

# TRENDS IN ALUMINIUM ALLOY DEVELOPMENT AND THEIR JOINING METHODS

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**Abstract.** The growing concerns on issue of energy saving and environmental conservations has considerably increased the demand for lightweight structures in automobile, aerospace and marine industries. Aircraft manufacturers adhere to the life cycle approach for selection of materials as cost reduction has become the main criteria in many airlines. Aluminium alloys have been the primary material choice in the structural parts of aerospace and marine sectors for more than 80 years. Although modern composites, due to their excellent fatigue strength, corrosion resistance, reduced weight and high specific properties, appears to be a tempting replacement for aluminium alloys; its higher initial cost and expensive maintenance limits its widespread usage in airframe construction. Among the high performance materials, Aluminium is a low cost and easily produced metal that can relatively be subjected to high levels of stresses. Nowadays highly customized aluminium alloys are developed to meet the requirements of aerospace industries, which can effectively compete with composite materials. Increasing application of aluminium in various industrial sectors is the main driving force for technologists to develop a viable and efficient technology for joining aluminium alloys. These developments avoid adverse effects of welding on the mechanical, chemical and metallurgical properties of aluminium alloys desired for longer life. The main objective of this article is to explore the development and usage of aluminium alloys in aerospace industries. The improvements in the mechanical properties of the Al-Cu (2xxx series), Al-Zn (7xxx series), and Al-Li alloys have been discussed and compared. Additionally, a critical review of the advancements in joining methods of aluminium alloys has been performed.

## 1. INTRODUCTION

Energy efficiency has become top priority of national and international policies. Excessive energy consumption in the past has resulted in significant rise in CO<sub>2</sub> levels and thus major climate changes. Also, the airlines are concerned with energy consumption due to the significant rise in fuel cost. Therefore aircraft manufacturers are obliged to address both, the concerns of government to minimize ecological impact as well as the airline's demand for fuel efficient aircraft. In these continuously changing economic times, aircraft manufacturers are on a con-

stant quest for finding ways to reduce the fuel consumption of aircrafts. The best way to reduce the weight of the aircraft is through incorporating lighter materials that results in reduced fuel consumption. The continuous aging of the civil and military aircraft creates a demand for aircraft that fly beyond their original design lives. This poses different problems, including the ability of aircraft's material to maintain damage tolerance [1]. The structural integrity of the aircraft is threatened by the simultaneous presence of fatigue and/or corrosion at multiple locations and this is termed as Multi-site damage (MSD) [2]. One of the major causes for most

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aircraft crashes is fatigue failure of structures; aerospace designers have given more importance in finding relevant material properties especially for the fuselage and wing structures which are more prone to the fatigue failures [3].

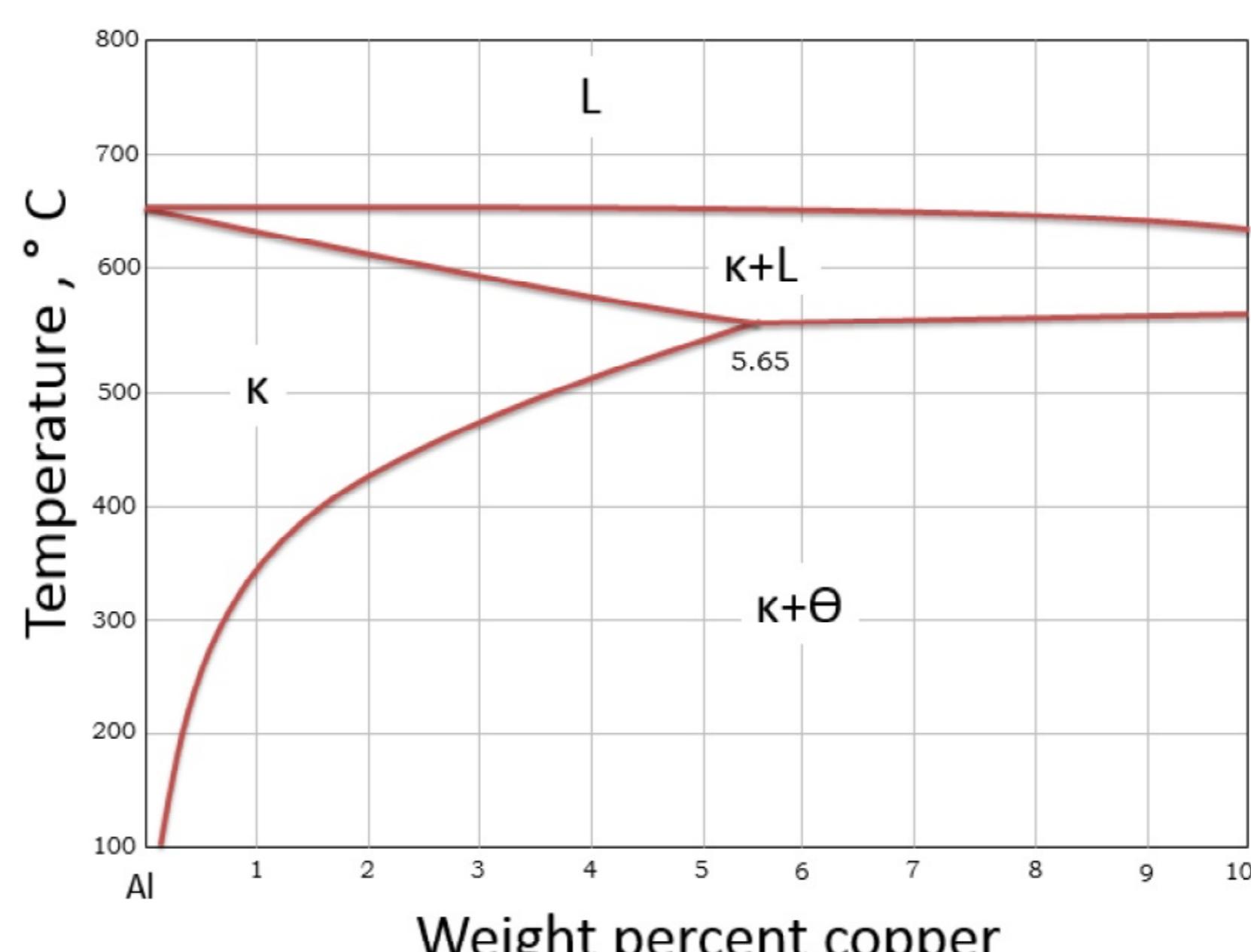
In-order to meet such demanding applications, materials capable of withstanding extreme stress, temperature and pressure variations need to be developed with strict quality requirements that would allow them to remain stable on a lasting basis. Aluminium appears to be a better choice because of their well-known mechanical behaviour, easiness with design, manufacturability and established inspection techniques. In the aircraft industries the high strength 2000 series alloys are well known for its excellent damage tolerance and high resistance to fatigue crack propagation. The 7000 series aluminium alloys show higher strength when compared to any other classes of aluminium alloys. The Aluminium-Lithium (Al-Li) alloys are light weight, high performance aluminium alloy, developed to compete with conventional aluminium alloys, carbon-fibre composites, and metal-matrix composites for aerospace applications, particularly in transport aircraft structures. Metal matrix composites (MMC) finds potentially successful engineering applications in aerospace structures, therefore they become one of the hot topics in research related to joining sciences. Aerospace application use high elastic modulus of the ceramics and the high metal ductility to achieve better combination of properties. Very high strength to weight ratio of the MMC's which has metal alloys reinforced with ceramics, makes it attractive for use in the aerospace applications. MMCs are structures which contains two or more macro components that dissolve within one another. However solutions are yet to be found for problems related to joining metal matrix composite materials (especially the ceramic-reinforced aluminium alloy matrix composites) using fusion welding processes. Lack of thermodynamic balance between the metal and ceramic due to their difference in chemical and physical properties is the major cause for problems such as undesirable intermetallic-compounds (IMC) formation, uncontrolled solidification and micro-segregation or inhomogeneous distribution of reinforcement material. The high strength to weight ratios and high strength to density ratios of the MMCs played an important role in development of Hubble Space Telescope's antenna mast, the space shuttle Orbiter's structural tubing, control surfaces and propulsion systems for aircraft [4-6].

