Chapter 7
Aero Steels: Part 1—Low Alloy Steels

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Abstract This chapter demonstrates the objectives of adding alloying elements to steel through their effects on microstructure and consequent improvements in mechanical properties. Classifications and designations followed by different international standards are briefly outlined. The development of medium carbon low alloy steels used for aerospace applications is described, including their compositions and mechanical properties. Salient aspects of the physical metallurgy including heat treatment and surface hardening methods are brought out. The engineering properties of ultra high strength steels are briefly mentioned. The efforts towards indigenous development and manufacture of some aero steels are also presented.

Keywords Low alloy steels · Chemical compositions · Processing · Heat treatment · Fatigue · Fracture · Corrosion

7.1 Introduction

"Steel may lack the high-tech image that attaches to materials like titanium, carbon fibre reinforced composites and most recent nano materials, but make no mistake, its versatility, strength, toughness, low cost and wide availability are unmatched" [1].

The metallurgy of steels has grown far beyond the historical definition of 'Steel is an alloy of iron and carbon'. Present-day steels are complex alloys of Fe and a host of major and minor alloying elements, whose concentrations are judiciously selected to achieve the desired mechanical properties for the intended applications.

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Modern computational and technological advances, coupled with the availability of tools for metallurgical characterization and non-destructive testing, have facilitated the production of clean steels with narrow compositional limits and property scatter. All these factors have contributed to the availability of inexpensive high strength–high toughness steels for aeronautical applications.

Over the years, because of the availability of high specific strength (strength/density) materials such as high strength aluminium alloys and titanium alloys, the usage of steels in aircraft structures and aeroengines has gradually decreased from 40 % to about 15 %. However, steels are the primary choices for applications like gears, bearings, undercarriages and high strength fasteners used in aeronautical engineering.

Steel is classified as carbon steel when the contents of the residual elements manganese and silicon are less than 0.5 wt% each. However, when deliberate additions of manganese and silicon beyond 0.5 wt% are made they become alloying additions in plain carbon steels. The principal elements contained in alloy steels are Mn, Si, Ni, Cr, Mo, V, W and Co, either singly or in combination. Alloy steels with total alloy content not exceeding 8 wt% are called low alloy steels [2].

The limitations of carbon steels are overcome by the addition of alloying elements in various combinations to derive the benefits of synergetic effects. The objectives of adding alloying elements to primary steel are to

(a) improve the hardenability
(b) increase resistance to softening on tempering
(c) increase wear resistance
(d) improve corrosion and oxidation resistance
(e) improve machinability
(f) improve mechanical properties both at room temperature and high temperatures
(g) improve fabricability and weldability, and
(h) produce fine grains that result in a good combination of strength and toughness.

As compared to plain carbon steels, alloy steels are expensive due to the ever-increasing costs of the alloying elements. Hence their use in the design of a steel should be made judiciously.

7.2 Classification and Designation

Alloy steels are generally classified based on *chemical composition* (Ni steels, Cr steels, Ni–Cr steels, etc.), *microstructure* (pearlitic, ferritic, martensitic, etc.), *functionality* (structural steels, tool steels, etc.) and *specific attributes* (magnetic steels, heat-resistant steels, corrosion-resistant steels, etc.). International standards have, however, classified steels mainly based on their composition, since this is deemed to be rational and convenient for both producers and users.

The designations followed by different international agencies are adopted for general engineering purposes. Aerospace steel standards are mostly derived from their corresponding general engineering standards, with narrower composition ranges, strict control on trace/deleterious elements and drastic reduction in inclusion sizes, shapes and populations.

In order to differentiate the aerospace grades from general engineering grades, every country/manufacturer has designated the standards with some alphanumeric feature. For example, the ASTM standard is replaced by aerospace materials standard (AMS). The aeronautical steels are also covered by defence standards like MIL Standard (American), DEFSTAN (British), etc. In addition, General Electric (GE), Rolls Royce (RR) and Pratt & Whitney (P&W) have their own internal standards.

The AMS grades are generally assigned based on their mill form, product description and supply condition. Hence, instead of reproducing the list, further information can be accessed on various steel grades and mill forms from the AMS designations (see Ref. [3]). For the sake of convenience and brevity the compositions of popular low alloy steels used in aerospace applications are listed in Table 7.1 as per their AISI/SAE designations [4]. Some of their major applications are listed in Table 7.2 [5, 6].

Table 7.1 Chemical compositions of UHSS low alloy aerospace steels (wt%) [4]

SAE	C	Mn	Si	Ni	Cr	Mo	V
4037	0.35–0.40	0.70–0.90	0.15–0.35	–	–	0.20–0.30	–
4130	0.28–0.33	0.40–0.60	0.20–0.35	–	0.80–1.10	0.15–0.25	–
4140	0.38–0.43	0.75–1.00	0.20–0.35	–	0.80–1.10	0.15–0.25	–
4340	0.38–0.43	0.60–0.80	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30	–
6150	0.48–0.53	0.70–0.90	0.20–0.35	–	0.80–1.10	0.15–0.25	0.15 min
300M	0.40–0.46	0.65–0.90	1.45–1.80	1.65–2.00	0.70–0.95	0.30–0.45	0.05 min
D6ac	0.42–0.48	0.60–0.90	0.15–0.30	0.40–0.70	0.90–1.20	0.90–1.10	0.05–0.10
9260	0.56–0.64	0.75–1.00	1.80–2.20	–	–	–	–

N.B: The maximum limits of sulphur and phosphorus in all the grades are 0.02 and 0.025, respectively

Table 7.2 UHSS low alloy steels used in aerospace applications [5, 6]

