HP 9-4-25 and HP 9-4-20 grades only a martensitic treatment is recommended.

HP 9-4-30: This steel is widely used because of an optimum combination of strength and fracture toughness: HP 9-4-25 has lower strength and HP 9-4-45 has poor fracture toughness. HP 9-4-30 steel is usually melted in an electric arc furnace followed by VAR. Forging temperatures should not exceed 1120 °C. This steel has good hardenability and a fully martensitic structure can be obtained in section thicknesses up to 150 mm.

The heat treatment requirements are as follows:

1. **Normalizing.** Austenitize between 870 and 925 °C and hold for 1 h per 25 mm of thickness, and air cool.
2. **Annealing.** Heat to 620 °C, soak for 24 h and furnace cool.

Table 8.1 Chemical compositions (wt%) of HP 9-4-X steels

Steels	C	Mn	Si	P	S	Ni	Co	Mo	Cr	V	Al
HP 9-4-45	0.42–0.48	0.10–0.25	0.10 max	0.01 max	0.01 max	7.0–8.5	3.5–4.5	0.2–0.35	0.2–0.35	0.06–0.12	–
HP 9-4-30	0.29–0.34	0.10–0.35	0.10 max	0.01 max	0.01 max	7.0–8.0	4.25–4.75	0.9–1.1	0.9–1.1	0.06–0.12	–
HP 9-4-25	0.24–0.30	0.10–0.35	0.10 max	0.01 max	0.01 max	7.5–9.0	3.5–4.5	0.35–0.55	0.35–0.55	0.06–0.12	–
HP 9-4-20	0.16–0.23	0.10–0.35	0.20 max	0.01 max	0.01 max	8.5–9.5	4.25–4.75	0.9–1.1	0.65–0.85	0.06–0.12	–

Table 8.2 Standard thermal treatments for HP 9-4-X steels

Steels	Normalizing temperature (°C)	Austenitizing temperature (°C)	Quenching media	Cryogenic treatment	Tempering temperature (°C), and microstructure
HP 9-4-45	870–900	790–815	Oil	Refrigerate at -73°C	205 for 2 + 2 h <i>tempered martensite</i>
	870–900	790–815	Molten salt at 240–245 °C	–	240–245 for 4–8 h <i>AC bainite</i>
HP 9-4-30	900–930	830–855	Oil	Refrigerate at -73°C	540 for 2 + 2 h <i>tempered martensite</i>
	900–930	830–855	Molten salt at 445–455 °C for 6–8 h	–	445–455 for 6–8 h <i>bainite</i>
HP 9-4-25	900–930	830–855	Oil or water	–	540 for 2 h <i>tempered martensite</i>
HP 9-4-20	885–915	800–830	Water	–	540–565 for 4–8 h <i>tempered martensite</i>

AC Air cooled

Table 8.3 Mechanical properties of HP 9-4-X steels

Materials and conditions	UTS (MPa)	0.2 % YS (MPa)	Elongation on 50 mm (%)	RA (%)	CVN impact (J)	K_{Ic} (MPa $\sqrt{\text{m}}$)	Hardness (R _c)
HP 9-4-45 (martensitic)	1930–2070	1680–1790	6–10	20–35	14–16	55–77	51
HP 9-4-45 (bainitic)	1790–1930	1520–1620	12–14	40–50	27–41	71–104	51
HP 9-4-30 (martensitic)	1520–1660	1310–1380	12–16	50–60	27–34	110–132	44
HP 9-4-30 (bainitic)	1520–1660	1310–1389	12–16	50–60	34–41	132–148	44
HP 9-4-25 (martensitic)	1345–1450	1225–1325	15–18	55–65	43–54	>154	42
HP 9-4-20 (martensitic)	1310–1480	1240–1345	14–20	61–71	68–98	170–192	41

- Hardening.** Austenitize at 830–860 °C and soak for 1 h per 25 mm of thickness (1 h minimum); quench in water or oil. Cryogenic treatment of at least 1 h at -87 to -60°C is applied to convert retained austenite into martensite.
- Tempering.** Heat to 200–600 °C, depending on the desired strength and toughness. Double tempering is preferred: the most widely used tempering

Table 8.4 Room temperature mechanical properties of HP 9-4-30 steel

Heat treatment	UTS (MPa)	0.2 % YS (MPa)	Elongation in 4D (%)	RA (%)	CVN impact (J)	K_{Ic} (MPa \sqrt{m})	Hardness (R _C)
845 °C OQ + -73 ° C + double temper at 205 °C	1650–1790	1380–1450	8–12	25–35	20–27	66–99	49–53
845 °C OQ + -73 ° C + double temper at 550 °C	1520–1650	1310–1380	12–16	35–50	24–34	99–115	44–48

treatment is heating to between 540 and 580 °C and soaking for 2 h, and air cool, followed by 2 h more at the same elevated temperature.

5. Stress relief after welding restrained systems. Heat to 540 °C and hold for 24 h; air cool to ambient temperature.

HP 9-4-30 can be formed by bending and rolling, and is weldable in the heat-treated condition. Tungsten inert gas welding is recommended, and after welding the components have to be stress relieved at 540 °C for 24 h. This steel is available as billet, bar, rod, plate, sheet and strip. It is extensively used in pressure vessels, rotor shafts, drop hammer rods, aircraft structural components and high strength shock absorbing automotive parts.

8.2.4 AF1410 Steel

This steel is resistant to stress corrosion cracking and can be used in advanced submarine hulls and aircraft components. The chemical composition and mechanical properties of AF1410 steel are given in Tables 8.5 and 8.6. Processing and heat treatments are discussed in the following paragraphs.