The increase in demand for complex structures reciprocates the need for improved joining method.

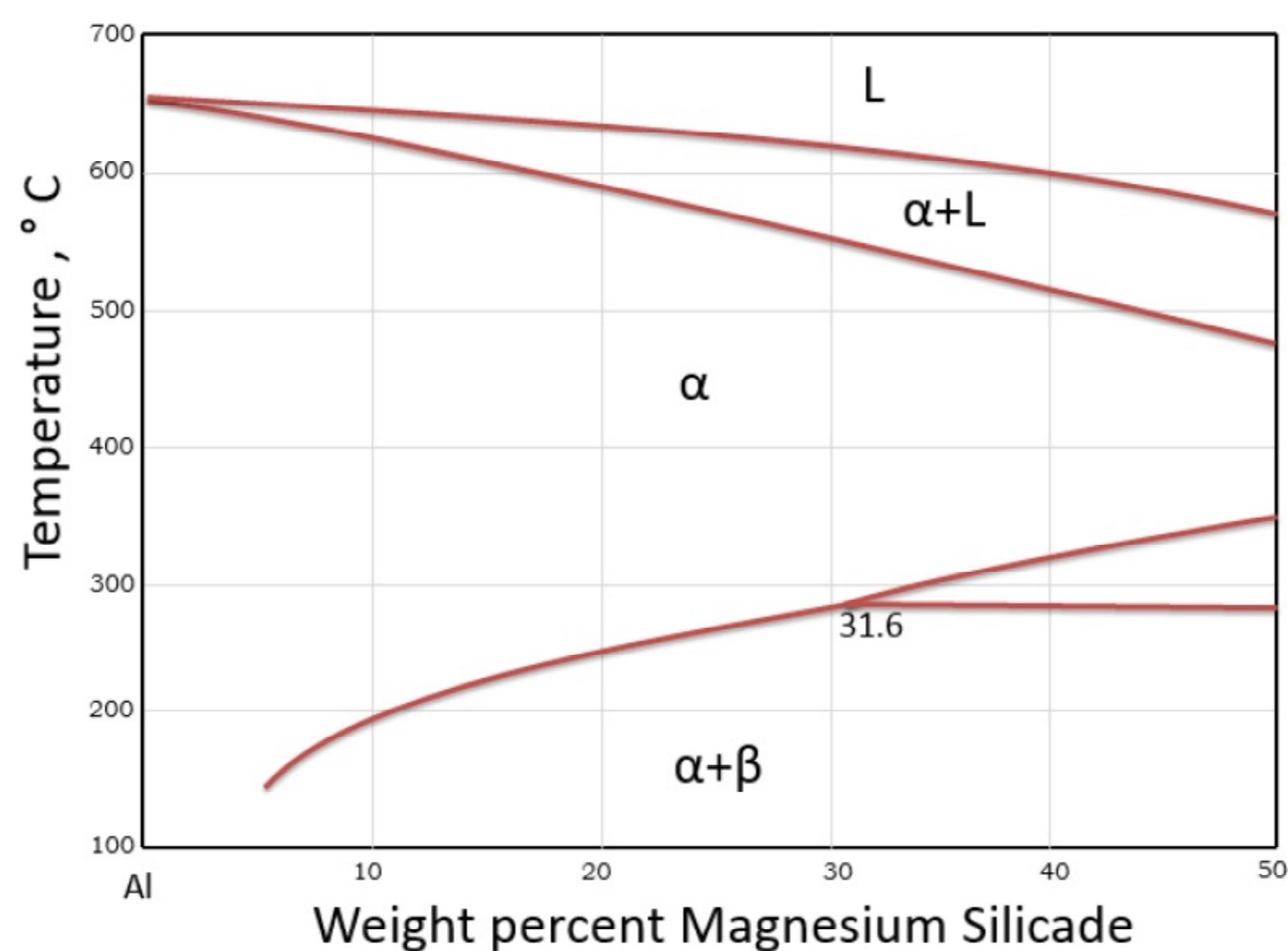
New and advanced methods of manufacturing aircraft fuselage has emerged as a result of continuous research activities by the aircraft manufacturers thereby replacing the use of rivets to welding, bonding and extrusion [7]. Welding, a crucial candidate in improving an aircraft's life-cycle cost, strength, quality and reliability, has been improved to meet the requirements of the aircraft design safety regulations. Factors which lead to weld inefficiencies are to be effectively managed, if industries are to meet their quality requirements and fulfil a high-volume production demand. Welding methods for aluminium is quite similar to those of steels. However, different welding techniques were developed for aluminium as their physical, mechanical and other properties are peculiar from other materials. Notable developments in aluminium welding techniques due to its commercialization have significantly solved the limitations (oxide removal, reduced strength in weld and heat affected zone) related to aluminium welding [8].