SAE no. and type	Applications
4130 (Cr–Mo)	Sheet fittings, landing gear axles, turbine components (rotors, shafts and discs), highly stressed airframe components
4130 (Cr–Mo) 4140 (Cr–Mo) 4340 (Ni–Cr–Mo)	Axles, rotors, gears, perforators, high strength forged and machined parts, landing gear, highly stressed fuselage fittings, propeller hubs, snap rings, crankshafts
6150 (Cr–Mo–V)	Propeller cones and snap rings, springs, shafts, gears, pinions, axles, heavy duty pins, bolts
9260 (Mn–Si)	Springs
300M (Ni–Cr–Si–Mo)	Landing gear, airframe parts, fasteners
D6ac (Cr–Mo–Ni–V)	Landing gear, motor cases for solid fuel rockets, shafts, gears, springs

7.3 Compositions of Low Alloy Steels

Most of the aerospace low alloy steels are based on Cr–Mo–Si and Ni–Cr–Mo–Si combinations with varying carbon contents:

- Low Ni and low Cr steels contain a little over two parts of nickel to one part of chromium by weight. The combined effect of both elements results in increased hardenability and strength. The retardation of the austenite → pearlite transformation during cooling from the austenite region avoids severe quenching problems. However, these steels are susceptible to temper embrittlement, which must be avoided.
- Low carbon Ni–Cr steels are used for case carburising since Cr is a carbide former for the case, and both Ni and Cr improve the toughness of the core.
- The susceptibility of Ni–Cr and Cr–Mn steels to temper embrittlement is reduced by the presence of 0.5 wt% Mo.
- Cr–Mo steels possess good machinability and mechanical properties.
- Ni–Cr–Mo steels possess the best combination of strength, ductility and toughness among low alloy steels.

As little as 0.1 wt% of vanadium in low alloy steels restricts grain coarsening during heat treatment. Vanadium forms finely dispersed carbides and nitrides that do not go into solution during austenitization. Vanadium also provides resistance to softening during tempering, and the finely dispersed vanadium carbides give a secondary hardening effect to steels.

Silicon up to 1.2 wt% is added to low alloy steels to retard softening during tempering. Modified Cr–Mo and Ni–Cr–Mo steels for aerospace applications are based on this concept. Finally, many nitriding grades contain Al and/or enhanced Cr levels.

Several variants of Cr–Mo–Ni steels have been developed especially for landing gear components like pistons, barrels and struts. These grades are 300M (or S155), 4330V, 4335V, 4340, D6ac, 35NCD16 (or S28). These steels are classified in the category of ultrahigh-strength steels.

7.3.1 Ultrahigh-Strength Steels (UHSS)

Structural steels with a minimum yield strength of 1380 MPa are referred to as ultrahigh-strength steels. Medium carbon low alloy steels that fall in this category are used for aerospace applications. The designations of these steels are AISI/SAE 4130, 4140, 4340, 300M (modified 4340), AMS 6434 and D6ac. The chemical compositions of these ultrahigh-strength steels (UHSS) are given in Table 7.1 and their aerospace applications are listed in Table 7.2.

AISI 4130 steel is amenable to intermediate hardening and is immune to temper embrittlement. Suitable hardening and tempering enables retention of good mechanical properties like tensile, impact and fatigue up to 370 °C. However, the impact properties at cryogenic temperatures are poor. This steel is suitable for case hardening by nitriding.

AISI 4140 Steel has a higher carbon content than 4130 steel and therefore deeper hardenability and higher strength. Hardening and tempering gives good mechanical properties retained up to 480 °C. The steel is susceptible to hydrogen embrittlement at high strength levels. The steel is weldable and can also be nitrided for certain applications.

AISI 4340 steel is a deep hardenable Ni–Cr–Mo steel that is immune to temper embrittlement and gives a good combination of strength and toughness when suitably heat treated. It retains useful mechanical properties up to about 200 °C, as indicated in Fig. 7.1. This steel also has high impact toughness even at cryogenic temperatures [7]. However, it is prone to hydrogen embrittlement and stress corrosion cracking (SCC) at high strength levels (as are all the other low alloy steels: see Chap. 19 in Volume 2 of these Source Books).

300M Steel is a version of 4340 steel modified by the addition of 1.6 wt% Si. It contains slightly higher carbon as compared to 4340 steel and also vanadium. Addition of silicon to the steel provides deeper hardenability and resistance to softening when tempered at higher temperatures as compared to 4340 steel. The silicon content also shifts tempered martensite embrittlement (TME) to higher temperatures. At higher strength levels the steel is prone to hydrogen embrittlement and SCC. It is a weldable steel.

D6a and D6ac steel is a deep hardenable ultrahigh-strength steel that is immune to temper embrittlement and maintains a very high yield to tensile strength ratio up to 1930 MPa. Air-melted steel is designated by grade D6a, while air melted followed by vacuum arc remelting is designated by grade D6ac. Like other steels in its class it is susceptible to SCC.

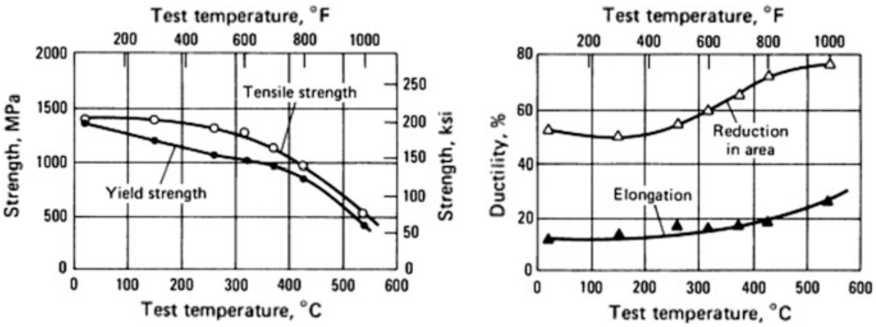

Fig. 7.1 Variation in tensile properties with test temperature for 4340 steel heat treated to a room temperature tensile strength of 1380 MPa [8]

7.3.2 Bearing Steels

The most popular bearing steel is AISI 52100 (1C–1.2Cr) grade, which can sustain service temperatures from −50 to +150 °C in a neutral environment.