The preferred melting route for AF1410 is VIM followed by VAR. However, melting may be carried out employing VIM followed by VAR/electroslag remelting (ESR). Melting practice requires that trace and impurity elements be kept very low to achieve high fracture toughness. AF1410 is forgeable to 1120 °C, and a minimum of 40 % reduction should be given below 900 °C to attain optimum properties. This steel is air hardenable up to 75-mm-thick sections and is easily weldable, with continuous-wave gas tungsten arc welding preferred.

Table 8.5 Chemical composition (wt%) of AF1410 steel

Steel	C	Mn	Si	P	S	Ni	Co	Mo	Cr	V	Al	Fe
AF1410	0.13–0.17	0.10 max	0.10 max	0.01 max	0.01 max	9.5–10.5	13.5–14.5	0.9–1.1	1.8–2.2	–	–	Balance

Table 8.6 Effect of quench media on mechanical properties of AF1410 steel

Quench medium	UTS (MPa)	0.2 % YS (MPa)	Elongation in 4D (%)	RA (%)	CVN impact (J)	K_{Ic} (MPa \sqrt{m})
Air	1680	1475	16	69	69	174
Oil	1750	1545	16	69	65	154
Water	1710	1570	16	70	65	160

The microstructure after quenching from the austenitizing temperature consists of highly dislocated Fe–Ni lath martensite. The choice of ageing and tempering schedules is very important, as may be inferred from the following reactions:

- Ageing/tempering at 425 °C gives rise to Fe₃C, while tempering at 455 °C results in precipitation of (Fe–Cr–Mo)-containing M₂C carbides.
- Ageing/tempering at 480 °C converts the (Fe–Cr–Mo)-containing M₂C carbides into (Mo–Cr)-containing M₂C carbides.
- Increasing the temperature to 510 °C results in M₂C beginning to coarsen; and at 540 °C M₆C starts replacing M₂C.

AF1410 steel attains maximum strength when aged for 5 h at 480 °C, the peak secondary hardening temperature. The toughness is very dependent on ageing temperature: minimum impact toughness results from ageing at 425 °C; over the range 425–540 °C, the impact energy attains a maximum value when aged at 508 °C. Ageing above 540 °C reduces both strength and toughness.

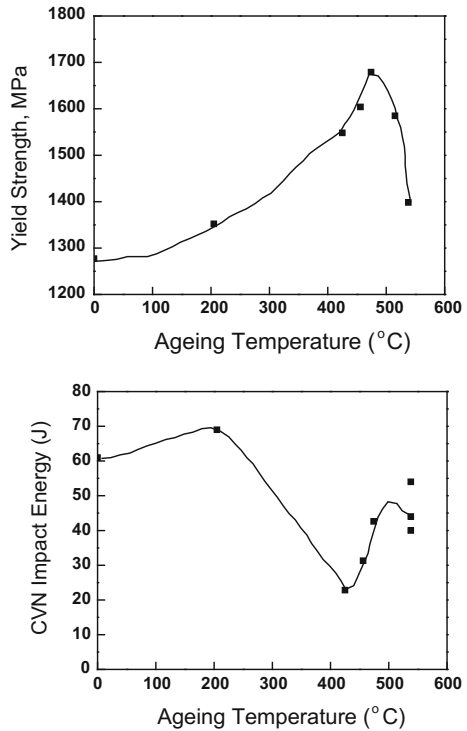
The heat treatment requirements are as follows:

1. Normalizing and overageing. Austenitize between 880 and 900 °C and hold for 1 h per 25 mm of thickness, and air cool and overage at 675 °C for 5 h minimum. This treatment is best suited to achieve good machinability.
2. Stress relief. After normalizing and overageing a stress relief treatment at 675 °C may be applied.
3. Hardening. Double austenitize at 870–900 °C and soak for 1 h per 25 mm of thickness (1 h minimum); quench either in water, oil or air; a cryogenic treatment for 1 h at –87 to –60 °C is optional.
4. Tempering/ageing. The most widely used tempering treatment is heating to 480–510 °C for 5–8 h followed by air cooling. The effects of ageing temperature on the strength and impact energy are shown in Fig. 8.3.

8.2.5 AerMet Steels

AerMet steels are another group of Ni–Co–Cr–Mo secondary hardening steels used for many critical aerospace applications. Based on the attainable strength levels, AerMet steels are designated as AerMet 100, AerMet 310 and AerMet 340.

Fig. 8.3 Variations of strength and impact toughness with ageing temperature for AF1410 steel [12]



- AerMet 100 steel provides high hardness and strength coupled with extraordinary fracture toughness and stress corrosion resistance. This steel is used up to about 425 °C for landing gear components, jet engine shafts, drive shafts, structural tubing, fasteners, actuators, armour and ordnance.
- AerMet 310 alloy possesses higher strength than AerMet 100 and may be used in similar applications for components requiring ultrahigh strength, high fracture toughness and exceptional stress corrosion cracking resistance.
- AerMet 340 possesses the highest strength and may be considered for applications like structural tubing, drive shafts, springs, connecting rods and crank shafts.

The chemical compositions and mechanical properties of AerMet steels are given in Tables 8.7 and 8.8. Processing and heat treatments are discussed in the following paragraphs.