## 2. DEVELOPMENTS IN ALUMINIUM-COPPER (2XXX SERIES) ALLOYS

The Aluminium-Copper (Al-Cu) alloys are high strength alloys, which are used for high strength structural applications where the main design criterion is damage tolerance. Fig. 1 depicts the aluminium-rich end of the aluminium copper equilibrium diagram. As the maximum solubility of copper in aluminium is 5.65% at 547 °C and to a minimum of 0.49% at 300 °C, aluminium alloys with copper content in the range of 2.5% to 5% responds to heat treatment by age hardening. In-order to improve the strength of the alloy, the alloy is heated into the kappa single phase region and then rapidly cooled.



**Fig. 1.** The aluminium rich portion of the aluminium-copper alloy system, replotted from [10].



**Fig. 2.** The figure show the aluminium-rich portion of the Aluminium-Zinc alloy system, replotted from [10].

This is followed by either natural or artificial aging which leads to the precipitation of the theta phase thereby increasing the strength of the alloy [9]. Precipitation of the  $\text{Al}_2\text{Cu}$  and  $\text{Al}_2\text{CuMg}$  phases has resulted in higher strength in these alloys. Also these alloys have very good crack growth resistance and superior damage tolerance when compared to other series of aluminium alloys.

The aircraft material selection is a complex process with different material property requirements for different components in-order to have a reliable design. The aircraft wing acts as a beam that is loaded in bending during the flight. The wing box consists of top and bottom skins, stringers (longitudinal members), spars that make-up the sides of the wing box and ribs. The aircraft wing encounters several loads while in flight for e.g. loads during manoeuvring, loads from the landing gear during take-off and landing and trailing edge loads. The loads are transmitted to the central attachment of the fuselage. Compressive yield strength and modulus of elasticity in compression are the static material properties to be considered for design of top skin-stringer, while tensile strength, tensile yield strength and tensile modulus are the static material properties to be considered for design of lower skin-stringer. As these components experience alternating loads during flight, the material requires very high resistance to fatigue and high damage tolerance. The young's modulus, resistance to fatigue crack initiation, fatigue crack growth rate, corrosion resistance are important in material selection for fuselage structures. The fuselage skin (a semi-monocoque structure) of the aircraft needs to sustain the cabin pressure (tension) and shear loads. The circumferential frames need to maintain the fuselage shape and redistribute loads onto the skin. Fracture toughness

is the main design limitation factor while selecting the materials [11].

The excellent damage tolerance and high resistance to fatigue crack propagation of 2024 aluminium alloy in T3 aged condition has made it an important aircraft structural material [12]. It is one of the widely used alloys in fuselage construction. The 2024 alloy has 17% improvement in toughness and 60% slower fatigue crack growth rate compared to other 2000 series alloys [13]. However the application of this alloy is limited to the highly stressed regions because of its low yield stress level and relatively low fracture toughness [14]. Significant improvements in the design properties associated with fuselage skin durability were attained with 2524-T3 aluminium alloy. The 2524-T3 alloy, when compared with 2024-T3 alloy can provide 15% to 20% improvement in fracture toughness and twice the resistance to fatigue growth [13], thereby leading to weight savings and 30 to 45% longer service life [1]. Fatigue strength of the 2524-T34 alloy is 70% of the yield strength whereas for 2024-T351 fatigue strength is about 45% of the yield strength [15]. Slow fatigue crack growth rates of 2524 alloy contribute to its improvement in component life. The main reason for the better performance of 2524 alloy is due to its less damaging configuration for corrosion features [1]. Thus the 2024 alloy was replaced by the 2524 aluminium alloy for fabrication of aircraft fuselage skin in the Boeing 777 Jetliner [1,13]. Similar fracture toughness, corrosion resistance levels and higher strength values than 2024-T351 has been obtained with 2224-T351 and 2324-T39 alloys for lower wing skin applications [16]. Thus the 2xxx series alloys form an important part of the aircraft construction.

