

Chapter 2

Aluminium Alloys for Aerospace Applications

P. Rambabu, N. Eswara Prasad, V.V. Kutumbarao and R.J.H. Wanhill

Abstract This chapter starts with a brief overview of the historical development of aerospace aluminium alloys. This is followed by a listing of a range of current alloys with a description of the alloy classification system and the wide range of tempers in which Al alloys are used. A description is given of the alloying and precipitation hardening behaviour, which is the principal strengthening mechanism for Al alloys. A survey of the mechanical properties, fatigue behaviour and corrosion resistance of Al alloys is followed by a listing of some of the typical aerospace applications of Al alloys. The Indian scenario with respect to production of primary aluminium and some aerospace alloys, and the Type Certification process of Al alloys for aerospace applications are described. Finally there is a critical review of some of the gaps in existing aerospace Al alloy technologies.

Keywords Aluminium • Alloys • Castings • Wrought products • Mechanical properties • Fatigue • Fracture • Corrosion • Applications

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2.1 Introduction

Aluminium alloys have been the main airframe materials since they started replacing wood in the late 1920s. Even though the role of aluminium in future aircraft will probably be somewhat diminished by the increasing use of composite materials, high-strength aluminium alloys are, and will remain, important airframe materials.

The attractiveness of aluminium is that it is a relatively low cost, lightweight metal that can be heat treated to fairly high-strength levels; and it is one of the most easily fabricated of the high-performance materials, which usually correlates directly with lower costs. Disadvantages of aluminium alloys include a low modulus of elasticity, rather low elevated-temperature capability ($\leq 130\text{ }^{\circ}\text{C}$), and in high-strength alloys the susceptibility to corrosion [1].

Dramatic improvements in aluminium alloys have occurred since they were first introduced in the 1920s. These improvements, shown in Fig. 2.1, are a result of increasing understanding of chemical composition, impurity control and the effects of processing and heat treatment. The data in Fig. 2.1 pertain to established aerospace aluminium alloys; newer ones (such as AA7085) are under evaluation, as are the third-generation aluminium–lithium (Al–Li) alloys discussed in Chap. 3 of this Volume. The chemical compositions of some aerospace grade aluminium alloys [2] are given in Table 2.1.

One of the earliest aerospace Al alloys was Duralumin (AA2017) which had a yield strength of 280 MPa. Property improvements have come through development of new alloy systems, modifications to compositions within particular systems, and from the use of a range of multistage ageing treatments (tempers) [3].

Fig. 2.1 Yield strengths versus year of introduction of Al alloys [1]

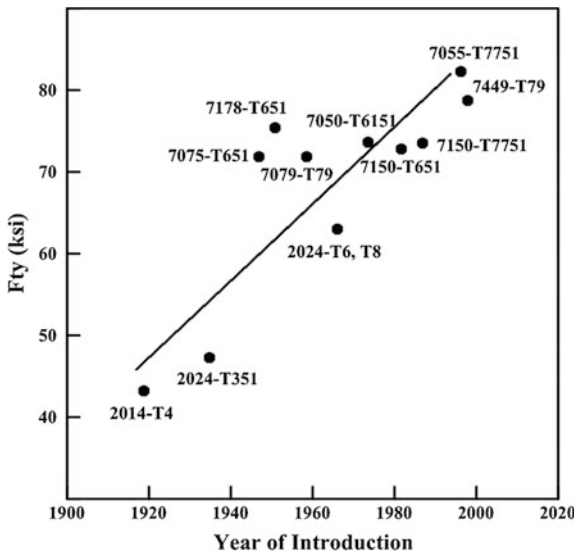


Table 2.1 Chemical compositions of some aerospace aluminium alloys [2]

Alloy	Cu	Mg	Zn	Mn	Si	Fe	Cr	Ti	Zr
AA2014	3.9–5.0	0.2–0.8	0.25 _{max}	0.4–1.2	0.5–1.2	0.7 _{max}	0.10 _{max}	0.15 _{max}	–
AA2017	3.5–4.5	0.4–0.8	0.25 _{max}	0.4–1.0	0.2–0.8	0.7 _{max}	0.10 _{max}	0.15 _{max}	–
AA2024	3.8–4.9	1.2–1.8	0.25 _{max}	0.3–0.9	0.50	0.50	0.10	0.15	–
AA2219	5.8–6.8	0.02 _{max}	0.10 _{max}	0.2–0.4	0.20 _{max}	0.30 _{max}	–	0.02–0.10	0.1–0.25
AA5083	0.10 _{max}	4.0–4.9	0.25 _{max}	0.4–1.0	0.40 _{max}	0.40 _{max}	0.05–0.25	0.15 _{max}	–
AA6061	0.15–0.4	0.8–1.2	0.25 _{max}	0.15 _{max}	0.4–0.8	0.7 _{max}	0.04–0.35	0.15 _{max}	–
AA7050	2.0–2.6	1.9–2.6	5.7–6.7	0.1 _{max}	0.12 _{max}	0.15 _{max}	0.04 _{max}	0.10 _{max}	0.08–0.15
AA7075	1.2–2.0	2.1–2.9	5.1–6.1	0.3 _{max}	0.4 _{max}	0.5 _{max}	–	0.10 _{max}	–
AA7150	1.9–2.5	2.0–2.7	5.9–6.9	0.10	0.12	0.15	0.04	0.08–0.15	0.06
AA7178	1.6–2.4	2.4–3.1	6.3–7.3	0.30	0.4	0.5	0.18–0.28	0.20	–
AA7475	1.2–1.9	1.9–2.6	5.2–6.2	0.06 _{max}	0.10 _{max}	0.12 _{max}	0.18–0.25	0.06 _{max}	–

Experiments with different levels of the alloying elements led to the Al–Cu–Mg alloy AA2014, which developed better properties than AA2017 after artificial (T6) ageing. Other experiments led to the development of AA2024-T3. This alloy attained a higher yield strength than AA2017-T4 by modest amounts of cold deformation followed by natural ageing, and has significantly higher ductility than AA2014-T6.

Several investigators found that aluminium alloys containing both zinc and magnesium developed substantially higher strengths than those containing either of the alloying elements added singly, and significantly higher strengths were obtained from these alloys. These findings led to the development of the Al–Zn–Mg–Cu alloy AA7075 in the early 1940s. A higher strength alloy, AA7178, was later developed [4], but low toughness led to alloys with much lower Fe and Si contents, e.g. AA7050 and AA7475.