Table 8.7 Chemical compositions (wt%) of AerMet steels

Steels	C	Ni	Co	Mo	Cr	Ti	Al	Fe
AerMet 100	0.23	11.1	13.4	1.2	3.1	0.05 max	–	Balance
AerMet 310	0.25	11.0	15.0	1.4	2.4	0.05 max	–	Balance
AerMet 340	0.33	12.0	15.60	1.85	2.25	–	–	Balance

Table 8.8 Mechanical properties of AerMet steels after ageing at 485 °C

Steels	UTS (MPa)	0.2 %YS (MPa)	Elongation in 4D (%)	RA (%)	CVN impact (J)	K_{Ic} (MPa \sqrt{m})	Hardness (R_C)
AerMet 100	1980	1697	16	67	45.6	132	53.0–54.0
AerMet 310	2170	1900	14.5	63	27.1	71.5	55
AerMet 340	2379	2068	11	53	15	37	56.5

The AerMet steels are manufactured using VIM + VAR melting. Forging for primary breakdown should be done at a maximum starting temperature of 1230 °C. Finish forging should be done from 980 °C, with a finishing temperature less than 900 °C. Forged parts should be air cooled to ambient temperature followed by annealing. After annealing, the forgings should be normalized to restore the properties of the dead zones.

Machining of AerMet steels is more difficult than for normal medium carbon low alloy steels (Rockwell hardness R_C38), and requires carbide-tipped tools. After rough machining, a stress relief treatment may be given at 425 °C for 1–3 h, as desired. AerMet 100 is weldable and requires no pre-heating or post-heating. All three steels are available in the form of billet, plate, round bars, sheets, tubes, strip and wire, including welding wire.

The heat treatment requirements are as follows:

1. Normalizing.

- AerMet 100: Austenitize between 900 and 925 °C and hold for 1 h per 25 mm of thickness, and air cool. Optimum softening for machining is obtained by normalizing at 900 °C followed by overage annealing at 675 °C for 16 h.
 - AerMet 310: Austenitize at 970 °C and hold for 1 h per 25 mm of thickness, and air cool. Optimum softening for machining is obtained by normalizing at 970 °C followed by overage annealing at 675 °C for 16 h.
 - AerMet340: Austenitize at 968 °C and hold for 1 h per 25 mm of thickness, and air cool. Optimum softening for machining is obtained by normalizing at 968 °C followed by overage annealing at 675 °C for 16 h.
2. Stress relief. After normalizing and overageing a stress relief treatment at 675 °C may be applied.
 3. Annealing. Heat to 677 °C, soak for 16 h, and air cool. The maximum annealed hardness is R_C 40.
 4. Hardening. Austenitize at 870–900 °C for AerMet 100; 900–925 °C for AerMet 310; and 955–988 °C for AerMet340. Soak for 1 h per 25 mm of thickness (1 h minimum). The alloys should be cooled from the austenitizing temperature to 65 °C in 1–2 h to obtain optimum properties. Water quenching is not recommended. However, sections larger than 50 mm diameter or 25 mm thickness

must be quenched with oil in order to reach 65 °C in 1–2 h. Individual sections up to 50 mm diameter or 25-mm-thick plates should be air cooled to 65 °C in 1–2 h. Cryogenic treatment is then to be given for 1 h at –75 °C, followed by warming to room temperature.

5. Tempering/ageing. The standard ageing treatment is to hold at a temperature between 475 and 488 °C for 5 h. AerMet steels should never be aged below 468 °C, since this results in very low toughness.
6. Straightening. Though AerMet steels show minimum distortion during heat treatment, some parts may require mechanical straightening. Prior to straightening a low temperature stress relief treatment at 175/205 °C for 5 h has to be given after cryogenic treatment.
7. Decarburization. Similar to other carbon-containing high strength steels, AerMet alloys undergo decarburization during hardening. Heat treatment should be done in a neutral atmosphere furnace, salt bath or under vacuum. The depth of decarburization should be determined by microhardness measurements of a small test sample and should never exceed 10 % of the thickness/diameter.

8.2.6 Ferrium Steels

Ferrium C61 and C64 steels are carburizing steels that provide higher core strength and corrosion resistance, high fracture toughness, high temperature resistance and high surface hardenability as compared to medium carbon low alloy steels intended for similar applications, e.g. AISI 9310 and AISI 8620. Ferrium C61 develops a surface hardness of R_C 60–62, and Ferrium C64 develops a surface hardness of R_C 62–64. These Ferrium alloys attain these superior properties due to nano-size M_2C carbide dispersions in a Ni–Co lath martensitic matrix.

The chemical compositions and mechanical properties of Ferrium C61 and C64 are given in Tables 8.9 and 8.10. These alloys are generally double vacuum melted (VIM + VIM/VAR). They can be used as gears, shafts, actuators and other power transmission components. They have the advantages of compactness, weight savings, high temperature resistance and durability compared to other regularly used steels for similar applications.

Table 8.9 Chemical compositions (wt%) of Ferrium steels

Steels	C	Ni	Co	Mo	Cr	W	Fe
Ferrium C61	0.15	9.5	18.00	1.10	3.5	–	Balance
Ferrium C64	0.11	7.50	16.30	1.75	3.50	0.20	Balance

Table 8.10 Mechanical properties of Ferritic steels

Steels	UTS (MPa)	0.2 % YS (MPa)	Elongation in 4D (%)	RA (%)	Achievable surface hardness (R_C)	Core hardness (R_C)	K_{Ic} (MPa \sqrt{m})	Tempering temperature ($^{\circ}C$)
Ferritic C61	1656	1552	16	70	60–62	48–50	143	482
Ferritic C64	1580	1373	18	75	62–64	48–50	93.5	496

8.3 Maraging Steels

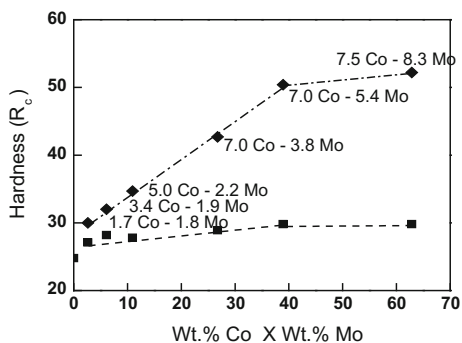
The maraging steels are a group of interstitial-free Ni–Co–Mo–Ti high alloy steels. Maraging steels belong to a class of ultrahigh strength steels where the strengthening mechanism is different from the classical mechanism associated with carbon martensite, bainite or precipitation of carbides during tempering. Maraging steels have very low carbon content, replacing this with elements like Mo and Ti that produce age hardening in Fe–Ni martensite. These steels attain ultrahigh strength from precipitation of intermetallic compounds during ageing of martensite, hence the name *maraging*.