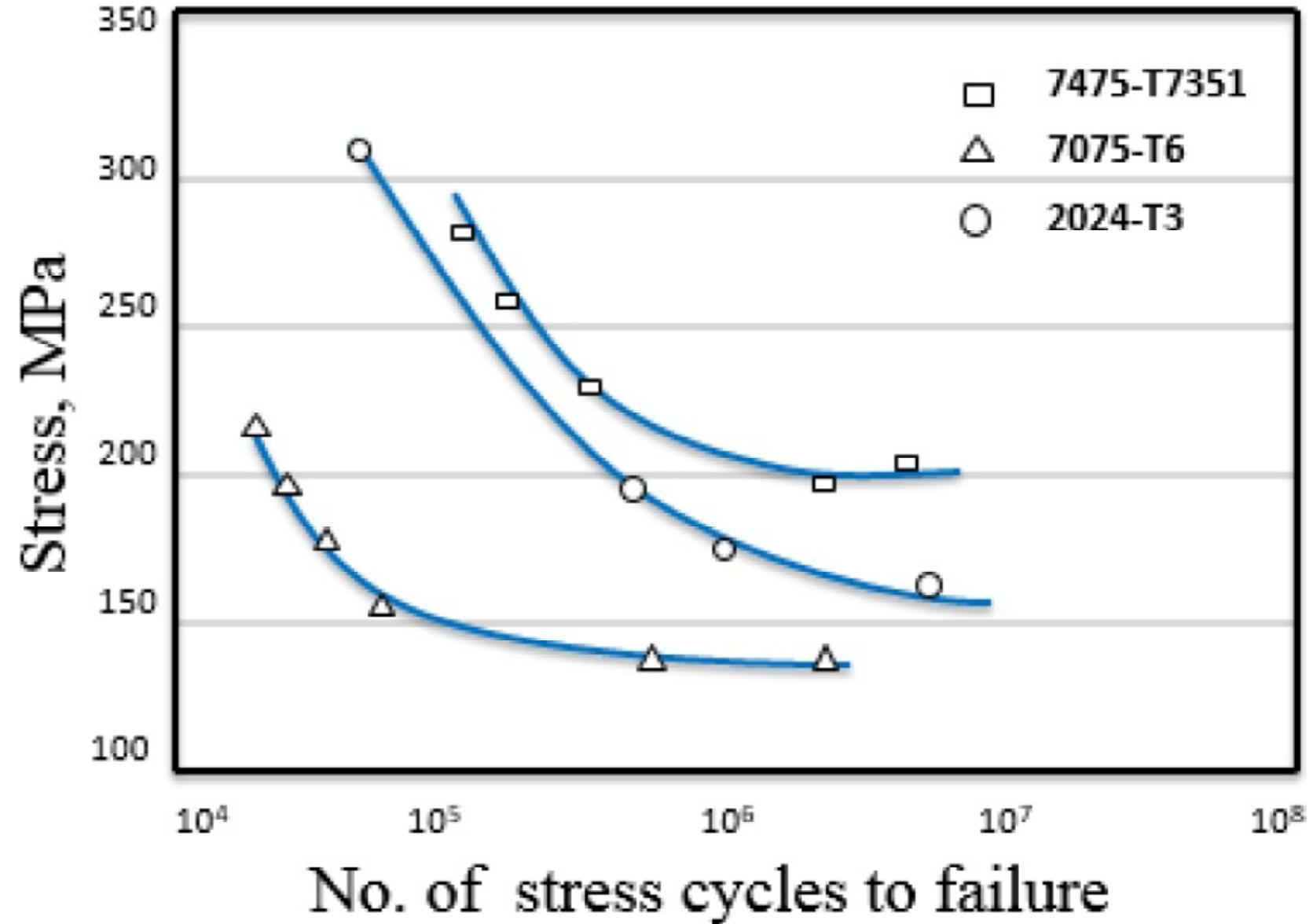
### 3. ADVANCEMENTS IN ALUMINIUM-ZINC (7XXX SERIES) ALLOYS

The 7000 series aluminium alloys show higher strength when compared to other classes of aluminium alloys [4]. It can be seen from Fig. 2 that the solubility of zinc in aluminium decreases from 31.6 percent at 275 °C to 5.6 percent at 125 °C. Commercial wrought alloys contain zinc, magnesium, and copper with smaller additions of manganese and chromium. For e.g. the 7136 alloy make use of the chromium and zirconium to control grain growth and recrystallization [17].

The 7000 series of aluminium alloys are used to manufacture aircraft structural parts such as upper wing skins, stringers and horizontal/vertical stabilizers. The horizontal and vertical stabilizers have

quite the same structural design criteria as for the wing. The horizontal stabilizer's upper and lower surfaces experience bending and therefore critical in compression loading. Hence modulus of elasticity in compression is the most important property [11]. The critical design parameters of the upper wing structural components are compressive strength and fatigue resistance [18].

Of all the aluminium alloys the Al-Zn-Mg-Cu versions have proved to exhibit the highest strength. Addition of 2% copper in combination with magnesium and zinc could significantly improve the strength of the 7000 series alloys. The highest tensile strengths obtainable in aluminium alloys have been developed in Alloy 7075 (5.5% zinc, 2.5% magnesium, 1.5% copper), alloy 7079 (4.3% zinc, 3.3% magnesium, 0.6% copper), and alloy 7178 (6.8% zinc, 2.7% magnesium, 2.0% copper). The 7075-T6 alloys have very high strength-to-weight ratio, low production cost and good machinability, therefore they are preferred choices for aircraft structural parts. Although these alloys have proved to be the strongest they have the least resistance to corrosion. Susceptibility of these alloys to stress corrosion cracking can be controlled with proper heat treatment and with addition of some materials like chromium. New versions of the 7000 series alloys have been developed that has a higher fatigue and corrosion resistance that has resulted in weight savings [16,17,19]. Alloy 7050 has a very good balance between resistance to stress corrosion cracking, strength and toughness. Alloy 7050-T76, without any compromise in strength have solved the problems related to corrosion in 7075-T6. Excellent fatigue performance, higher toughness and comparable strength to 7075-T6 has been achieved with 7050-T76 alloy. The higher copper content in 7075 is the main reason for its excellent combination of strength, corrosion characteristics and SCC resistance [20]. However, low toughness and environmental sensitive fracture-in-service, particularly under cyclic loading conditions have restricted its application[21]. Higher strength and superior damage tolerance than 7050-T76 alloy can be achieved with 7150-T77 extrusions [20]. Boeing 777 Jetliner's fuselage stringers (longitudinal members) were fabricated with 7150-T77 extrusions as they offered high strength, corrosion resistance and fracture toughness. Using 7055-T7751 plates in Boeing 777 jetliners contributed an estimated 635 Kg weight savings and also provided a 10% gain in strength, higher toughness and significantly improved corrosion resistance [13,22].



**Fig. 3.** The graph represents the S-N curves of various aluminium alloys, replotted from [14].

From studies it has been observed that the 7475 alloy has better performance than 7075 and 7050 alloys and with proper treatment, 7475 alloy can be used to reduce the overall weight of the aerospace structure thus replacing the generally used 7075 and 7050 alloy versions. Jahn and Luo [23] mentioned that alterations in quenching and ageing conditions and reduction in iron and silicon contents have significantly enhanced the properties of 7050 alloy, resulting in the development of 7475 alloy with high toughness values among the commercially available high strength aluminium alloys. Verma et al. [14] reported that the 7475 aluminium alloy, the modified version of the 7075 alloy has an excellent combination of high strength, resistance to fatigue crack propagation and superior fracture toughness both in air and aggressive environment. And so this controlled-toughness alloy with above mentioned properties is best suited for aerospace application which demands similar property requirements. In Fig. 3, where the fatigue crack growth rates for different aluminium alloys are compared, it can be observed that the 7075-T6 has the lowest fatigue resistance values and the 7475 has higher fatigue resistance when compared to other two alloys.