In order to achieve a high rolling contact fatigue life, bearing steels are manufactured with high levels of cleanliness. Vacuum induction melting followed by vacuum arc remelting is found to give maximum freedom from non-metallic inclusions in bearing steels.

7.4 Effects of Alloying Elements

7.4.1 Critical Transformation Temperatures

The critical transformation temperatures are those that correspond to allotropic transformation when the steel is heated from ambient temperature to near its melting point. These are the A_1, A_3, and A_4 temperatures (A_2, which occurs at 770 °C, corresponds to a magnetic change). The A_1 temperature is at 723 °C, and is called the lower critical temperature, where the ferrite → austenite transformation starts. The A_3 temperature is at 910 °C, and is called the upper critical temperature, above which BCC (α) iron transforms to FCC (γ) iron. The A_4 temperature is at 1400 °C, above which FCC (γ) iron transforms to BCC (δ) iron.

Ni, Mn, Co and Cu are some elements that raise the A_4 temperature and lower the A_3 temperature, thereby widening the γ phase field, see Fig. 7.2a. Cr, Mo, W, V, Al and Si have the reverse effect, since they raise the A_3 temperature and lower the A_4 temperature. This restricts the field over which austenite is stable, eventually forming what is commonly called a 'γ loop' in more highly alloyed steels, see Fig. 7.2b. The former group of alloying elements is called 'austenite stabilizers' while the latter group is called 'ferrite stabilizers'.

Most of the austenite (γ) stabilizing elements have an FCC crystal structure and easily dissolve in austenite. They also retard the precipitation of carbides in steels. The ferrite (α) stabilizers have a BCC crystal structure and therefore dissolve easily in ferrite.

7.4.2 Formation and Stability of Carbides

The elements which form stable carbides when added to steels are Cr, W, V, Mo, Ti and Nb. The formation of carbides increases the hardness of steels. The carbides are single, double or complex, containing one or more alloying elements and iron in them. Examples are M_3C, M_7C_3 and $M_{23}C_6$.

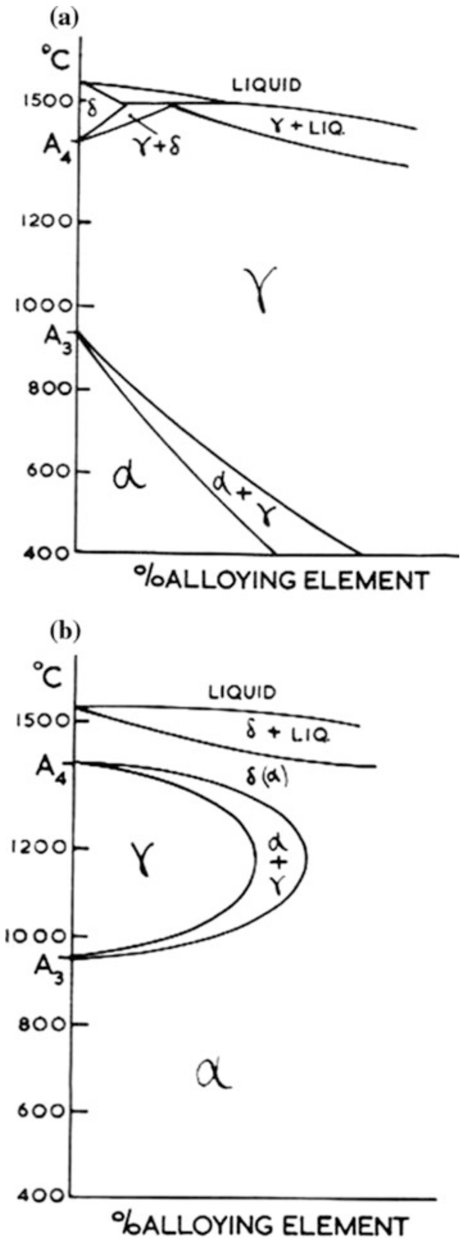

Fig. 7.2 Relative effects of additions of alloying elements on the polymorphic transformation temperatures A_3 and A_4: **a** tending to stabilize γ, and **b** tending to stabilize α, resulting in a 'γ loop'

Mn is a weak carbide-forming element and increases the stability of other carbides present in steels. Elements like Ni, Co, Si and Al, which have no chemical affinity for carbon, tend to make iron carbides unstable by releasing free graphitic carbon. Hence these elements are added to very low carbon steels or together with carbide-forming elements to medium carbon steels. For example, most of the low alloy steels containing Ni also contain Cr for counterbalancing the graphitizing tendency of Ni.

When a steel containing carbon and any of the carbide-forming alloying elements is quench-hardened and tempered, alloy carbides are formed in the microstructure. The type and composition of such carbides depend on the chemical composition of the steel being tempered and the tempering parameters (temperature and time). At low tempering temperatures M_3C-type carbides are formed. With increase in tempering temperature this carbide is gradually replaced by M_7C_3 and finally $M_{23}C_6$-type carbides.

The advantages of using an alloy steel that form alloy carbides are as follows:

(a) Alloy carbides harder than cementite (Fe_3C at 840HV) impart greater wear resistance to steel, e.g. $M_{23}C_6$ which has hardness 1200HV.
(b) For a given tempering parameter an alloy steel retains greater hardness compared to a plain carbon steel of similar carbon content.
(c) Steels containing V, Mo and W exhibit a secondary hardening effect that raises the softening temperature of the quenched and tempered steel.

7.4.3 Grain Size

Coarse-grained structures result due to heating a steel to high temperature either during processing, heat treatment, or in service, causing a reduction in strength and toughness of the steel. Grain growth can be retarded by the addition of small amounts of V, Ti, Nb and Al. V is the most potent grain refiner: as little as 0.1 wt% forms finely dispersed carbides and nitrides that are relatively insoluble at high temperatures and act as barriers to grain growth. Ti and Nb additions have a similar effect. Aluminium added as deoxidiser in high-grade steel converts to Al_2O_3 that also acts as a grain refiner.