As aircraft became larger it became necessary to use thicker-section airframe components. However, thick-section products of the high-strength 7XXX alloys like AA7075-T6 and particularly AA7079-T6 were found to be susceptible to stress corrosion cracking (SCC) in the short transverse direction. The overaged T73 and T76 tempers were developed in the early 1960s to make AA7075 more resistant to SCC and exfoliation corrosion.

Subsequently alloy 7475 was developed from 7075 to improve the fracture toughness. Then a new generation of alloys, including AA7050-T7351, was developed during the 1970s to fit the need for a material that would develop high strength in thick-section products, good resistance to SCC and exfoliation corrosion, and good fracture toughness and fatigue characteristics. These developments are continuing, with one of the latest alloys being AA7085.

Other developments include higher toughness 2XXX alloys and the third generation of Al–Li alloys, as already mentioned.

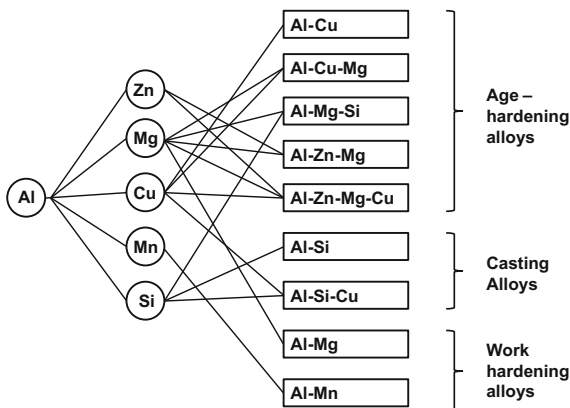
2.2 Classification and Designation

Aluminium alloys are classified as heat treatable or non-heat treatable, depending on whether or not they respond to precipitation hardening [2, 5]. The heat treatable alloys contain elements that decrease in solid solubility with decreasing temperature, and in concentrations that exceed their equilibrium solid solubility at room temperature and moderately higher temperatures. The most important alloying elements in this group include copper, lithium, magnesium and zinc [5].

A large number of other compositions rely instead on work hardening through mechanical reduction, usually in combination with various annealing procedures for property developments. These alloys are referred to as non-heat-treatable or work-hardening alloys.

Some casting alloys are essentially non-heat-treatable and are used as-cast or in thermally modified conditions uninfluenced by solutionizing or precipitation effects [2]. Figure 2.2 gives an overview of the principal types of aluminium alloys.

Fig. 2.2 The principal types of aluminium alloys [2]



2.2.1 Wrought Alloys

A four-digit numerical designation system is used to identify wrought aluminium and aluminium alloys. As shown below, the first digit of the four-digit designation indicates the group.

Aluminium, $\geq 99.00\%$ —1XXX. Aluminium alloys grouped by major alloying element(s); Copper—2XXX; Manganese—3XXX; Silicon—4XXX; Magnesium—5XXX; Magnesium and Silicon—6XXX; Zinc—7XXX; Other elements—8XXX; Unused series—9XXX.

2.2.2 Cast Alloys

A system of four-digit numerical designations incorporating a decimal point is used to identify aluminium and aluminium alloys in the form of castings and foundry ingots. The first digit indicates the alloy group.

Aluminium, $\geq 99.00\%$ —1XX.X. Aluminium alloys grouped by major alloying element(s); Copper—2XX.X; Silicon with added copper and/or magnesium—3XX.X; Silicon—4XX.X; Magnesium—5XX.X; Zinc—7XX.X; Tin—8XX.X; Other elements—9XX.X; Unused series—6XX.X

2.2.3 Temper Designations

The temper designation system is used for all product forms (both wrought and cast), with the exception of ingots. The system is based on the sequences of mechanical or thermal treatments, or both, used to produce the various tempers. The temper designation follows the alloy designation and is separated from it by a

hyphen. Basic temper designations consist of individual capital letters. Major subdivisions of basic tempers, where required, are indicated by one or more digits following the letter. These digits designate sequences of treatments that produce specific combinations of characteristics in the product. Variations in treatment conditions within major subdivisions are identified by additional digits.

T1—Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition. This designation applies to products that are not cold-worked after an elevated-temperature shaping process such as casting or extrusion, and for which mechanical properties have been stabilized by room temperature ageing. This designation also applies to products that are flattened or straightened after cooling from the shaping process, whereby the cold-work effects imparted by flattening or straightening *are not* accounted for in the specified property limits.

T2—Cooled from an elevated-temperature shaping process, cold-worked, and naturally aged to a substantially stable condition. This designation refers to products that are cold-worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion, and for which the mechanical properties have been stabilized by room temperature ageing. This designation also applies to products in which the effects of cold-work, imparted by flattening or straightening, *are* accounted for in the specified property limits.

T3—Solution heat treated, cold-worked, and naturally aged to a substantially stable condition. T3 applies to products that are cold-worked specifically to improve strength after solution heat treatment and for which mechanical properties have been stabilized by room temperature ageing. This designation also applies to products in which the effects of cold work, imparted by flattening or straightening, *are* accounted for in the specified property limits.

T4—Solution heat treated and naturally aged to a substantially stable condition. This designation signifies products that are not cold-worked after solution heat treatment and for which mechanical properties have been stabilized by room temperature ageing. If the products are flattened or straightened, the effects of the cold-work imparted by flattening or straightening *are not* accounted for in the specified property limits.

T5—Cooled from an elevated-temperature shaping process and artificially aged. T5 includes products that are not cold-worked after an elevated-temperature shaping process such as casting or extrusion and for which the mechanical properties have been substantially improved by precipitation heat treatment. If the products are flattened or straightened after cooling from the shaping process, the effects of the cold-work imparted by flattening or straightening *are not* accounted for in the specified property limits.

T7—Solution heat treated and overaged or stabilized. T7 applies to wrought products that have been precipitation heat treated beyond the point of maximum strength to provide some special characteristics, such as enhanced resistance to stress corrosion cracking or exfoliation corrosion. This designation also applies to

cast products that are artificially aged after solution heat treatment to provide dimensional and strength stability.

T8—Solution heat treated, cold-worked, and artificially aged. This designation applies to products that are cold-worked specifically to improve strength after solution heat treatment and for which mechanical properties or dimensional stability, or both, have been substantially improved by precipitation heat treatment. The effects of cold work, including any cold work imparted by flattening or straightening, *are* accounted for in the specified property limits.