Verma et al. [14] reported that in aircraft design where the main design criterion is high fracture toughness, the 7475 alloy sheets and plates are recommended for specific fracture critical components. This is because 7475 alloy has strength very close to that of 7075 alloys and 40% higher fracture toughness values than 7075 alloys in the same temper conditions. In high stress regions the performance of 7475-T7351 is comparable to that of 2024-T3 but in low stress regions the 7475-T7351 is superior to all other comparable alloys such as 7075-T6, 2017-T4, 2017-T3 [14]. 7075 alloy has yield strength above

**Table 1.** Third Generation Al-Li alloys, modified from [24].

Alloys	Li	Cu	Mg	Ag	Zr	Mn	Zn	Density $\rho$ , (g/cm <sup>3</sup> )	First introduced
2196	1.75	2.9	0.5	0.4	0.11	0.35	0.35	2.63	LM/Reynolds/McCook.2000
2297	1.4	2.8	0.25		0.11	0.3	0.5	2.65	LM/Reynolds.1997
2198	1.0	3.2	0.5	0.4	0.11	0.5	0.35	2.69	Reynold/McCook/Alcan.2005
2099	1.8	2.7	0.3		0.09	0.3	0.7	2.63	Alcoa.2003
2199	1.6	2.6	0.2		0.09	0.3	0.6	2.64	Alcoa.2005
2050	1.0	3.6	0.4	0.4	0.11	0.35	0.25	2.70	Pechiney/Alcan.2004
2060	0.75	3.9	0.85	0.2	0.11	0.3	0.4	2.72	Alcoa.2011
2055	1.15	3.7	0.4	0.4	0.11	0.3	0.5	2.70	Alcoa.2012

500 MPa when under T651 temper conditions however it has lower ductility. The 7475-T7351 has superior ductility than 7075-T651 alloy but marginally inferior yield strength [14]. Thus the developments in the 7000 series alloys have provided excellent combination of high strength, resistance to fatigue crack propagation, superior fracture toughness, resistance to stress corrosion cracking and superior damage tolerance.

#### 4. ADVANCEMENTS IN ALUMINIUM-LITHIUM (Al-Li) ALLOYS

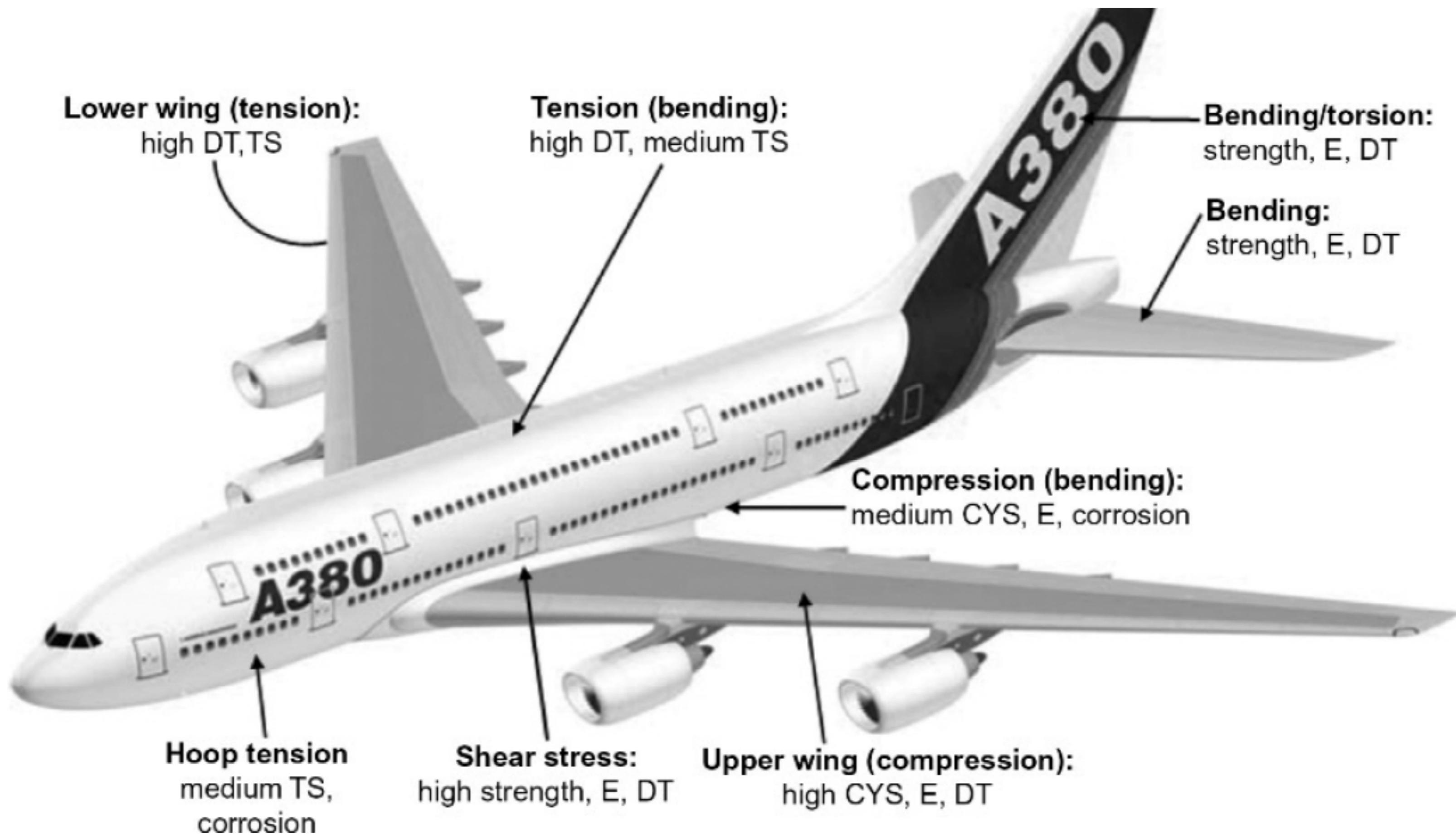
The aero-structural performance has significantly improved with the introduction of Al-Li products through density reduction, stiffness increase in fracture toughness and fatigue crack growth resistance and enhanced corrosion resistance. Addition of lithium to aluminium is special because for each 1% of Li addition, approximately 3% of the density is decreased, for each 1% Li addition, approximately 6% increase in Young's elastic modulus is achieved, Li additions enable the formation of potent hardening precipitates, Li additions impart higher fatigue crack growth resistance. Also aluminium alloys containing Li respond to age hardening [24].