Maraging steels have a wide range of aerospace applications such as missile casings, aircraft forgings, cannon recoil springs, Belleville springs, bearings, transmission shafts, fan shafts in commercial jet engines, couplings, hydraulic hoses and bolts.

The development of maraging steels was started in the late 1950s by the International Nickel Company [3]. Initial work started with 20 and 25 wt% nickel steel [4]. However, the 20 and 25 % nickel-containing steels were not pursued further as they were very brittle at ultrahigh strength levels [5].

The most common maraging steels are based on the 18Ni–Co–Mo type: the effects of cobalt and molybdenum on hardening of Fe–Ni martensite were studied in detail in the 1960s. Figure 8.4 shows the synergistic effect of cobalt and molybdenum on the age hardenability of Fe-18 % Ni alloys [6].

Fig. 8.4 Effects of Co \times Mo contents on maximum hardness of Fe-18.5–20.1 wt % Ni alloys [6]: *filled diamonds* maraged 3–10 h at 425–480 $^{\circ}C$; *filled squares* annealed 1 h at 870 $^{\circ}C$, air cooled



The Fe-18 % Ni binary was chosen as base since higher nickel contents result in excessive retained austenite. Generally, the heat treatment of maraging steels consists of solutionizing at 815–820 °C, followed by air cooling to room temperature, which results in complete transformation to martensite. In these steels complete hardenability is achieved irrespective of cooling rate, since the carbon content is low and the nickel content is high. In the annealed condition the hardness is around R_C 30 and the steels can be readily machined or fabricated. Ultrahigh strength is achieved by maraging, namely ageing at 485 °C for 3–6 h. Maraging steels can be welded without preheat in both the annealed and aged conditions.

8.3.1 Effects of Alloying Elements in Maraging Steels

The main alloying elements in maraging steels are Ni, Co, Mo and Ti (in addition to iron):

Nickel: Ni ensures a lath martensite structure, lowers the resistance of the crystal lattice to dislocation movements, and reduces the energy of interaction of dislocations with interstitial atoms [7]. Nickel promotes stress relaxation and reduces susceptibility to brittle fracture.

Cobalt: Co lowers the lattice resistance to dislocation movements and reduces the energy of interaction between dislocations and interstitial atoms. In addition, cobalt raises the M_s temperature and allows increased amounts of alloying elements that induce hardening during ageing without leading to retained austenite. Further, cobalt increases the amount of age hardening by reducing the solubility of the hardening elements Ti and Mo in α -iron, thereby increasing the volume fraction of the precipitates. Figure 8.5 shows (somewhat indirectly) the effect of cobalt and titanium on the UTS for all the specific grades (grades 200 through 500) of maraging steels.

Molybdenum: Mo lowers the diffusion coefficients of a number of elements in the grain boundaries and thereby reduces the preferential precipitation of second phase particles during ageing. This helps in increasing the ductility and plasticity in the aged condition.

Titanium: Ti acts as a hardening element as well as refining element by binding residual carbon.

Aluminium: At concentrations above 0.2–0.3 wt% aluminium lowers the ductility. The addition of aluminium also leads to limited hardening of the martensite.

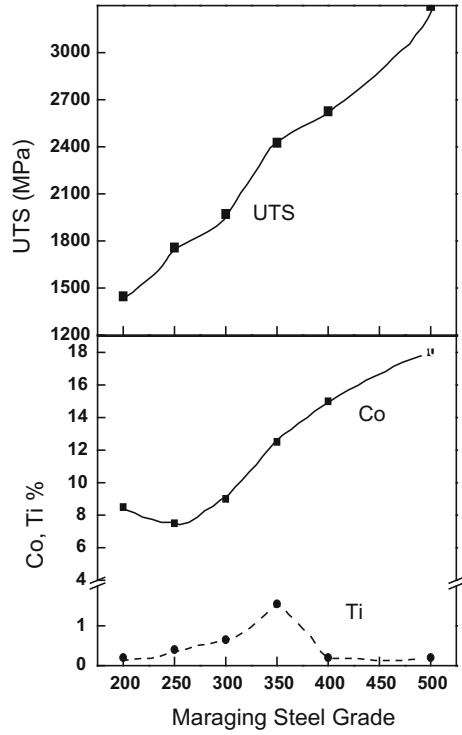
Manganese: Mn leads to the formation of martensite at low nickel contents, and reduces the ductility after ageing.

Chromium: Cr additions increase the corrosion resistance and increase the strain hardening coefficient of the martensite.

Silicon: Silicon above 0.1 wt% reduces the ductility.

Microstructure: The microstructure of maraging steels consists of soft Fe–Ni lath martensite. The martensite hardens during ageing owing to the following two mechanisms:

Fig. 8.5 UTS and cobalt and titanium contents plotted against the maraging steel grades [13]



1. Fine uniform precipitation of intermetallic precipitates or austenite.
2. An ordering reaction in the cobalt-containing solid solution.