7.4.4 Eutectoid Point

Austenite stabilizers lower the eutectoid temperature whilst the ferrite stabilizers raise it (Fig. 7.3a). All alloying elements lower the eutectoid carbon content (Fig. 7.3b). This explains why low alloy steels can produce similar microstructures and properties as plain carbon steels with much less carbon content.

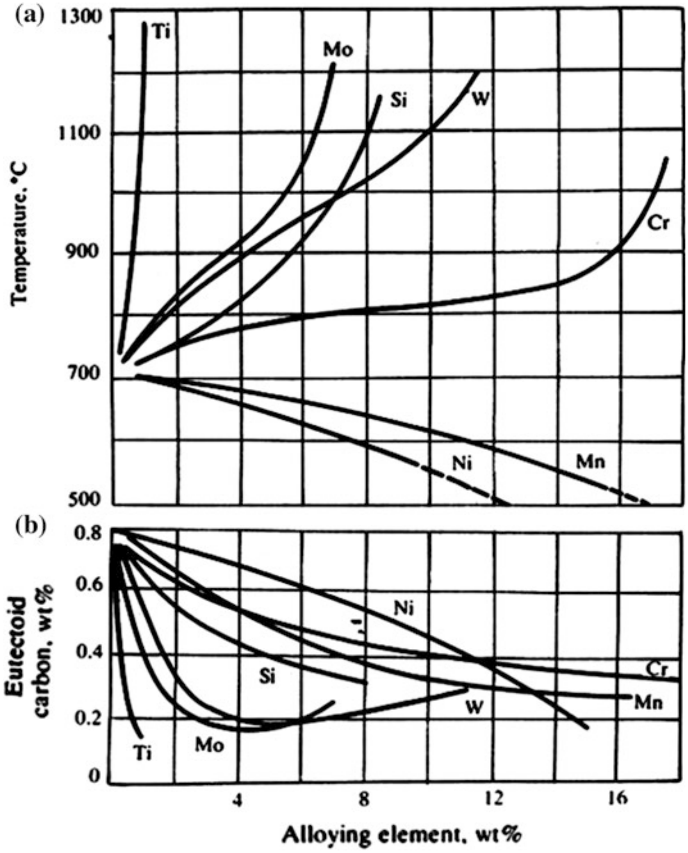

Fig. 7.3 Effects of alloying elements on **a** eutectoid temperature and **b** the eutectoid carbon content [9]

7.4.5 Hardenability

Hardenability of a steel is the relative ease with which a steel can be prevented from decomposition of austenite to ferrite and pearlite, thereby allowing the formation of martensite. The maximum cooling rate that will produce martensite in a steel is known as the critical cooling rate (CCR) of the steel. The CCR of carbon steels is high and hence their hardenability is low. Alloying with elements like Mn, Cr, Ni and Mo helps in increasing the hardenability of a steel.

For a particular strength level in a given composition of steel, there will be a maximum section size in which the desired transformation can be achieved. This is the *limiting ruling section* (LRS), which is the largest diameter for a given steel that can achieve certain mechanical properties after a specified heat treatment.

Table 7.3 Improvements in tempered steel hardenability (increased LRS) by alloying [10]

Steel grade	C	Mn	Cr	Mo	Ni	LRS mm	UTS (MPa)	YS (MPa)	% El min	Impact CVN, J min
150 M40	0.36–0.44	1.30–1.70	–	–	–	13	850–1000	635	12	22
530 M40	0.36–0.44	0.60–0.90	0.90–1.20	–	–	29	850–1000	680	13	50
605 M36	0.32–0.40	1.30–1.70	–	0.22–0.32	–	63	850–1000	680	13	50
709 M40	0.36–0.44	0.70–1.00	0.90–1.20	0.25–0.35	–	100	850–1000	680	13	50
817 M40	0.36–0.44	0.45–0.70	1.00–1.40	0.20–0.35	1.30–1.70	150	850–1000	680	13	50

The benefits of alloying in order to achieve deep-hardening improvements in mechanical properties are illustrated in Table 7.3 [10]. Note that combinations of several alloying elements give the most improvement in LRS.

Besides improvements in LRS, one of the most important effects of alloying is that small additions of alloying elements allow much slower quenching rates to produce martensite, such that oil or air quenching can be resorted to instead of water quenching. This helps in avoiding distortion or cracking of components, see Sect. 7.4.6. A disadvantage is that all alloying elements, except cobalt, lower the martensitic start (M_s) and martensitic finish (M_f) temperatures. This results in retention of austenite in the as-quenched structure of alloy steels. The retained austenite content is kept below 2 % in UHSS by judicious heat treatment.

7.4.6 Volume Change

The austenite → martensite transformation in steels is accompanied by an increase in volume. This effect can often lead to transformation stresses causing distortion and cracks in components. Judicious selection of alloying elements can reduce the risk of cracking of steel components during quenching, as mentioned in the last paragraph of Sect. 7.4.5.

7.4.7 Resistance to Softening While Tempering

Most low alloy steels soften rapidly with increase in tempering temperature. However, it is well known that silicon additions to steel improve the resistance of martensite to softening on tempering [11]. Such improved properties are of considerable importance in low alloy steels, since resistance to softening allows for

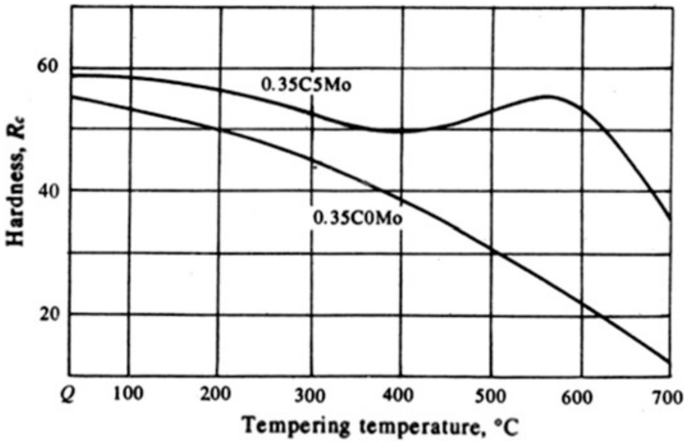

Fig. 7.4 Variation in hardness with tempering temperature for two different steels [12]

greater relief of thermal and transformation stresses on tempering. This leads to good combinations of strength and toughness.