T9—Solution heat treated, artificially aged, and cold-worked. This group is comprised of products that are cold-worked specifically to improve strength after they have been precipitation heat treated.

T10—Cooled from an elevated-temperature shaping process, cold-worked, and artificially aged. T10 identifies products that are cold-worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion and for which the mechanical properties have been substantially improved by precipitation heat treatment. The effects of cold work, including any cold work imparted by flattening or straightening, *are* accounted for in the specified property limits.

2.3 Age-Hardenable Aluminium Alloys

Although most metals will alloy with aluminium, comparatively few have sufficient solid solubility to serve as major alloying additions, see Table 2.2. Some of the transition metals, e.g. chromium, manganese and zirconium, which have solid solubilities below 1 at.% confer important improvements to alloy properties by forming intermetallic compounds that control the grain structure. Apart from tin, which is sparingly soluble, the maximum solid solubilities in binary aluminium alloys occur at the eutectic and peritectic temperatures [6].

The heat treatment given to aluminium alloys to increase strength is age hardening. As stated at the beginning of Sect. 2.2, the basic requirement for an alloy to be amenable to age-hardening is a decrease in solid solubility of one or more of the alloying elements with decreasing temperature. Heat treatment normally involves the following stages:

1. Solution treatment at a relatively high temperature within the single-phase region.
2. Rapid cooling or quenching, usually to room temperature to obtain a super-saturated solid solution (SSSS) of the age-hardening elements in aluminium.
3. Controlled decomposition of the SSSS to form a finely dispersed precipitate, usually by ageing for convenient times at one and sometimes two intermediate temperatures.

Table 2.2 Solid solubility of elements in aluminium [6]

Element	Temperature for maximum solid solubility (°C)	Maximum solid solubility	
		(wt%)	(at.%)
Cadmium	649	0.4	0.09
Cobalt	657	< 0.02	< 0.01
Copper	548	5.65	2.40
Chromium	661	0.77	0.40
Germanium	424	7.2	2.7
Iron	655	0.05	0.025
Lithium	600	4.2	16.3
Magnesium	450	17.4	18.5
Manganese	658	1.82	0.90
Nickel	640	0.04	0.02
Silicon	577	1.65	1.59
Silver	566	55.6	23.8
Tin	228	~ 0.06	~ 0.01
Titanium	665	~ 1.3	~ 0.74
Vanadium	661	~ 0.4	~ 0.21
Zinc	443	82.8	66.4
Zirconium	660.5	0.28	0.08

The complete decomposition of an SSSS is usually a complex process which may involve several stages. Typically, Guinier–Preston (GP) zones and an intermediate precipitate may be formed in addition to the equilibrium phase.

Most aluminium alloys that respond to ageing will undergo some hardening at ambient temperatures. This is called ‘natural ageing’ and may continue almost indefinitely, although the rate of change becomes extremely slow after months or years. Ageing at sufficiently elevated temperature (artificial ageing) is characterized by a different behaviour in which the hardness usually increases to a maximum and then decreases. The highest value of hardness occurs at one particular temperature, which varies with each alloy.

Maximum hardening in commercial alloys normally occurs when a critical dispersion of GP zones, or an intermediate precipitate, or a combination of both, are present. In some alloys more than one intermediate precipitate may be formed.

The softening that occurs on prolonged artificial ageing is known as ‘overageing’. For commercial heat treatments an ageing schedule is usually selected to give the desired response to hardening (strengthening) within a convenient period of time.

Some alloys are cold-worked (e.g. stretching or compression, up to 5 %) after quenching and before ageing. The cold-work increases the dislocation density and provides more sites at which heterogeneous nucleation of intermediate precipitates may occur during ageing [6]. The result is an improvement in the strength properties.

2.4 Effects of Alloying Elements

The effect(s) of various alloying elements [2] are given below in alphabetical order. Some of the effects, particularly with respect to impurities, are not well documented and are specific to particular alloys or conditions.

Chromium: Is a common addition to many alloys of the aluminium–magnesium, aluminium–magnesium–silicon, and aluminium–magnesium–zinc groups, in which it is added in amounts generally not exceeding 0.35 wt%. Above this limit chromium tends to form very coarse constituents with other impurities or additions such as manganese and titanium.

Chromium has a low diffusion rate and forms a fine dispersed phase in wrought products. The dispersed phase inhibits nucleation and grain growth. Hence during hot working or heat treatment, chromium prevents grain growth in aluminium–magnesium alloys and recrystallization in aluminium–magnesium–silicon or aluminium–magnesium–zinc alloys.

The main drawback of chromium in heat treatable alloys is the increase in quench sensitivity when the hardening phase tends to precipitate on the preexisting chromium-phase particles.

Copper: Aluminium–copper alloys containing 2–10 wt% Cu, generally with other additions, form an important family of Al alloys. Both cast and wrought aluminium–copper alloys respond to solution heat treatment and subsequent ageing, with an increase in strength and hardness and a decrease in elongation. The strengthening is maximum between 4 and 6 wt% Cu, depending upon the influence of other constituents. N.B: the ageing characteristics of binary aluminium–copper alloys have been studied in greater detail than for any other system, but all commercial aerospace alloys contain other alloying elements.

Copper–Magnesium: The main benefit of adding magnesium to aluminium–copper alloys is the increased strength following solution heat treatment and quenching. In certain wrought alloys of this type, ageing at room temperature (natural ageing) causes an increase in strength accompanied by high ductility. Artificial ageing, at elevated temperatures, results in a further increase in strength, especially the yield strength, but at a substantial sacrifice in tensile elongation.

For both cast and wrought aluminium–copper alloys, as little as about 0.5 wt% Mg is effective in changing the ageing characteristics. In wrought products the effect of magnesium additions on strength can be maximized in artificially aged materials by cold-working prior to ageing. In naturally aged materials, however, the benefit to strength from magnesium additions can *decrease* with cold-working.

The effect of magnesium on the corrosion resistance of aluminium–copper alloys depends on the type of product and thermal treatment.

Copper–Magnesium plus Other Elements: Al–Cu–Mg alloys containing manganese are the most important and versatile class of commercial high-strength wrought aluminium–copper–magnesium alloys. In general, tensile strength increases with separate or simultaneous increases in magnesium and manganese, and the yield strength also increases, but to a lesser extent. Further increases in

tensile strength and particularly yield strength occur on cold-working after heat treatment.