The generally observed intermetallic precipitates are Ni_3Mo and Ni_3Ti .

The chemical compositions and mechanical properties for several maraging steels are given in Tables 8.11 and 8.12. Processing and heat treatments are discussed in Sect. 8.3.2.

Table 8.11 Chemical compositions (wt%) of maraging steels

Steels	C	Ni	Co	Mo	Ti	Al	Fe
18 Ni 200	<0.03	18	8.5	3.3	0.2	0.1	Balance
18 Ni 250	<0.03	18	8.5	5.0	0.4	0.1	Balance
18 Ni 300	<0.03	18	9.0	5.0	0.7	0.1	Balance
18 Ni 350	<0.03	18	12.5	4.2	1.6	0.1	Balance
18 Ni Cast	<0.03	17	10.0	4.6	0.3	0.1	Balance

Table 8.12 Mechanical properties and fracture toughness data for maraging steels

Steels	UTS (MPa)	0.2 %YS (MPa)	Elongation on 50 mm (%)	RA (%)	CVN impact (J)	K_{Ic} (MPa \sqrt{m})	Hardness (R _C)
18 Ni 200	1500	1400	10	60	35–68	155–240	44–48
18 Ni 250	1800	1700	8	55	24–45	99–165	48–50
18 Ni 300	2050	2000	7	40	16–26	88–143	51–55
18 Ni 350	2450	2400	6	25	–	35–50	–
18 Ni Cast	1750	1650	8	35	20	105	–

8.3.2 Processing and Heat Treatments of Maraging Steels

Maraging steels can be manufactured using either air or vacuum induction melting. For steels with higher titanium contents vacuum melting is desirable. VAR improves cleanliness and results in superior properties. Hence the general melting practice for aerospace quality is VIM followed by VAR.

Cast grade maraging steel can be melted and cast in air, since the steel has sufficient castability and fluidity [8]. For investment castings to have a good surface finish, vacuum melting is recommended [9, 10].

The wrought maraging steel grades are easily workable by means of forging, rolling, drawing and extrusion. Homogenizing of ingots at 1260 °C is recommended. Hot working may be carried out at temperatures between 1260 °C and 815 °C. To minimize scale formation the hot working may be started in the temperature range 1150–1049 °C. Finishing at low temperatures is desirable to obtain a fine grain size and optimum properties.

Precipitation of TiC films should be avoided. These films form during slow cooling after hot working in the temperature range 650–1095 °C. It is also important to note that long dwell times in this temperature range should be avoided. However, it is safe to heat the steel into this temperature range, since stable carbides will already have precipitated.

Maraging steels can be cold-worked in the solution-annealed condition. They have a very low work-hardening rate and hence can be subjected to heavy reductions.

The heat treatment requirements for wrought maraging steels are as follows:

1. Solutionizing. Solutionize at 820 °C for 1 h for each 25 mm of thickness, and air cool.
2. Ageing. Ageing is carried out for most grades at 480 °C for 3 h. In the case of 18Ni350, the ageing time is extended to 12 h.

For the 18Ni cast grade solutionizing is done at 1150 °C for 1 h for each 25 mm thickness. Primary ageing is at 595 °C for 1 h. This is followed by another solutionizing treatment at 820 °C for 1 h, and subsequent ageing at 480 °C for 3 h.

8.4 Precipitation Hardening (PH) Steels

Precipitation hardening (PH) stainless steels are a family of corrosion resistant alloys that achieve high strengths from the precipitation of alloy carbides and solid solution strengthening. These steels contain a minimum of 12 wt% chromium to obtain stainless properties. Many 12 % Cr steels have been developed to attain high strengths via the addition of carbide-forming elements such as tungsten, molybdenum and vanadium; several others derive their strength from precipitation of intermetallic compounds.

The family of PH stainless steels may be divided into three main types:

1. **Low-carbon martensitic.** Typical examples and chemical compositions of these steels are given in Table 8.13.
2. **Semi-austenitic.** These have a microstructure of single-phase austenite in the annealed condition, but transform to fully martensitic after ageing, or refrigeration, or deformation. Typical examples and chemical compositions of these steels are given in Table 8.14.

Table 8.13 Chemical compositions (wt%) of low carbon martensitic PH stainless steels

Steels	C	Cr	Ni	Cu	Mo	Ti	Al	Others	Fe
17-4 PH	0.07 max	15– 17.5	3–5	3–5	–	–	–	0.15–0.45 (Cb + Ta) 0.4 Mn	Balance
AM 363	0.05 max	11	4.0	–	–	1.0	–	–	Balance
PH 13-8Mo	0.05 max	12.25– 13.25	7.5– 8.5	–	2.0– 2.5	–	0.90– 1.35	–	Balance
Custom 450	0.05 max	14.0– 16.0	5.0– 7.0	1.25– 1.75	0.5– 1.0	–	–	8 × C min Nb	Balance

Table 8.14 Chemical compositions (wt%) of semi-austenitic PH stainless steels

Steels	C	Cr	Ni	Cu	Mo	Ti	Al	Others	Fe
15-7Mo PH	0.07	15.1	7.1	–	2.2	–	1.1	0.70 Mn	Balance
17-7 PH	0.07	17.0	7.1	–	–	–	1.1	0.70 Mn	Balance
AM 350 PH	0.08	16.5	4.3	–	2.8	–	–	0.1 N	Balance
AM 355 PH	0.13	15.5	4.3	–	2.8	–	–	0.1 N	Balance
PH 14–8Mo	0.04	14.4	8.2	–	2.2	–	1.1	–	Balance

Table 8.15 Chemical compositions (wt%) of fully austenitic PH stainless steels

Steels	C	Cr	Ni	Cu	Mo	Ti	Al	Others	Fe
17-10P PH	0.07	17.2	10.8	—	—	—	—	0.28 P, 0.75 Mn	Balance
(A286 Specification) AISI 600	0.04	15.25	26.0	—	1.25	2.15	0.15	0.25 V, 0.007 B	Balance

3. Fully austenitic. Fully austenitic grades are stable down to room temperature. The chemical compositions of fully austenitic steels are given in Table 8.15. Fully austenitic steels are the least widely used of the three classes of PH steels.