Silicon additions also displace tempered martensite embrittlement (TME) to higher temperatures, as mentioned in Sect. 7.3.1, thus allowing tempering at elevated temperatures [13, 14]. The TME phenomenon in silicon-modified AISI 4340 (300M) steel was studied by Horn and Ritchie [15]. They suggested that displacement of TME to higher tempering temperatures is due to the Si enhancing the stability of carbides and retarding the formation and growth of cementite.

Carbide-forming elements like Cr, Mo and V at large concentrations are more effective in retarding softening of steel on tempering. These elements not only retard softening but also provide secondary hardening at higher temperatures of 500–550 °C, owing to fine alloy carbide precipitation. Alloy carbides resist softening up to around 550–600 °C. Above 600 °C there is a decrease in hardness, see Fig. 7.4, owing to carbide coarsening.

7.5 Strengthening Mechanisms

The strength of steels can be increased by (i) alloying, (ii) grain refinement, (iii) precipitation and dispersion of hard particles, (iv) martensitic and bainitic transformations, (v) retardation of softening during tempering and (vi) strain hardening.

Alloying: Designing steel compositions is a complex science. The choice of alloying elements depends on the desired microstructure to give the required mechanical properties. It is also essential to consider hot workability, heat treatment and joining. The general guidelines are as follows:

- Achieve the desired hardenability with Cr additions for martensitic transformation with the lowest quench rate to avoid distortion, warpage and quench cracks.
- Add Ni, Mn, W, etc. to increase the matrix strength.
- Increase temper embrittlement resistance.
- Induce secondary hardening during tempering with judicious additions of Si, Co, Al, V and Nb.
- Alter transformation characteristics to facilitate thermomechanical treatments like ausforming.
- Keep carbon as low as possible, i.e. deviate from the concept of increasing strength with increasing carbon.

Martensitic and Bainitic Transformations: Quite a few low and high alloy steels are strengthened by a martensitic transformation. The resultant martensite is strong but brittle. Tempering restores ductility by softening the matrix. If suitable alloy additions are made to retard softening during tempering, by decreasing the carbide growth rate, it is possible to temper at higher temperatures to achieve higher toughness without significantly sacrificing strength. Modified 4340 with addition of 1 wt% silicon (300M) is an outstanding example of this concept. An additional advantage is the elimination of tempered martensite embrittlement (TME), often encountered in steels tempered between 200 and 350 °C. This elimination of TME enables tempering above the susceptible temperature range without strength reduction.

Another form of embrittlement, temper embrittlement (TE), is observed in quenched and tempered steels when tempered between 500 and 600 °C. This can be avoided by the addition of about 0.5 wt% Mo.

Thermomechanical Treatments: Yet another, but less popular method, to increase the strength of low alloy steels is to design the composition in such a way that austenite can be deformed prior to martensite transformation (Ausforming) to introduce high dislocation densities. Ausforming results in high strength with good toughness. However, it is rarely employed in aerospace alloys.

7.6 Melting of Low Alloy Steels

Aerospace specifications stipulate stringent control of chemical composition and non-metallic inclusion limits to minimize scatter in the mechanical properties. Judicious combinations of primary (arc melting, induction melting or vacuum induction melting) and secondary (vacuum arc remelting or electro-slag remelting) techniques are usually employed to produce high-quality steels with close compositional tolerances. These modern melting practices help in reducing the contents of dissolved gases (hydrogen, oxygen and nitrogen) to very low levels. The non-metallic inclusion contents are reduced to <0.001 wt% by the combination of VIM + VAR, and ESR also helps in reducing the inclusion contents.

7.7 Fabrication of Low Alloy Steels

Large landing gears are usually press-forged at slow and controlled strain rates. Steel forgings are normalized to refine the as-forged grain size and minimize residual stresses before the forgings are hardened and tempered. Forged products possess the best combination of strength, ductility and toughness in low alloy steels.

Low alloy steel plates are welded by gas, arc and electron beam welding techniques. Welding rods of the same composition and of comparable strength are used. The plates are preheated and also subjected to inter-pass heating to avoid cracking. After welding, the welded plate structures are either stress relieved, followed by hardening and tempering; or hardened and tempered immediately after welding. These procedures depend on the complexity of the fabricated structure.

Welded structures of high strength low alloy steels are susceptible to hydrogen embrittlement and SCC [16]. Therefore absorption of hydrogen during welding should be minimized/avoided, and stress relieving should be carefully done to avoid SCC.

Post-fabrication electroplating should be preceded by a stress relief treatment to avoid hydrogen embrittlement during plating; and electroplating should be immediately followed by 'baking' to remove any galvanically absorbed hydrogen and minimize the risk of hydrogen embrittlement.

7.8 Heat Treatment

Heat treatment is employed in order to bring about changes in microstructure to obtain the desired properties. The heat treatment process consists of the following:

(a) Heating the steel to a predetermined high temperature, the austenitizing temperature.
(b) Soaking the steel at the austenitizing temperature for sufficient time to obtain a homogeneous austenite structure.
(c) Cooling the steel to room temperature at a particular cooling rate to produce the correct microstructure.