The introduction of first generation of Al-Li alloys can be traced back to mid-1920s but official patented composition was released in 1945 [25]. Al-Li alloys were big success following its implementation in the Navy aircrafts with excellent service life record of 20 years without any reported cracks and corrosion issues. The second generations of Al-Li alloys which had Li concentrations above 2% were developed with intense research and development in the late 1970s and early 1980s. The second generation alloys included the 2090, 2091, 8090 and 8091 alloys. The introduction of 2090-T81 plate, 2090-T86 extrusions and 2090-T83 and T84 sheet replaced the usage 7075-T6 alloys in the aircraft

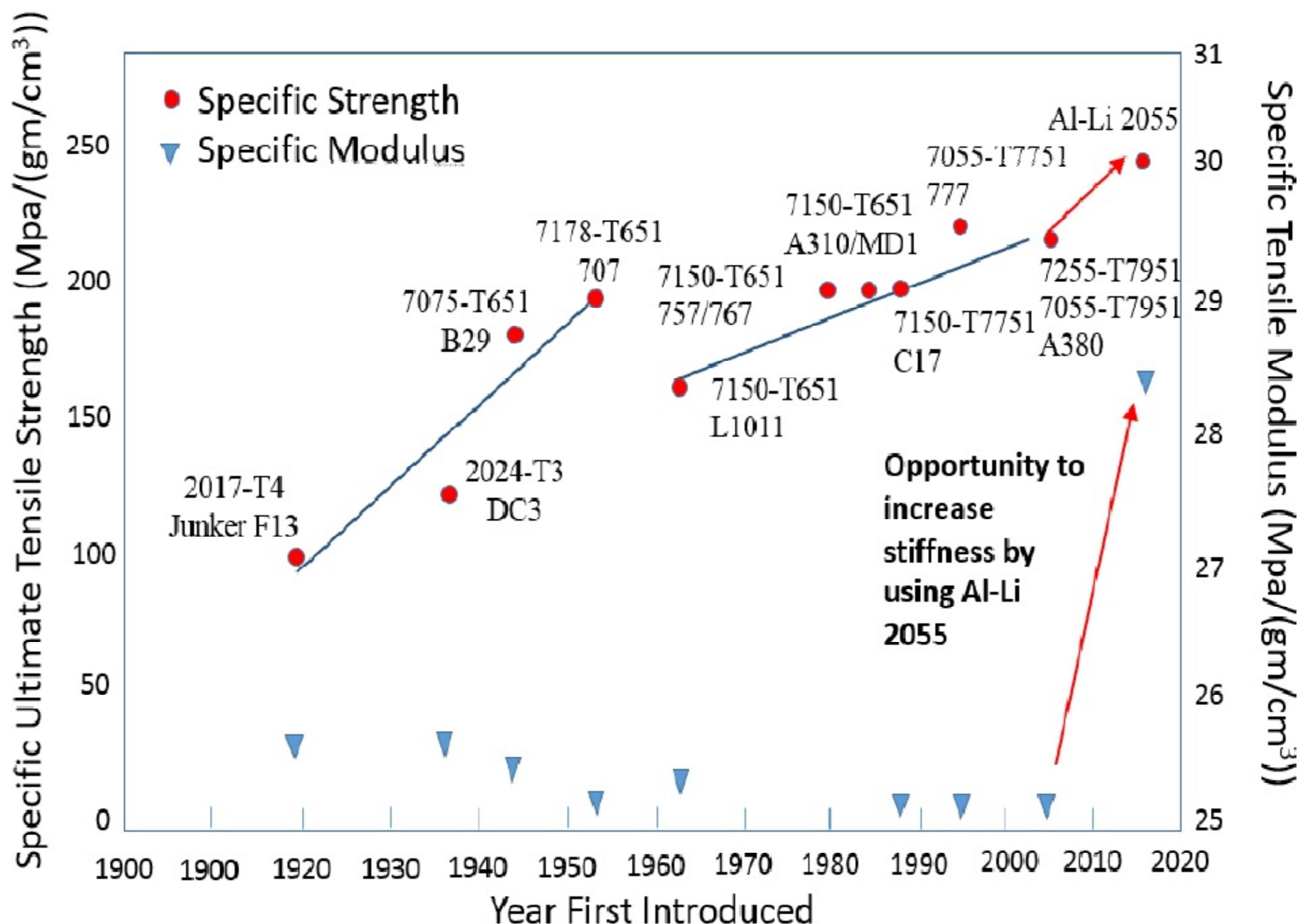
industries. However the popularity of second generation Al-Li alloys were short-lived following reports of material characteristics which were deemed undesirable by airframe designers. The favourable characteristics of the second generation Al-Li were lower density, higher modulus of elasticity, higher fatigue life (lower fatigue crack growth rates). Similarly, the negative performance characteristics of 2nd generation Al-Li products were lower short-transverse fracture toughness, lower plane stress ( $K_c$ ) fracture toughness/residual strength in sheet and higher anisotropy of tensile properties [24].

The third generation Al-Li alloys were developed to improve the shortcomings of second generation Al-Li alloys which includes significant in-plane and through-thickness anisotropy in mechanical properties resulting in crack deviation and micro-cracking during cold-hole expansion and other problems such as low fracture toughness, poor corrosion resistance, loss of toughness after simulated thermal exposure [24]. This resulted in the development of light weight and high performance aluminium alloy. They were developed to compete with conventional aluminium alloys, carbon-fibre composites, and metal-matrix composites for aerospace applications, particularly in transport aircraft structures. Weight reduction is important in aircraft manufacturing as it promotes reduced fuel consumption therefore material density is very important for the efficiency of aerospace structures. Reducing the density of the material is the best way to reduce the weight of the aircraft parts. The material density of Al-Li alloys were 2 to 8% less than those of the conventional 2XXX alloys (2.80 g/cm<sup>3</sup>) and 7XXX alloys (2.85 g/cm<sup>3</sup>). Even a very small improvement in densities can result in significant reduction in fuel consumption [26]. Table 1 shows some of the developed third generation aluminium alloys.

Space programs that use the Al-Li alloys include the Orion capsule for manned space missions in



**Fig. 4.** Stresses encountered by different section of the aircraft along with the property requirements for the material selection for these parts.



**Fig. 5.** Material property developments for the upper wing structure of the aircraft, replotted from [26].

the future [27,28] and the SpaceX Falcon 9 Launcher [29]. Studies have been made by European Space Organisation (ESA) on possibility of using the Al-Li alloys in future cryogenic tanks [30,31]. The space shuttle's cryogenic fuel tank has been assigned alloy 2195 as an effective replacement of the alloy 2219 in view of its higher strength, higher modulus and lower density [19].