8.4.1 Mechanical Properties of Typical PH Stainless Steels

Mechanical properties for different heat treatment conditions of some of the steels listed in Tables 8.13, 8.14 and 8.15 are given in Table 8.16.

Table 8.16 Mechanical properties of different PH steels solution treated at 1038 ± 15 °C, followed by air cooling and ageing at different ageing temperatures

Steels	Conditions	UTS (MPa)	0.2 %YS (MPa)	Elongation in 4D (%)	Hardness
17-4 PH	H900	1448	1379	7	R _C 45
	H925	1379	1345	8	R _C 43
	H1025	1276	1172	8	R _C 38
	H1075	1207	1148	8	R _C 37
	H1150	1103	1034	11	R _C 35
17-7 PH	Austenite conditioning	896	276	35	R _B 85
	TH1050	1379	1276	9	R _C 43
	RH950	1620	1517	6	R _C 48
	Cold reduction to condition C	1517	1310	5	R _C 43
	CH900	1827	1793	2	R _C 49
15-7Mo PH	Austenite conditioning	896	372	35	R _B 88
	TH1050	1448	1379	7	R _C 44
	RH950	1655	1552	6	R _C 48
	Cold reduction to condition C	1517	1310	5	R _C 45
	CH900	1828	1793	2	R _C 50
AM 355 PH	H850	1489	1255	19	R _C 48
	H1000	1276	1179	15	R _C 40

(continued)

Table 8.16 (continued)

Steels	Conditions	UTS (MPa)	0.2 %YS (MPa)	Elongation in 4D (%)	Hardness
AM 350 PH	H850	1275 min	1000 min	8 min	R _C 38
	H1000	1140 min	1035 min	8 min	R _C 37
Custom 450	Annealed	979	814	13	R _C 28
	H900	1351	1296	14	R _C 42.5
	H950	1289	1269	16	R _C 41.5
	H1000	1193	1165	17	R _C 30
	H1050	1103	1048	20	R _C 37
	H1150	979	634	23	R _C 28
PH 13-8Mo	RH950	1620	1482	12	R _C 48
	H950	1551	1449	12	R _C 47
	H1000	1482	1413	13	R _C 45
	H1050	1310	1241	15	R _C 43
	H1100	1103	1034	18	R _C 35
	H1150	1100	724	20	R _C 33
	H1150 M	896	586	22	R _C 32
17-10P PH	Annealed	613	255	70	R _B 82
	H700	985	675	20	R _C 32

8.4.2 Processing and Heat Treatments of PH Stainless Steels

The heat treatment requirements for PH stainless steels involve precipitation strengthening, which is generally done in three steps: solution treatment, quenching and precipitation or ageing:

1. **Solutionizing.** This treatment is done at a temperature where the pre-existing precipitates dissolve and alloying elements go into supersaturated solid solution. Typical solution treatment temperatures are in the range of 980–1065 °C.
2. **Quenching or cooling.** This can be done in air or oil or water, but must be fast to retain a supersaturated solid solution.

The low-carbon martensitic steels transform to martensite at relatively low temperatures, e.g. 250 °C for 17-4 PH.

The semi-austenitic steels are supplied in the metastable austenite condition. They may also contain up to 20 % of delta ferrite in equilibrium with austenite at the solution temperature. The martensite finish temperature of these steels is well below room temperature, and hence a conditioning treatment at ~750 °C should be carried out to achieve an austenite to martensite transformation after a forming operation. A cryogenic treatment is required if the conditioning temperature used is above 930 °C.

Fully austenitic steels have very low martensite start temperatures and hence cannot be transformed to martensite.

3. Precipitation and age hardening

Martensitic PH steels, for example 17-4 PH steels, are aged in the temperature range between 480 and 620 °C to achieve the required strength. Precipitation of hardening in this class of steels is achieved by precipitation of intermetallic phases such as Ni₂Al, Ni₃Ti, Ni₃(TiAl), Ni₃Al, Ni₃Nb, Ni₃Cu and carbides.

For the semi-austenitic steels the ageing temperatures are within the range 500–600 °C. Hardening occurs by precipitation of intermetallic compounds and carbides, resulting in room temperature yield strengths up to 1400 MPa.

In the case of fully austenitic grades, improvements in strength can be obtained from ageing between 500 and 750 °C, resulting in precipitation of a very fine coherent intermetallic Ni₃Ti phase. The precipitation reaction is very sluggish in this class of steels. Fully austenitic steels possess good toughness and may be used at cryogenic temperatures.

8.4.3 *Weldability of PH Stainless Steels*

Martensitic PH steels: These can be welded by most of the conventional arc welding (GTAW) processes in the solution-treated condition: Tungsten inert gas (TIG) welding results in the best GTAW toughness, since it produces clean weld metal. However, electron beam (EB) and laser welding give still better toughnesses.