Additions of manganese and magnesium decrease the fabrication characteristics of aluminium–copper alloys, and manganese also causes a loss in ductility. Hence the concentration of manganese does not exceed about 1 wt% in commercial alloys. Additions of cobalt, chromium, or molybdenum to the wrought Al-4 wt% Cu-0.5 wt% Mg type of alloy increase the tensile properties on heat treatment, but none offers a distinct advantage over manganese.

The cast aluminium–copper–magnesium alloys containing iron are characterized by dimensional stability and improved bearing characteristics, as well as high strength and hardness at elevated temperatures. However, in a wrought Al-4 wt% Cu-0.5 wt% Mg alloy, iron in concentrations as low as 0.5 wt% lowers the tensile properties in the heat-treated condition unless the silicon content is sufficient to sequester the iron as FeSi intermetallic particles. When sufficient silicon is present to combine with the iron, the strength properties are unaffected, although the FeSi particles are detrimental to fracture toughness, see Sect. 2.5.1.

However, if there is excess iron, it unites with copper to form the Cu_2FeAl_7 constituent, thereby reducing the amount of copper available for heat-treating effects. Silicon also combines with magnesium to form Mg_2Si precipitates that contribute to the age-hardening process, see below.

Silver substantially increases the strength of heat treated and aged aluminium–copper–magnesium alloys. Nickel improves the strength and hardness of cast and wrought aluminium–copper–magnesium alloys at elevated temperatures. However, addition of about 0.5 wt% Ni lowers the tensile properties of the heat-treated wrought Al-4 %Cu-0.5 %Mg alloy at room temperature.

Magnesium–Silicon: Wrought alloys of the 6XXX group contain up to 1.5 wt% each of magnesium and silicon in the approximate ratio to form Mg_2Si , i.e. 1.73:1. The maximum solubility of Mg_2Si in Al is 1.85 wt%, and this decreases with temperature. Precipitation upon age-hardening occurs by formation of Guinier–Preston zones and a very fine precipitate. Both confer an increase in strength to these alloys, though not as great as in the case of the 2XXX or the 7XXX alloys.

Al– Mg_2Si alloys can be divided into three groups. In the first group the total amount of magnesium and silicon does not exceed 1.5 wt%. These elements are in a nearly balanced ratio or with a slight excess of silicon. Typical of this group is AA6063, which nominally contains 1.1 wt% Mg_2Si and is widely used for extruded sections. Its solution heat-treating temperature of just over 500 °C and its low quench sensitivity are such that this alloy does not need a separate solution treatment after extrusion, but may be air quenched at the press and artificially aged to achieve moderate strength, good ductility, and excellent corrosion resistance.

The second group nominally contains 1.5 wt% or more of magnesium + silicon and other additions such as 0.3 wt% Cu, which increases strength in the T6 temper. Elements such as manganese, chromium, and zirconium are used for controlling grain structure. Alloys of this group, such as AA6061, achieve strengths about 70 MPa higher than in the first group in the T6 temper. However, this second group requires a higher solution treating temperature than the first and they are quench

sensitive. Therefore they generally require a separate solution treatment followed by rapid quenching and artificial ageing.

The third group contains an amount of Mg_2Si overlapping the first two but with substantial excess silicon. An excess of 0.2 wt% Si increases the strength of an alloy containing 0.8 wt% Mg_2Si by about 70 MPa. Larger amounts of excess silicon are less beneficial. Excess magnesium, however, is of benefit only at low Mg_2Si contents because magnesium lowers the solubility of Mg_2Si .

In excess silicon alloys, segregation of silicon to the grain boundaries causes grain-boundary fracture in recrystallized structures. Additions of manganese, chromium, or zirconium counteract the effect of silicon by preventing recrystallization during heat treatment. Common alloys of this group are AA6351 and the more recently introduced alloys AA6009 and AA6010. An addition of lead and bismuth to an alloy of this series (AA6262) improves machinability.

Silicon: In wrought alloys silicon is used with magnesium at levels up to 1.5 wt% to produce Mg_2Si in the 6XXX series of heat treatable alloys.

High-purity aluminium–silicon casting alloys exhibit hot shortness up to 3 wt% Si, the most critical range being 0.17–0.8 wt% Si. However, in aluminium–copper–magnesium alloys silicon additions (0.5–4.0 wt%) *reduce* the cracking tendency. Small amounts of magnesium added to any silicon-containing alloy will render it heat treatable, but the converse is not true, since excess magnesium over that required to form Mg_2Si sharply reduces the solid solubility of this compound.

Modification of the silicon morphology in casting alloys can be achieved through the addition of sodium in eutectic and hypoeutectic alloys and by phosphorus in hypereutectic alloys.

Titanium: Is used primarily as a grain refiner of aluminium alloy castings and ingots. When used alone, the effect of titanium decreases with time of holding in the molten state and with repeated remelting. The grain-refining effect is enhanced if boron is present in the melt or if it is added as a master alloy containing boron largely combined with titanium as TiB_2 .

Zinc–Magnesium: Addition of magnesium to aluminium–zinc alloys develops the strength potential of this alloy system, especially in the range of 3–7.5 wt% Zn. Magnesium and zinc form MgZn_2 , which produces a far greater response to heat treatment than occurs in the binary aluminium–zinc system.

On the negative side, increasing additions of both zinc and magnesium decrease the overall corrosion resistance of aluminium, such that close control over the microstructure, heat treatment, and composition are often necessary to maintain adequate resistance to stress corrosion and exfoliation corrosion. For example, depending upon the alloy, stress corrosion is controlled by some or all of the following: overageing; cooling rate after solution treatment; maintaining an unrecrystallized structure via additions such as zirconium, copper or chromium (see zinc–magnesium–copper alloys); and adjusting the zinc–magnesium ratio closer to 3:1.

Zinc–Magnesium–Copper: Addition of copper to the aluminium–zinc–magnesium system, together with small but important amounts of chromium and manganese, results in the highest strength aluminium-base alloys (7XXX series) commercially available.

In this alloy system, zinc and magnesium control the ageing process. The effect of copper is to increase the ageing rate by increasing the degree of supersaturation and perhaps through nucleation of the CuMgAl_2 phase. Copper also increases the quench sensitivity upon heat treatment. In general, copper reduces the resistance to general corrosion of aluminium–zinc–magnesium alloys, but increases the resistance to stress corrosion. Minor alloy additions, such as chromium and zirconium, have a marked effect on mechanical properties and corrosion resistance.