Fig. 4 shows the typical load conditions and the property requirements in the structural parts of the

aircraft. The key property requirements for the structural components in the aeroplane are compressive yield strength and modulus - upper wing structure, fracture toughness, ultimate tensile strength and spectrum fatigue crack growth – Lower wing and fracture toughness and fatigue crack growth - fuselage component. Fig. 5 shows that the materials were developed with the main strategy of reducing the weight by increasing the strength of the upper wing. However consequent problems related to cor-

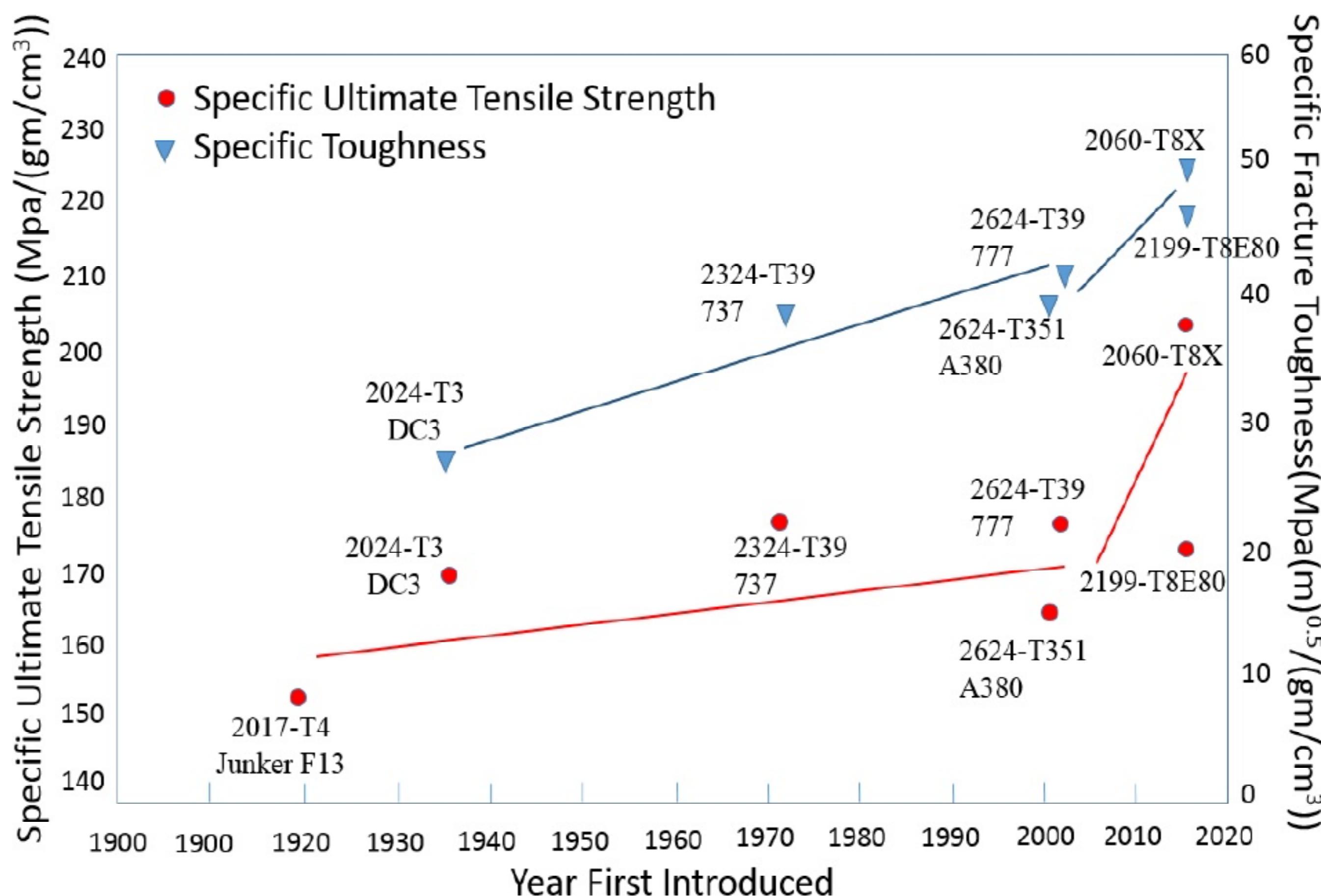


Fig. 6. Material property developments for the lower wing structure of the aircraft, replotted from [26].