Pre-heating of the weld joints is generally not required, since the low-carbon martensite is soft. However, for welds over 25 mm thickness pre-heating around 100 °C is suggested to prevent the risk of cracking. An interpass maximum temperature of 200 °C is recommended because these steels transform to martensite at relatively low temperatures. If the weld joint is highly restrained a post-weld heat treatment has to be carried out to avoid cracking of the weld. Matching filler materials are available for all the martensitic grades.

Semi-austenitic PH steels: Common arc and resistance welding processes can be used with stainless steel grade 17-7PH. However, during fusion welding inert gas shielding should be used to prevent oxidation of aluminium during the process.

Austenitic PH steels: Fully austenitic alloys have to be welded in the solution-treated condition. These steels are solutionized at 980 °C. To develop strength in welded joints an ageing treatment has to be carried out for 15 h at 720 °C. Pre-heating of welds is not necessary for these steels.

8.5 Illustration of Martensitic PH Steels Diversity: Custom 455, 465 and 475

The Carpenter Technology Corporation has developed many specialty steels, including Custom 450 (see Tables 8.13 and 8.16) and Custom 455, 465 and 475. Typical aerospace uses are for landing gear components, slat components, torque tubes and pneumatic cylinders.

Custom 455 is relatively soft and formable in the annealed condition. This steel can be used at temperatures close to 595 °C and shows excellent oxidation resistance. It has generally high corrosion resistance comparable to that of 17 % Cr ferritic (non-hardenable) steels (Type AISI 430).

Custom 465 is a premium melted steel designed to have excellent fracture toughness and notch tensile strength in the aged condition H950. In the H1000 condition this steel has a superior combination of strength, toughness and stress corrosion cracking resistance compared with Custom 455 and PH 13-8Mo. Its corrosion resistance is high and comparable to that of the fully austenitic steels like AISI 304.

Custom 475 is also a premium melted steel, capable of high strength up to 2000 MPa, good toughness and ductility, and high corrosion resistance similar to that of Custom 455.

The nominal chemical compositions of Custom 455, 465 and 475 and their mechanical properties are given in Tables 8.17 and 8.18.

8.5.1 Processing and Heat Treatments of Custom 455, 465 and 475 Stainless Steels

Hot working: Custom 455 is forgeable in the temperature range 900–1260 °C. Optimum properties can be achieved by heating the material uniformly to 1035–1150 °C and soaking for 1 h. The forging finishing temperature should be between 815 and 925 °C to achieve optimum grain size and properties after heat treatment. The forgings are cooled to room temperature and annealed.

Custom 465 is forgeable in the temperature range 1010–1095 °C. The forgings are cooled to room temperature and solution treated prior to age hardening.

Cold Working: All three steels can be cold-worked easily. Cold working prior to ageing results in much higher strengths.

Machinability: All three steels are easily machinable, and the machining practices are similar to those used for other high strength alloys.

Availability: Custom 455 and 465 are available in the form of round bars, square bars, flat bars, billet, strip and wire. Custom 475 is available in the form of strip and wire.

Table 8.17 Nominal chemical compositions of Custom steels 455, 465 and 475

Steels	C	Cr	Ni	Cu	Mo	Ti	Nb	Nb + Ti	Mn	S	P	Si	Ta	Fe
Custom 455	0.05 max	11.0–12.5	7.5–9.5	1.5–2.5	0.5 max	0.8–1.4	0.5 max	0.1–0.5	0.5 max	0.03 max	0.04 max	0.5 max	0.5 max	Balance
Custom 465	0.02 max	11.0–12.5	10.75–11.25	1.5–2.5	0.75–1.25	1.5–1.8	0.5 max	0.1–0.5	0.25 max	0.01 max	0.015 max	0.25 max	0.5 max	Balance
Steel	C	Cr	Ni		Mo	Co	Al	Mn		S	P	Si		Fe
Custom 475	0.02 max	10.5–11.5	7.5–8.5	7.5–8.5	4.5–5.5	8.0–9.0	1.0–1.5	0.50 max	0.01 max	0.015 max	0.015 max	0.50 max	0.50 max	Balance

Table 8.18 Mechanical properties of Custom 455, 465 and 475 steels after ageing at different temperatures

Steels	Conditions	UTS (MPa)	0.2 % YS (MPa)	Elongation in 4D (%)	RA (%)	CVN impact (J)	Hardness (R _C)	K _{Ic} (MPa√m)
Custom 455	H900	1724	1689	10	45	12	49	~ 40
	H950	1620	1551	12	50	19	48.0	~ 55
	H1000	1448	1379	14	55	27	45.0	85
	H1050	1310	1207	15	55	48	40.0	~ 100
Custom 465	H950	1765	1669	13	62	30	49.5	104.5
	H975	1703	1620	13	61	36	48.0	120.0
	H1000	1593	1510	15	63	55	47.5	142.0
	H1050	1482	1386	17	66	70	45.5	152.9
Custom 475	H950	1765	1669	13	62	30	49.5	104.5
	H975	1703	1620	13	61	36	48.0	120.0
	H1000	1593	1510	15	63	55	47.5	142.0
	H1050	1482	1386	17	66	70	45.5	152.9

The heat treatment requirements for these steels are as follows:

1. Solution treated or annealed.

- Custom 455: Heat to 815–845 °C and cool rapidly. Water quenching is recommended for small sections.
- Custom 465: Heat to 980 ± 10 °C, hold for 1 h and cool rapidly. Sections above 300 mm should be subjected to rapid air cooling, while sections below 300 mm should be quenched in a suitable coolant. Cryogenic treatment at –70 °C for 8 h after solutionizing and prior to ageing results in an optimum ageing response.
- Custom 475: Heat to 925–935 °C, hold for 1 h and cool rapidly. Cryogenic treatment at –70 °C for 8 h after solutionizing and prior to ageing results in optimum ageing response. This cryogenic treatment should be given within 24 h of solution treatment.