Zirconium: Additions in the range 0.1–0.3 wt% are used to form a fine precipitate of intermetallic particles that inhibit recovery and recrystallization. An increasing number of alloys, particularly in the aluminium–zinc–magnesium family, use zirconium additions to increase the recrystallization temperature and to control the grain structure in wrought products. Zirconium additions render this family of alloys less quench sensitive compared to chromium additions.

Higher levels of zirconium are employed in some superplastic alloys to retain the required fine substructure during elevated temperature forming. Zirconium additions have been used to reduce the as-cast grain size, but the effect is less than that of titanium. In addition, zirconium tends to reduce the grain-refining effect of titanium plus boron additions so that it is necessary to use more titanium and boron to grain refine zirconium-containing alloys.

2.5 Mechanical Properties

2.5.1 *Strength and Fracture Toughness*

As previously mentioned, aluminium alloys may be divided into two groups depending upon whether or not they respond to precipitation hardening. For alloys that do not respond to ageing treatments, it is the finely dispersed precipitates that have the dominant effect in inhibiting dislocation motion and thereby raising yield and tensile strengths.

For the other group the grain size of cast alloys and the dislocation structures produced by cold-working in the case of wrought alloys are of prime importance. Some of the mechanical properties of wrought age-hardening aerospace aluminium alloys are given in Table 2.3.

Coarse intermetallic compounds have relatively little effect on yield or tensile strength but they can cause a marked loss of ductility in both cast and wrought products. The particles may crack at small plastic strains forming internal voids which, under the action of further plastic strain, coalesce leading to premature fracture.

Early work on the higher strength aluminium alloys was directed primarily at maximizing tensile properties in aerospace materials. Since the 1960s the emphasis in alloy development has shifted away from tensile strength as the primary consideration, and more attention is given to optimizing a combination of properties

Table 2.3 Typical mechanical properties of some standard and widely used aerospace aluminium alloys

Alloy	Temper	Density (g/cm ³)	Elastic modulus (GPa)	Tensile properties			HCF limit (MPa)	Fracture toughness (MPa√m)	References
				Yield (MPa)	Tensile (MPa)	% El			
AA2014	T6	2.80	72.4	415	485	13	125	26.4 (T651)	[2, 9, 10]
AA2219	T62	2.84	73.8	290	415	10	105	36.3 (T87)	[2, 9, 10]
AA2024	T4	2.77	72.4	325	470	20	140	22.0 (T851)	[2, 9, 10]
AA7050	T74	2.83	70.3	450	510	13	170	38.5 (T73651)	[2, 9, 10]
AA7075	T6	2.80	71.0	505	570	11	160	28.6 (T6)	[2, 9, 10]

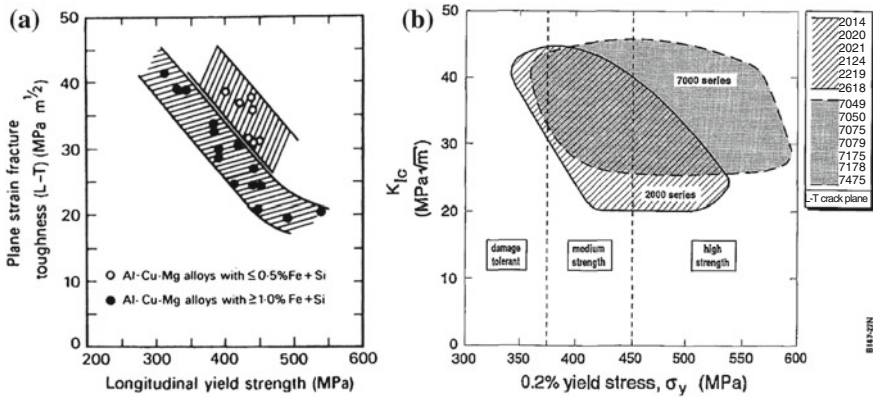


Fig. 2.3 Plane-strain fracture toughness of **a** Al-Cu-Mg alloys with differing levels of iron and silicon [3]; **b** 2XXX and 7XXX alloys covering three strength regimes [7]. Note the general inverse relationship between strength and fracture toughness

and the alloys' behaviour under a variety of service loadings and environmental conditions.

Yield strength is important for resisting deformation under service loads, but in the presence of cracks and other flaws it is the fracture toughness that generally becomes the more important parameter. Minimum fracture toughness requirements have become mandatory, and in the high-strength alloys the generally inverse relationship between strength and toughness, see Fig. 2.3, limits the level of yield strength that can be safely employed by the designer.

The major step in the development of aluminium alloys with greatly improved fracture toughness has come from controlling the levels of the impurity elements iron and silicon. This effect is shown in Fig. 2.3a for alloys based on the Al-Cu-Mg system: it can be seen that plane-strain fracture toughness values may be doubled by maintaining the combined levels of these elements below 0.5 wt% as compared with similar alloys in which this value exceeds 1.0 wt%. Consequently, some high-toughness versions of older alloy compositions are now commercially used with reduced impurity levels [3].

Figure 2.3b shows that in general the 7XXX series of alloys can attain superior combinations of strength and fracture toughness compared with 2XXX alloys.

2.5.2 Fatigue

Fatigue life and strength properties are always important design data for aircraft structures. The practical significance is, however, restricted to *notched* fatigue, since cracks start at stress concentrations, especially fastener holes [7].