Alloy steels require careful heating to prevent cracking from thermal shock. They require higher austenitizing temperatures and longer soaking times than plain carbon steels, owing to the lower rate of dissolution of alloying elements in the austenite. However, this carries the risk of grain growth (which should be avoided) during austenitizing. Cooling rates should also be carefully controlled in alloy steels. Some heat treatments normally employed for low alloy steels are described below.

Normalizing: This is carried out as a conditioning treatment before the final heat treatment. Medium carbon low alloy steel forgings are normalized before hardening to produce a finer grain structure and to minimize residual stresses. Normalizing at

815–930 °C, followed by tempering at 650–675 °C, produces a partially spheroidized structure that possesses adequate hardness suitable for machining.

Annealing: Depending upon the requirement, different annealing treatments, namely isothermal annealing, full annealing, process annealing and stress relief annealing, are employed.

Full annealing is carried out by heating to 730–870 °C, soaking for a suitable time period, and then slow furnace cooling. This treatment produces maximum softness in low alloy steels. Process annealing is carried out in wire drawing and cold rolling industries in order to remove the residual stresses of cold working processes. This process is *not* applicable to low alloy steels. Stress relieving treatment is used after fabrication processes like welding (Sect. 7.7), machining or cold working in order to relieve residual stresses.

Hardening: The steel is heated to the austenitizing temperature, held there for sufficient time for complete transformation to austenite and also to bring the carbides into solution, followed by quenching in a suitable medium (water, oil) to convert austenite into martensite.

Low alloy steels are heated to a temperature 50 °C above A_3 and soaked at that temperature for about 1 h per 25 mm section thickness. These steels are usually quenched in oil to avoid too-fast quenching problems, see subsection 7.4.5, but still fast enough to ensure complete transformation of austenite to martensite.

Tempering: Two important aspects that should be understood and considered while carrying out hardening and tempering of low alloy steels are (a) the effect of chemical composition on hardenability and (b) the effects of tempering temperature on variation in mechanical properties.

Although as-quenched steel is extremely hard and strong, it is also very brittle. Tempering is the treatment that is carried out on as-quenched steels in order to restore ductility and toughness at the cost of some loss of hardness and strength. During tempering of low alloy steels the as-quenched steel is re-heated to some intermediate temperature below the A_1 temperature, soaked for sufficient time (usually 2 h per 25 mm section), followed by air cooling to room temperature. In the case of steels prone to temper embrittlement, water quenching is done to avoid segregation of trace elements to prior austenite grain boundaries.

Embrittlement of Steels During Tempering: High strength martensitic steels are susceptible to embrittlement during tempering [17–19]. This embrittlement can result primarily from two types of thermal treatments, Fig. 7.5:

- Tempering as-quenched alloy steels in the range of 250–350 °C, resulting in tempered martensite embrittlement (TME).
- Tempering between 475 and 625 °C, causing temper embrittlement (TE).

The main characteristics of TME are (a) there is a minimum in fracture energy and (b) the fracture mode is usually transgranular owing to transformation of retained austenite at martensite lath boundaries. Sometimes intergranular fracture occurs, owing to impurities having segregated to prior austenite grain boundaries.

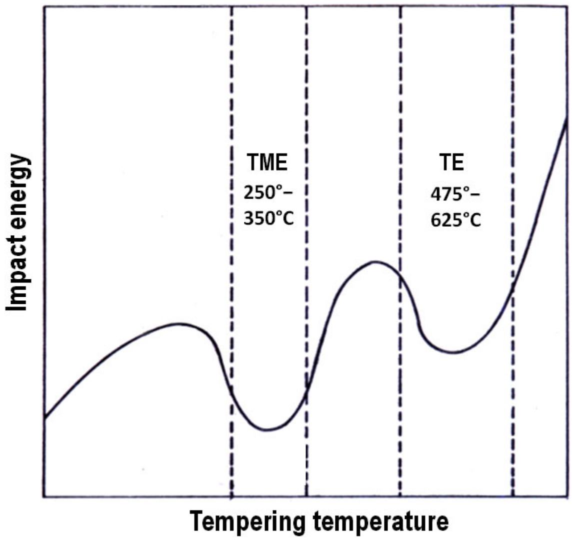

Fig. 7.5 Schematic illustration of TME and TE temperature ranges for low alloy steels

TE on the other hand is manifested by (a) a considerable increase in the ductile to brittle transition temperature, accompanied by a fall in the upper shelf energy in a notched bar test, and (b) intergranular fracture at prior austenite grain boundaries owing to co-segregation of impurities, namely As, Sb, Sn and P together with alloying elements like Ni and Cr.

TME is a rapid phenomenon that develops within the normal time of tempering and is irreversible. TE develops on prolonged heating or cooling through the susceptible temperature zone and is reversible: it can be eliminated by re-hardening the embrittled steel, tempering outside the susceptible temperature zone, and rapidly cooling through the susceptible temperature range.

7.9 Surface Hardening of Steels

Sometimes the service conditions of components like ball and roller bearings, gears, shafts, axles, cams, etc. require a hard, wear-resistant surface with a tough core. This kind of functional properties in a single component can be achieved only via surface hardening.

By employing a thermochemical treatment, carbon can be diffused to a regulated depth in a low carbon-alloy steel. Suitable hardening and tempering results in a hard wear-resistant case above a tough shock-resistant core. Similarly, nitrogen and boron can also be diffused to produce hardened surface cases. In all these treatments the solute elements C, N or B form hard phases that provide the wear resistance.

The popular surface hardening treatment methods are carburizing, cyaniding, carbonitriding, nitriding, boronizing and chromizing. These are described in detail in a recent ASM Handbook [20].

7.10 Engineering Properties

All the alloying elements dissolve in ferrite and result in solid solution strengthening. Chromium, tungsten, vanadium, molybdenum, titanium and niobium form stable carbides and therefore increase the hardness, retard softening on tempering, and also cause secondary hardening. Alloying elements that help in refining grain size result in improving the toughness of the steel. Thus the microstructural changes caused by alloying have remarkable influences in improving the mechanical properties of steels. The through-hardenable low alloy steels produce a wide range of mechanical strength, and so their mechanical properties are based on the tempering temperature employed, for example Table 7.4 [21].