2. Ageing:

- Custom 455, conditions H900, H950, H1000 and H1050: ageing between 480 and 565 °C for 4 h, followed by air cooling. The ageing temperature depends on the property requirements.
- Custom 465, conditions H900, H950, H1000, H1050 and H1100: ageing between 480 and 565 °C for 4 h, followed by water or oil quenching for optimum properties. The ageing temperature depends on the property requirements.
- Custom 475: conditions H975, H1000, H1025, H1050 and H1100: ageing between 525 and 595 °C for 4 h, followed by water or oil quenching for optimum properties. The ageing temperature depends on the property requirements.

8.5.2 Weldability of Custom 455, 465 and 475 Stainless Steels

Shielded fusion welding and resistance welding processes can be used for Custom 455, 465 and 475 stainless steels. Oxy-acetylene welding is not recommended since the carbon content increases in the welds.

Welding in the solution-annealed condition and subsequent ageing is recommended for optimum strength, ductility and corrosion resistance. If high residual stresses are likely, then welding in the overaged condition is advised. The component or part has then to be resolutionized and aged to achieve optimum properties.

8.6 Indian Scenario

In India Mishra Dhatu Nigam Ltd (MIDHANI), Hyderabad, manufactures some PH steels. Their chemical compositions and mechanical properties are given in Tables 8.19 and 8.20.

MIDHANI also manufactures considerable amounts of maraging steel 18 Ni 250, in all product forms; and this and other maraging steels are widely used in India for aerospace applications.

The other classes of high-alloyed steels like the Ni–Co–Cr–Mo secondary hardening steels (e.g. AF1410 and the AerMet family) are yet to enter the Indian market. It is to be noted that the AerMet class of alloys is patented by Carpenter Steel Corporation USA.

Table 8.19 Chemical compositions of PH stainless steels manufactured at MIDHANI, Hyderabad, India

Steels	C	Cr	Ni	Cu	Mo	Ti	Si	Mn	Others	Fe
MDN15-5 PHA	0.07	15.0	5.0	3.5	–	–	1.0	1.0	0.4Cb	Balance
MDN174A	0.07	17.0	4.0	4.0	–	–	1.0	1.0	0.4 (Cb + Ti)	Balance
MDN13-8Mo PHA	0.05	13.0	8.0	–	2.0	–	–	–	1 Al	Balance
MDN465A	0.02	11.5	11.0	–	1.0	1.6	–	–	–	Balance
MDN11-10T PH	0.03	10.0– 11.3	9.0– 10.3	0.3	1.8– 2.3	1.0– 1.4	0.15	0.10	0.15Nb	Balance

Table 8.20 Mechanical properties of PH stainless steels manufactured at MIDHANI, Hyderabad, India

Steels	Conditions	UTS (MPa)	0.2 % YS (MPa)	Elongation in 4D (%)	RA (%)	Hardness	K_{Ic} (MPa \sqrt{m})
MDN15-5 PHA	H1025	1069 min	1000 min	12 min	45 min	331–401 BHN	–
	H1150	931 min	724 min	16 min	50 min	277–352 BHN	–
MDN174A	H1025	1069 min	1000 min	12 min	45 min	331–401 BHN	–
	H1150	931 min	724 min	16 min	50 min	277–352 BHN	–
MDN13-8Mo PHA	H1000	1413	1310	10	60	43.0 min R _C	–
MDN465A	H950	1655	1515	10	45	47 R _C	77 min
	H1000	1515	1380	10	50	45.0 R _C	104 min
MDN11-10T PH	Hot Rolled/ST	880	785	6	–	306 BHN	–
	ST 800–820 °C/1 h/AC + Age 510–530 °C/3 h/AC	1420	1325	5	–	470–525 BHN	–

8.7 Summary

High-alloyed steels are capable of developing ultrahigh strengths coupled with high fracture toughness and stress corrosion resistance. These highly alloyed steels may be divided into three categories: secondary hardening steels, maraging steels and precipitation hardening stainless steels.

Secondary hardening steels must be fabricated in the soft-annealed condition. They have to be quenched and tempered to obtain ultrahigh strengths, which are due to precipitation of nano-size M_2C carbides in a nickel lath martensite. The tempering takes place in the range of 455–525 °C, and this results in high fracture toughness and high stress corrosion resistance at ultrahigh strength levels. Secondary hardening steels are useful for aerospace applications such as structural tubing, drive shafts, springs, connecting rods, fasteners, landing gear and crank shafts.

Maraging steels, on the other hand, do not require quenching. They can be air cooled from the solutionizing temperature and aged in the temperature range of 485–510 °C to achieve ultrahigh strength and excellent toughness. This strength and toughness is due to a fine precipitation of Ni_3Mo and Ni_3Ti intermetallic precipitates. Maraging steels can be fabricated in the solutionized condition, which is a major advantage. They have a wide range of aerospace applications such as missile casings, aircraft forgings, cannon recoil springs, Belleville springs, bearings, transmission shafts, fan shafts in commercial jet engines, couplings, hydraulic hoses and bolts.

Precipitation hardening (PH) stainless steels are classified into three categories: martensitic stainless steels, semi-austenitic stainless steels and fully austenitic stainless steels. These steels achieve ultrahigh strength due to precipitation of intermetallic phases or carbides, or by both, depending on the category of steel. PH stainless steels are used in aerospace applications such as landing gear components, slat components, torque tubes, pneumatic cylinders and many other parts.

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