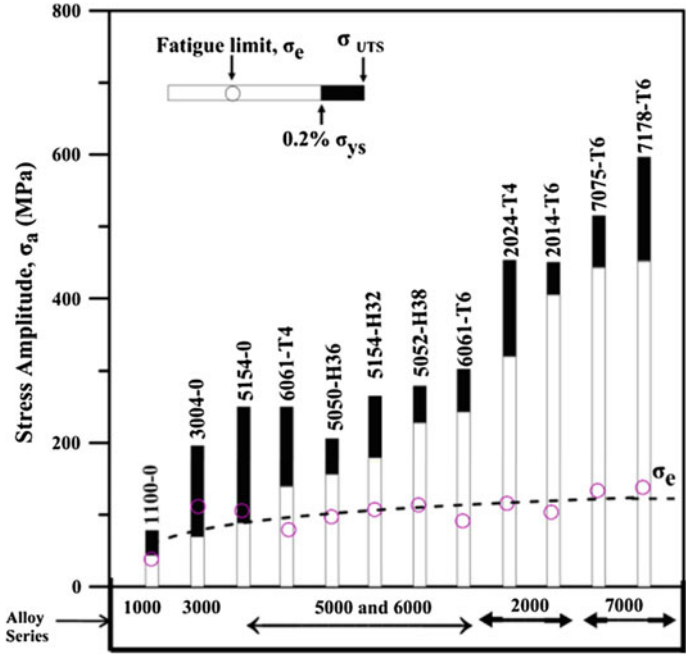


Fig. 2.4 Fatigue limits of conventional (non-lithium-containing) wrought aluminium alloys [11]

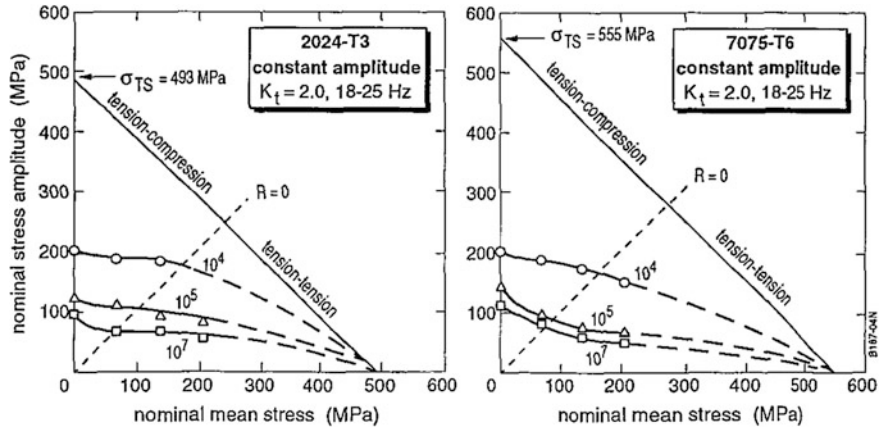


Fig. 2.5 Notched ($K_t = 2$) fatigue strengths of aircraft standard sheet alloys [7]

Unlike steels, the unnotched fatigue strengths of wrought aluminium alloys are not proportional to the static strengths, i.e. stronger alloys do not necessarily have a higher fatigue strength, see Fig. 2.4. This is even more marked for notched fatigue, and there is actually little difference in the high-cycle notched fatigue strengths of IM wrought alloys, for example Fig. 2.5.

2.5.3 Fatigue Crack Growth

Conventional (non-lithium-containing) 2XXX series alloys are generally superior to 7XXX series alloys under constant amplitude loading, for example Fig. 2.6, and gust spectrum loading (typical for transport aircraft), but not necessarily under manoeuvre spectrum loading representative for tactical (fighter) aircraft [8].

Also, for constant amplitude loading at low ΔK values, the alloy rankings depend strongly on the ageing treatment: naturally aged (T3X) and artificially aged (T8X) treatments for 2XXX series alloys, and artificially peak aged (T6X) and overaged (T7X) treatments for 7XXX series alloys [7].

Thus, summarising, fatigue crack growth testing, even at the basic materials level, when selecting candidate materials for further evaluation, should include realistic load histories and representative stress levels [8].

2.5.4 Corrosion Resistance

The corrosion resistance of any specific aluminium alloy depends on the environment as well as the alloy. Both chemical and physical environmental variables

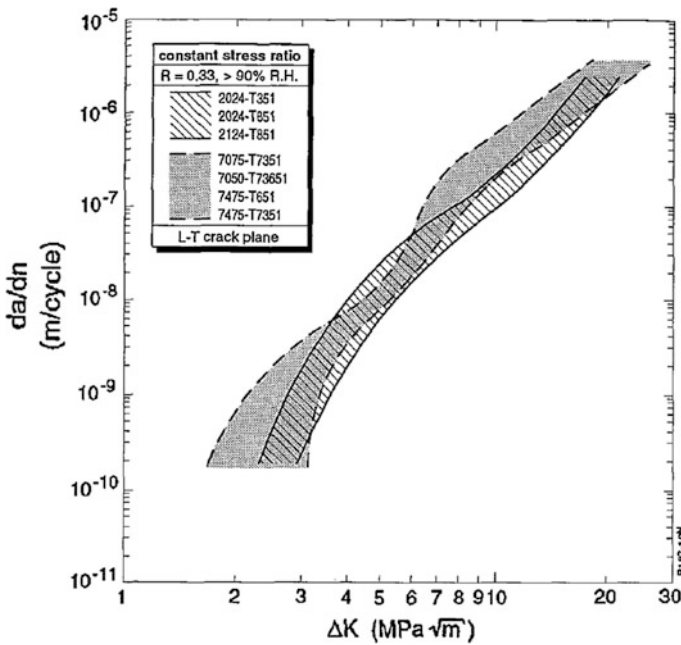


Fig. 2.6 Constant stress ratio fatigue crack growth rates for conventional 2XXX and 7XXX plate alloys [7]

affect corrosion. The influence of the environment depends on its composition and the presence of impurities, such as heavy metal ions. Physical variables are temperature, degree of movement and agitation, and pressure. Alloy variables that affect corrosion are composition and fabrication practice. These determine the microstructure, which controls whether localized corrosion occurs and the method of attack [9].

Conventional (non-lithium-containing) aerospace alloys always require some form of corrosion protection. This can be cladding with (nearly) pure aluminium and anodizing for sheet alloys; anodizing or ion vapour deposition for other types of products; and primer and paint systems.

Some aluminium alloys are susceptible to stress corrosion cracking (SCC), which occurs under the combined action of a continuous tensile stress and a specific corrosive environment. The most important aerospace aluminium alloys susceptible to SCC are the 2XXX-T8XX, 7XXX-T6XX and 7XXX-T7XX tempers [12]. Very rarely, SCC occurs in aluminium–magnesium–silicon alloys (6XXX).

The remedial measures against SCC include restricting the alloy strength levels, stress relief treatments, minimizing assembly stresses in built-up structures, and corrosion-resistant coatings, as above [12]. See also Chap. 19 in Volume 2 of these Source Books.