Fatigue: The fatigue strengths of steels, including low alloy steels, are generally good. An engineering 'rule of thumb' is that the fatigue limit is approximately

Table 7.4 Mechanical properties of some aerospace low alloy steels [21]

SAE no. and heat treatment condition	YS (MPa)	UTS (MPa)	El (%)	Hardness (HB or HRC)
4130				**HB**
H + T 315 °C	1340	1570	13.0	425
H + T 370 °C	1250	1475	15.0	400
H + T 540 °C	1000	1170	20.0	325
H + T 650 °C	830	965	22.0	270
4140				**HB**
H + T 205 °C	1740	1965	11.0	578
H + T 315 °C	1570	1720	11.5	495
H + T 425 °C	1340	1450	15.0	429
H + T 650 °C	790	900	21.0	277
4340				**HB**
H + T 205 °C	1860	1980	11.0	520
H + T 315 °C	1620	1760	12.0	490
H + T 425 °C	1365	1500	14.0	440
H + T 650 °C	860	1020	20.0	290
6150				**HB**
H + T 205 °C	1810	2050	1.0	610
H + T 315 °C	1720	1950	7.0	540
H + T 425 °C	1490	1585	11.0	470
H + T 595 °C	1080	1150	16.0	350

(continued)

Table 7.4 (continued)

SAE no. and heat treatment condition	YS (MPa)	UTS (MPa)	El (%)	Hardness (HB or HRC)
300M				**HRC**
H + T 100 °C	1240	2340	6	56.0
H + T 200 °C	1650	2140	7	54.5
H + T 315 °C	1690	1990	9.5	53.0
H + T 370 °C	1620	1930	9.0	51.0
D6a				
H + T 205 °C	1620	2000	8.9	
H + T 315 °C	1700	1840	8.1	–
H + T 425 °C	1570	1630	9.6	
H + T 540 °C	1410	1450	13.0	

0.5 × UTS. Since high strength and UHSS steels are not damage tolerant, see below, no fatigue cracking is permitted in aerospace components made from them. This means that fatigue design is on a *Safe-Life* basis, whereby service fatigue stresses should not cause cracking.

Fracture toughness: The fracture toughnesses of low alloy steels show a steep inverse relationship with yield strength. At yield strengths below 1500 MPa the fracture toughnesses are generally above 75 MPa $\sqrt{m}$, which is good. However, in the UHSS range, with yield strengths approaching 2000 MPa, the fracture toughnesses decrease to less than 30 MPa $\sqrt{m}$ [22]. From an engineering point of view this means as before that UHSS components must be designed as *Safe-Life* items.

In turn this also means that in-service cracking by fatigue (see above) and stress corrosion (see below) must be prevented; and also that UHSS components must be subjected to stringent quality control at all stages of the production process.

However, even in the lower strength range of good fracture toughness, low alloy steels are generally highly loaded to maximize their structural efficiency. Hence they cannot properly be regarded as damage tolerant. Other problems, e.g. stress corrosion, contribute to this limitation. Fatigue and fracture toughness data for some UHSS steels are presented in Table 7.5 [23].

Stress corrosion, hydrogen embrittlement and corrosion [24]: Low alloy steels such as 4330, 4330M, 4340, 300M, D6ac and H11 are all susceptible to SCC, and also hydrogen embrittlement at yield strengths above 1200 MPa; and they are *extremely susceptible* at yield strengths above 1400 MPa. This is why it is often advised to restrict the UTS to less than 1400 MPa. However, exceptions are made, notably for landing gear. K_{Iscc} values for 4340 steel tempered to different hardnesses are given in Table 7.6 [23].

Low alloy steels also have poor corrosion resistance, and all UHSS must be protected against corrosion and the risk of SCC. Reliance is made in the first instance on high-quality cadmium, chromium and nickel plating, sometimes in combination with each other. Additional protection is provided by paint systems on external surfaces.

Table 7.5 Fracture toughness and fatigue limit of some VAR UHSS steels [23]

Grade	Equivalent tensile strength (MPa)	K_{Ic} (MPa $\sqrt{m}$)	Fatigue limit (MPa)
4340			
Longitudinal	2035	60.4	965[a]
Transverse	2015	61.5	715[a]
		59.7[c]	
Longitudinal	2005	44.5	–
Transverse	2000	45.8	–
		48.8[c]	–
300M			
Longitudinal	2080	57.4	–
Transverse	2015	64.1	–
		61.4[c]	–
D6ac			
T 575 °C	1434	110	–
	1520	–	780[b]

[a]At 10^7 cycles
[b]At 10^6 cycles
[c]WR orientation

Table 7.6 Fracture toughness and K_{Iscc} for 4340 steel tempered to different hardnesses [23]

Hardness	Equivalent tensile strength (MPa)	K_{Ic} (MPa $\sqrt{m}$)	K_{Iscc} (MPa $\sqrt{m}$)
550	2040	53	8
430	1520	75	30
380	1290	110	33

7.11 Indian Scenario

A number of aerospace low alloy steel grades have been developed in India by both private and public sector industries. Many of the steels are type-approved by the Regional Centre for Military Airworthiness (Materials) Hyderabad, India. Chemical composition, heat treatment schedules, physical properties, mechanical properties (both room temperature and high temperature), supply conditions, melting practices, etc. are available.

A list of through-hardenable steels, case hardening steels and spring steels detailing the grades, production agencies and applications is given in Table 7.7. The properties are given in the literature [25].