2.6 Typical Aerospace Applications of Aluminium Alloys

Even though the role of aluminium in future commercial aircraft will probably be ‘threatened’ by the increasing use of composite materials, the high-strength aluminium alloys are, and will remain, important airframe materials. Even in fighter aircraft, which already have composite material percentages in the range of 40–50 %, aluminium still plays a significant role [1]. The attractiveness of aluminium is that it is a relatively low cost, lightweight metal that can be heat treated to fairly high-strength levels, and it is one of the most easily fabricated high performance materials, i.e. the manufacturing costs are relatively low.

Improvements in aluminium manufacturing technology include high-speed machining and friction stir welding (FSR):

- Although higher metal removal rates are an immediate benefit of high-speed machining, an additional cost saving is the ability to machine extremely thin walls and webs. This allows the design of weight competitive high-speed machined assemblies, in which sheet metal parts that were formally assembled with mechanical fasteners can now be machined from a single or several blocks of aluminium plate.
- FSR is a solid state joining process that has the ability to weld the 2XXX and 7XXX alloys, which are not suited to conventional fusion welding. FSR also allows the design of weight competitive assemblies with a minimum number of mechanical fasteners.



Fig. 2.7 Engineering property requirements for main structural areas in a transport aircraft: *CYS* compressive yield strength; *E* elastic modulus; *TS* tensile strength; *DT* damage tolerance properties (fatigue, fatigue crack growth, fracture toughness)

More specifically, the alloy property requirements vary depending on the application. A generic example is given in Fig. 2.7, which illustrates the engineering property requirements for several of the main structural areas in a transport aircraft, namely (i) fuselage and pressure cabins, (ii) wings and (iii) empennage (horizontal and vertical stabilizers).

The engineering properties required for these structures are strength (*TS*, *CYS*), stiffness (*E*), damage tolerance (*DT*: fatigue, fatigue crack growth, fracture toughness), and corrosion (general and stress corrosion). The rankings of the requirements differ for different areas, but there is much commonality.

Table 2.4 presents a survey of the actual and proposed uses of conventional 2XXX and 7XXX aluminium alloys in airframe structures. Alloy producers develop basically similar alloys for different product forms and applications. The most important contribution to this flexibility is the development of a range of alloy tempers that allow optimizations and trade-offs of properties, and hence the ability to match the alloys to particular applications.

2.7 Indian Scenario

4 % of the global primary Al production of about 50 million tons is produced in India by three large manufacturers: NALCO, HINDALCO and the Vedanta Group. Comparable quantities are produced by recycling (using domestic as well as imported scrap, mostly by thousands of small units). About 80 % of the primary

Table 2.4 Actual and proposed uses of conventional aerospace aluminium alloys in airframe structures [13]

Product	Strength levels	Alloy/temper	Applications
Sheet	Damage tolerant	2024-T3, 2524-T3/351	Fuselage/pressure cabin skins
Plate	Damage tolerant	2024-T351, 2324-T39, 2624-T351, 2624-T39	Lower wing covers
	Medium strength	2024-T62	Tactical aircraft fuselage panels
	Medium strength	2124-T851	Tactical aircraft bulkheads
	Medium strength	7050-T7451, 7X75-T7XXX	Internal fuselage structures
	High strength	7150-T7751, 7055-T7751, 7055-T7951, 7255-T7951	Upper wing covers
	Medium strength	7050-T7451	Spars, ribs, other internal structures
Forgings	High strength	7175-T7351, 7050-T7452	Wing/fuselage attachments
Extrusions	Damage tolerant	2024-T3511, 2026-T3511, 2024-T4312, 6110-T6511	Lower wing stringers Fuselage/pressure cabin stringers
	Medium/high strength	7075-T73511, 7075-T79511, 7150-T6511, 7175-T79511, 7055-T77511, 7055-T79511	Fuselage stringers and frames, upper wing stringers, floor beams, seat rails

aluminium is consumed domestically, while the rest is exported, making India an Al-surplus country.

This deceptive surplus is essentially due to the very low per capita consumption of aluminium (under 1 kg) compared to the US and Europe (25–30 kg), and even China (3 kg). The domestic consumption pattern gives a clue to the reasons for this situation: the Power Industry (mainly overhead cables and other conductors) is the principal consumer of domestic aluminium (48 %). Other sectors lag far behind: Transport 15 %; Construction 13 %; Machinery and Equipment 7 %; Consumer Durables 7 %; Packaging: 4 %; Others 6 %.

From the foregoing list it is clear that only very small amounts of aluminium and its alloys made in India go into the aerospace industry, which itself is at an early stage of development, particularly in the private sector. The only primary aircraft manufacturer is the public sector Hindustan Aeronautics Limited (HAL), which produces military aircraft, either of its own design or under licence from a foreign

manufacturer. The other major aerospace organization is the Indian Space Research Organization (ISRO). This is a research establishment producing highly advanced Space Vehicles that serve as technology demonstrators. Nonetheless these have high commercial potential.

Several hundred ancillary units fabricate component parts for aerospace applications. Two examples are Hindalco-Almex Aerospace Ltd (HAAL), Aurangabad, and PMI Engineering Exports Pvt Ltd, Chennai. The aluminium alloys they state they are able to produce include AA2014, AA2618, AA5083, AA6061, AA7010, AA7020, AA7050, AA7075 and AA7175: in short, a considerable variety.

Besides industry, there is considerable aerospace R&D activity in other institutions in India, led by several prestigious DRDO laboratories. Missile development programs at several of these laboratories are supplemented by extensive work on manufacture and property studies for a range of Al alloys including Al–Li alloys (see Chap. 3 of this Volume) at the Defence Metallurgical Research Laboratory, Hyderabad.

Some CSIR labs like the National Aerospace Laboratory (NAL), Bengaluru, and the Regional Research Laboratory, Trivandrum, a few University Departments and Research Institutions like the celebrated Indian Institute of Science, Bengaluru, complete the R&D picture.

2.7.1 Gaps in Indian Aerospace Aluminium Technologies

A Delphi Expert Panel study on Vision 2019 for the Indian Aerospace Industry (published in EM India June/July 2010, p.38) has concluded that India is fast emerging as an international player in the aerospace industry owing to the low cost of labour, the growing manufacturing sector and the rising stock of its R&D capabilities.

Most experts seem to be expecting India to be a leading MRO (maintenance, repair and overhaul) hub in Asia, particularly for military aircraft. However, foreign organizations will continue to dominate the aerospace industry in India, since domestic companies will find it difficult to keep up, given the technological gaps between them and foreign companies. This situation could change if global players start their cutting edge R&D activities in India in association with Indian collaborators, subject to the Government enabling improved internet protocol (IP) protection.

The Indian aerospace sector has the potential to develop basic competencies in aircraft manufacture, at least in respect of development of small and medium aircraft. Demand for individual personalized flights is now increasing, so we could see a boom in private aircraft manufacturing in India. However, besides shortcomings in design, manufacturing and avionics capabilities, the availability of suitable materials is a serious problem limiting the growth of this sector.

Traditionally aluminium alloys have been the favoured materials for airframe structures. However, polymer matrix composites with high-specific strength and

modulus are serious challengers to the use of Al alloys, which inherently suffer from low stiffness. Significant improvements in specific elasticity cannot be achieved in conventional Al alloys. However, some publications have mentioned that a very light (density 2.1 g/cm^3) Al–Be alloy designated as AlBeMet AM162 can achieve a nearly four times higher specific modulus than the industry standard AA7075 alloy, with comparable strength and ductility but only half the fracture toughness and considerably increased toxicity (due to Be). Other possibilities for achieving high stiffnesses in Al alloys need to be explored.

Indian primary aluminium manufacture is beset with major technological challenges, particularly the high electricity consumption during reduction of alumina to aluminium by elevated-temperature electrolysis and large quantities of difficult to dispose of byproducts like “Red Mud” and extremely toxic “Spent Pot Lining (SPL)”.

An important issue is maintaining the high quality of products required for aerospace applications, while at the same time keeping the costs down to an acceptable level. Manufacturing units in the secondary sector are beset with the problem of variable quality and heterogeneity of the raw material—aluminium scrap—making it difficult to produce high quality end products.

2.7.2 Type Certification of Aluminium Alloys in India

Aluminium alloys type-certified for Indian aeronautical and missile applications by the Centre for Military Airworthiness and Certification (CEMILAC), Bengaluru, India are listed in Table 2.5. The significance of aero certification is that the design, production and qualification are established for all type-certified alloys. The large number of such alloys being type-approved denotes that aluminium alloy technologies and their production are maturing in India.

2.8 Summary and Conclusions

Because of the unique combination of light weight, high strength, and ease of fabrication, aluminium alloys have been the mainstay of the aerospace industry for nearly a century. Even though polymer-based composites have emerged in recent years as formidable competitors in this respect, the pre-eminence of Al alloys in civil transport aircraft remains hardly diminished, particularly in view of their near-infinite recyclability and flame-retarding properties, two issues that complicate and restrict the use of polymer-based materials.

However, serious consideration now needs to be paid to the well-known inadequacies of aluminium alloys, such as the high cost and environmental issues

Table 2.5 Aluminium alloys type-approved by CEMILAC, India

Sl. No.	Nomenclature	Issued to	RCMA [*]	TA No. ^{**}
1.	Al alloy AG5MC Sheets	M/s Hindustan Al Corp. U.P.	A/C	47
2.	Al alloy AL-5 for Castings	M/s HAL, Koraput	KPT	142
3.	Extruded bars AG5MC	Ordnance Factory, Nagpur	F&F	251
4.	Al Sheet Grade INDAL "IS"	M/s Indian Al Co., Kolkatta	NSK	347
5.	Rivet Wire Gr V-65	Indian Ordnance Factory, Nasik	NSK	348
6.	INDAL-B26SW	INDAL-B26SW	NSK	367
7.	INDAL-3S-0	M/s Indian Al Co., Kolkatta	NSK	371
8.	INDAL-M57S-0	M/s Indian Al Co., Kerala	NSK	396
9.	INDAL-24SWG	M/s Indian Al Co., Kerala	NSK	399
10.	Bars 5052 (ASM)	M/s Hindustan Al., U.P.	NSK	420
11.	AL-19 for Castings	M/s HAL, Koraput	KPT	444
12.	B51S	M/s Indian Al Co., Kolkatta	A/C	491
13.	Al Sheet '2S'	M/s Indian Al Co., Kolkatta	NSK	492
14.	Castings AL-9, T4, T5	M/s HAL, Koraput	KPT	517
15.	AK-6 Stampings	M/s HAL, Koraput	KPT	588
16.	HE-15A Extruded Bars	Ordnance Factory, Nagpur	F&F	617
17.	L-77 Extruded Bars	M/s Indian Al Co., Kerala	F&F	618
18.	AU4G1 Extruded Bars	M/s Indian Al Co., Kerala	F&F	668
19.	AU2GN Extruded Bars	M/s Indian Al Co., Kerala	F&F	669
20.	AMG-2	M/s Indian Al Co., Kerala	NSK	688
21.	AK-4-1	M/s Indian Al Co., Kerala	NSK	689
22.	Gr. BRAZHIMS 10-3-1.5	M/s Indoswe Engg. Ltd., Pune	NSK	690
23.	AK-8	M/s Indian Al Co., Kerala	NSK	691
24.	Gr BRZHN-10-4.4	M/s Indoswe Engg. Ltd., Pune	NSK	692
25.	HE 15A(ST)	Ordnance Factory, Nagpur	F&F	724
26.	HE 20A (Extruded Bars)	Ordnance Factory, Nagpur	F&F	736
27.	AG5MC Bars	Ordnance Factory, Nagpur	F&F	751
28.	Forgings of HE-15A	M/s HAL F&F Division, Bengaluru	F&F	950
29.	Extruded Bars 7010A ST	M/s Ordnance Factory, Nagpur	F&F	984
30.	AU4G1, Extruded flats	M/s Ordnance Factory, Nagpur	F&F	1327
31.	5086 Extruded Bars	M/s Ordnance Factory, Nagpur	F&F	1330
32.	Al-356 Investment Castings	M/s IPCL, Gujarat	MAT	1517
33.	HF 15, T652 Forgings	M/s DSPL, Hyderabad	MAT	1705
34.	HF 15, T652 Forged Flats	M/s DSPL, Hyderabad	MAT	1728
35.	AA2219-T8511	Ordnance Factory, Nagpur	F&F	1729
36.	HF 15, T652 Forgings	M/s MMBL, Hyderabad	MAT	1833

* Regional Centre for Military Airworthiness

** Type Approved

associated with their production. The most frustrating limitation is their inherently low elastic modulus, a problem that defies a satisfactory solution by the metallurgist's staple of microstructural modification. Novel thinking is required to address this problem.

Inadequate facilities in India for the production of high-quality components required by the aerospace industry are other issues that need to be urgently remedied by government and private initiatives.

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