Table 7.7 Indigenous (Indian-manufactured) through-hardenable steels

Sl. no.	Alloy	Mill Form	Application	Production Agency
1.	Grade AISI 4130	Bars, Rods and Forgings	Engine mounting lugs, aircraft frame tubing for fuselage, jacks, shafts, fittings, bushings, gears, bolts, axles, structural plates	M/s. Mysore Iron and Steel Limited, Bhadravati, Shimoga Dist. Karnataka
2.	100C6	Forged Bars	Bearing races, balls and rollers bearing outer housing of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
3.	Grade 25CD4S	Bars	Rear and front flange of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
4.	Grade 35CDV4	Bars	Shafts, dowel bolts, studs and pins of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
5.	Grade 15CDV6	Bars	Turbine main shaft, junction wheel of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
6.	Grade 35NC6	Forged Bars	Nuts and washers of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
7.	BS S154, S98, S99	Forged Bars	Bolts, nuts, mounting pinions of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
8.	30NCD 16	Forged Bars	Axial compressor shaft of aeroengine	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
9.	BS S142	Forged Bars and Hot Rolled Bars	Aircraft frame tubing for fuselage, jacks, shafts, fittings, bushings, gears, shafting bolts, axles	M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
10.	38XMUAW and 30XGC AW	Hot Rolled Bars	Aircraft	M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
11.	MDN 127A	Plates and Strips	Stator plate, rotor segment, drive block	M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
	Russian Grades			
12.	20 G2	CD Wires	Aircraft fasteners	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
13.	38 Kh A	Hot Rolled Bars	Airframe and aeroengine parts	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur

(continued)

Table 7.7 (continued)

Sl. no.	Alloy	Mill Form	Application	Production Agency
14.	40 Kh	Bars/Rods	Aircraft parts	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
15.	18KhSN	Filler Wire	Filler wire and flux coated electrodes	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
16.	16KhSN	Wire	Fasteners viz. rivets and bolts (by cold upsetting)	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
17.	MDN LA2	Cold Drawn Wire	Fasteners viz. rivets and bolts (by cold upsetting)	M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
18.	30XCA	Forging	Forgings of steel parts in R11F/R25 and R29B series of engines	M/s HAL, Koraput
19.	20Kh4GMA	Wires	Filler wire (electrode) for welding	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
20.	30KhGSA	Forging, HR Bars, CD Bars and CD Hexagonal Rods	Forgings of steel parts in R11F/R25 and R29B series of engines and aircraft structural components	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur and M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
21.	30KhGSA-SSH	Wires	Aircraft fasteners	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
22.	30KhGSNA	Forgings	Aircraft machine components	M/s WG Forge and Allied Industries, PB 41, Thane, Mumbai
23.	30KhGSNA-SSH	CD Hexagonal, Rods, CD and HR Bars	Aircraft machine components	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
24.	30XGCN2A	All forms	Aircraft fasteners and transmission components	M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
	Case Hardening Steels			
25.	12KhN3A	Rods	Gears, shafts, ball joint pins	M/s. Firth (India) Steel Co. Ltd, Thane, Mumbai 400 604
26.	MDN LA1	Hot Rolled Bars	Gears, shafts, ball joint pins	M/s. Mishra Dhatu Nigam Ltd. (MIDHANI), Kanchanbagh, Hyderabad-58

(continued)

Table 7.7 (continued)

Sl. no.	Alloy	Mill Form	Application	Production Agency
27.	12NC12	Forged Bars	Gear shaft, bearing housing gears, output shaft, lay shaft gears, bearing housing valves, drive shaft	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
28.	16NCD13	Forged Bars	Drive shaft, gear shaft, spiral gear, spur gear	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur and M/s. Mishra Dhatu Nigam Ltd. (MIDHANI), Kanchanbagh, Hyderabad-58
29.	BS S82	Forged Bars	Gear driven, pinion driven, idler gear	M/s. Mishra Dhatu Nigam Ltd. (MIDHANI), Kanchanbagh, Hyderabad-58
30.	30 CD12	Forged Bars	Rear shaft, nose shaft, driving gear, bearing housing	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur
31.	MDN 40A	Forged Bars	Quill shaft, mounting trunnions, bevel pinion, bearing housing, driving pump gear	M/s. Mishra Dhatu Nigam (MIDHANI) Kanchanbagh, Hyderabad-58
32.	MDN 132A	Forged Bars	Bush front mounting, bevel gear driver	M/s. Mishra Dhatu Nigam Ltd. (MIDHANI), Kanchanbagh, Hyderabad-58
33.	AE 712 BD	Forged Bars and Hot Rolled Bars	Gears	M/s. Mishra Dhatu Nigam Ltd. (MIDHANI), Kanchanbagh, Hyderabad-58
34.	AE 69	Forged Bars and Hot Rolled Bars	Pin (R/H diffuser) and plunger (starting system), casing starting system, valve hydraulic flap control (jet) and cam shaft etc.	M/s. Mishra Dhatu Nigam Ltd. (MIDHANI), Kanchanbagh, Hyderabad-58
	Spring Steels			
35.	50KhFA	CD Wires	Aircraft springs	M/s. Firth (India) Steel Co. Ltd, Thane, Mumbai 400 604
36.	65S2VA-SH	CD Wires	Aircraft springs	M/s. Firth (India) Steel Co. Ltd, 40 MIDC, Hingana Road, Nagpur

7.12 Summary and Conclusions

Alloying elements added in small amounts, singly or in combination, to steel improve its fabricability, hardenability and mechanical properties. Most of the low alloy steels used for aerospace applications are based on the alloying addition combinations of Cr–Mo–Si and Ni–Cr–Mo–Si with varying carbon contents. Ultrahigh-strength steels are the most preferred for aerospace applications owing to their *high load density* capabilities, e.g. in landing gear. A combination of vacuum induction melting and vacuum arc remelting techniques is employed to produce high-quality steels. Low alloy steels are amenable to mechanical working, welding and heat treatment in order to make components with the desired dimensions and properties. A number of aerospace low alloy steel grades are presently developed and manufactured in India.

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