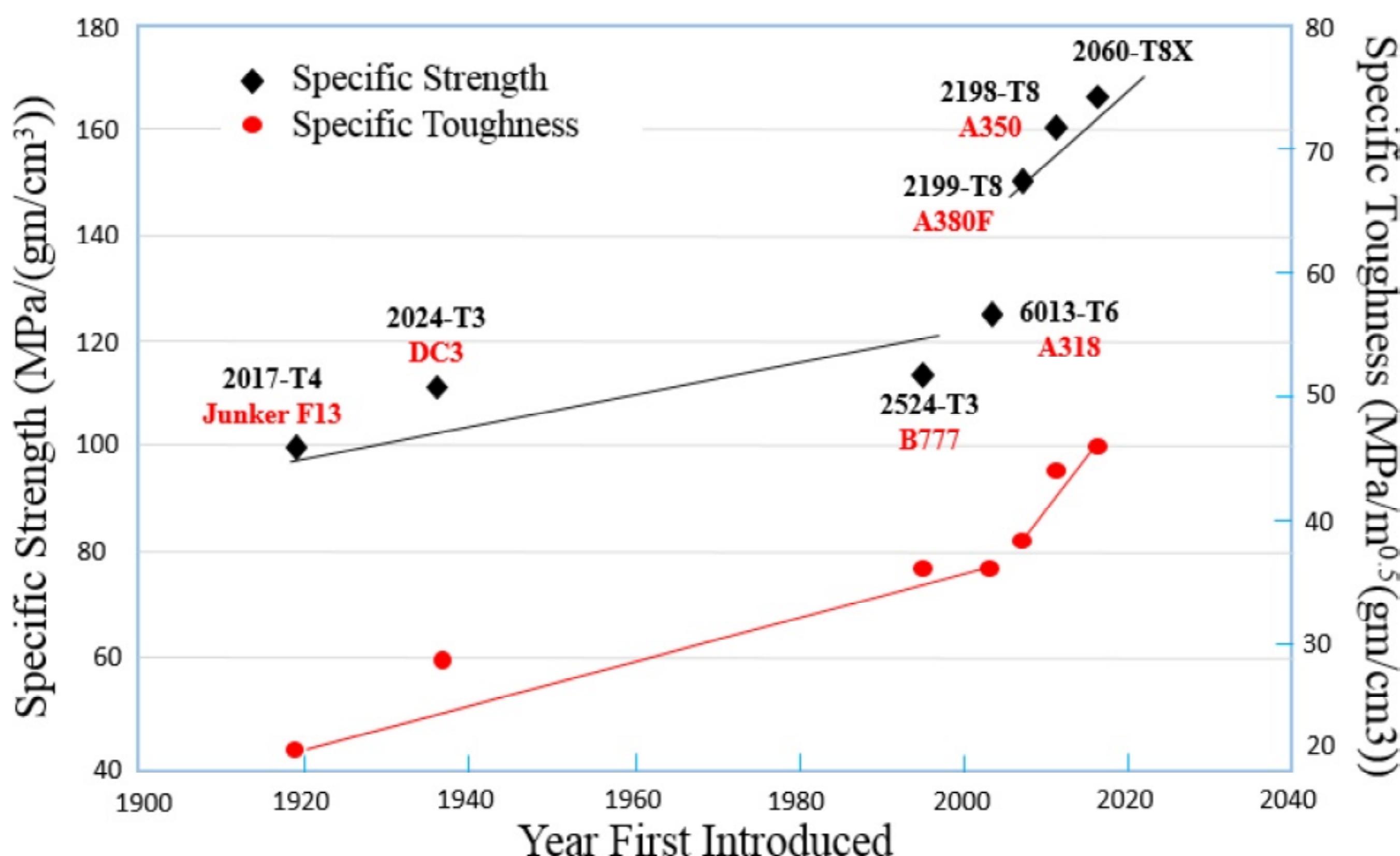


Fig. 7. Material property developments for the fuselage of the aircraft, replotted from [26].

rosion issues in the 707 aircraft led to the replacement of the T6 tempers with T7 tempers. T7 temper series alloys had improved exfoliation and stress corrosion cracking performance but had constant modulus for 7xxx products. This directly affects additional weight saving from buckling. However better modulus and improved strength were achieved with Al-Li alloys that promoted weight savings.

The main properties that are required for the lower wing structure application are the specific ultimate tensile strength and the fracture toughness, Fig. 6 shows two Al-Li alloys where the 2199 alloy has slower fatigue crack growth rate than the 2060. This is due to the presence of twice the concentration of

Li in 2199 alloy compared to 2060 alloy [26]. Also Al-Li alloy products such as 2091 offers superior resistance to fatigue crack growth and also exhibits 6-7% weight savings over 2024-T3 because of low density. So these alloys are attractive options for the fuselage skin [20].

Fig. 7 shows the evolution of materials with key properties satisfying the demands for the fuselage applications. Third generation Al-Li alloys such as the 2099 and 2199 were used in the manufacture of fuselage skin-stringer components. The combination of alloy 2199-T8E74 used as fuselage skin material and alloy 2099-T83 used as stringer mate-

**Table 2.** Actual and proposed uses of third-generation Al–Li Alloys to replace conventional alloys in aircraft, modified from [26].

	Alloy/Temper	Substitute for	Applications
Sheet	2098-T851, 2198-T8, 2199-T8E74, 2060-T8E30: damage tolerant/medium strength	2024-T3, 2524-T3/351	Fuselage/pressure cabin skins
Plate	2199-T86, 2050-T84, 2060-T8E86: damage tolerant 2098-T82P (sheet/plate): medium strength 2297-T87, 2397-T87: medium strength 2099-T86: medium strength 2050-T84, 2055-T8X, 2195-T82: high strength 2050-T84: medium strength	2024-T351, 2324-T39, 2624-T351, 2624-T39 2024-T62 2124-T851 7050-T7451, 7X75-T7XXX 7150-T7751, 7055-T7751, 7055-T7951, 7255-T7951 7050-T7451	Lower wing covers F-16 fuselage panels F-16 fuselage bulkheads Internal fuselage structures Upper wing covers Spars, ribs, other internal structures
Forgings	2050-T852, 2060-T8E50: high strength	7175-T7351, 7050-T7452	Wing/fuselage attachments, window and crown frames
Extrusion	2099-T81, 2076-T8511: damage tolerant 2099-T83, 2099-T81, 2196-T8511, 2055-T8E83, 2065-T8511: medium/high strength	2024-T3511, 2026-T3511 2024-T4312, 6110-T6511 7075-T73511, 7075-T79511 7150-T6511, 7175-T79511, 7055-T77511, 7055-T79511	Lower wing stringers, fuselage/pressure cabin stringers Fuselage/pressure cabin stringers and frames, upper wing stringers, Airbus A380 floor beams and seat rails

rial were 5% lighter than the 2524 and 7150 combinations for the same purpose [32].

Table 2 shows the list of Al–Li alloy sheets, plates, forgings and extrusions that are actually in use and proposed to replace the conventional alloys in the aircraft.

## 5. ADVANCEMENTS IN WELDING TECHNIQUES

Research focus on joining methods of aircraft materials have been directed towards the development of technologies that can reduce the weight of the aircraft, eliminate stress concentrations, reduce heat affected zones and improve joint efficiency. Aircraft manufacturers have adopted new joining methods such as welding, bonding and extrusions, thereby replacing the use of rivets. Rivets have certain disadvantages which has restricted its wide usage in aircrafts. This includes stress concentrations leading to fatigue crack and increased the weight of the

airframe. Table 3 depicts the weldability of aluminium alloys by traditional fusion welding and by frictional stir welding. The high strength 2000 and 7000 series alloys are more susceptible to weld cracking thereby making it difficult to join by traditional welding methods. It can be seen that almost all the aluminium alloys can be joined by friction stir welding with minimum damage to material. The weldability of aluminium is quite different from that of carbon steel, for e.g. aluminium does not have the problem of transformation, as it is only dependent on solidification. Unlike the carbon steels where the heating of the material by the arc would harden the base metal, the base aluminum alloy softens. Welding of aluminium is generally considered to be difficult than the steel due to high thermal conductivity, electrical conductivity, high thermal expansion coefficient, refractory aluminium oxide ( $\text{Al}_2\text{O}_3$ ) formation tendency, and low stiffness [33]. For e.g. processes like spot welding are not recommended for welding light metal aluminium alloys due to the high ther-

**Table 3.** Representation of weldability of various aluminium alloys, modified from [36].

	1XXX	2XXX	3XXX	4XXX	5XXX	6XXX	7XXX	8XXX
Traditional Welding	+	-	+	+	+	+	-	+/-
Friction Stir Welding	+	+	+	+	+	+	+	+

"-" - Mostly Non-Weldable

"+" - Mostly Weldable

mal conductivity of the light metals [34]. Significant variation in thermal conductivity and thermal expansion is a strong indication that distortion could occur more easily [35].

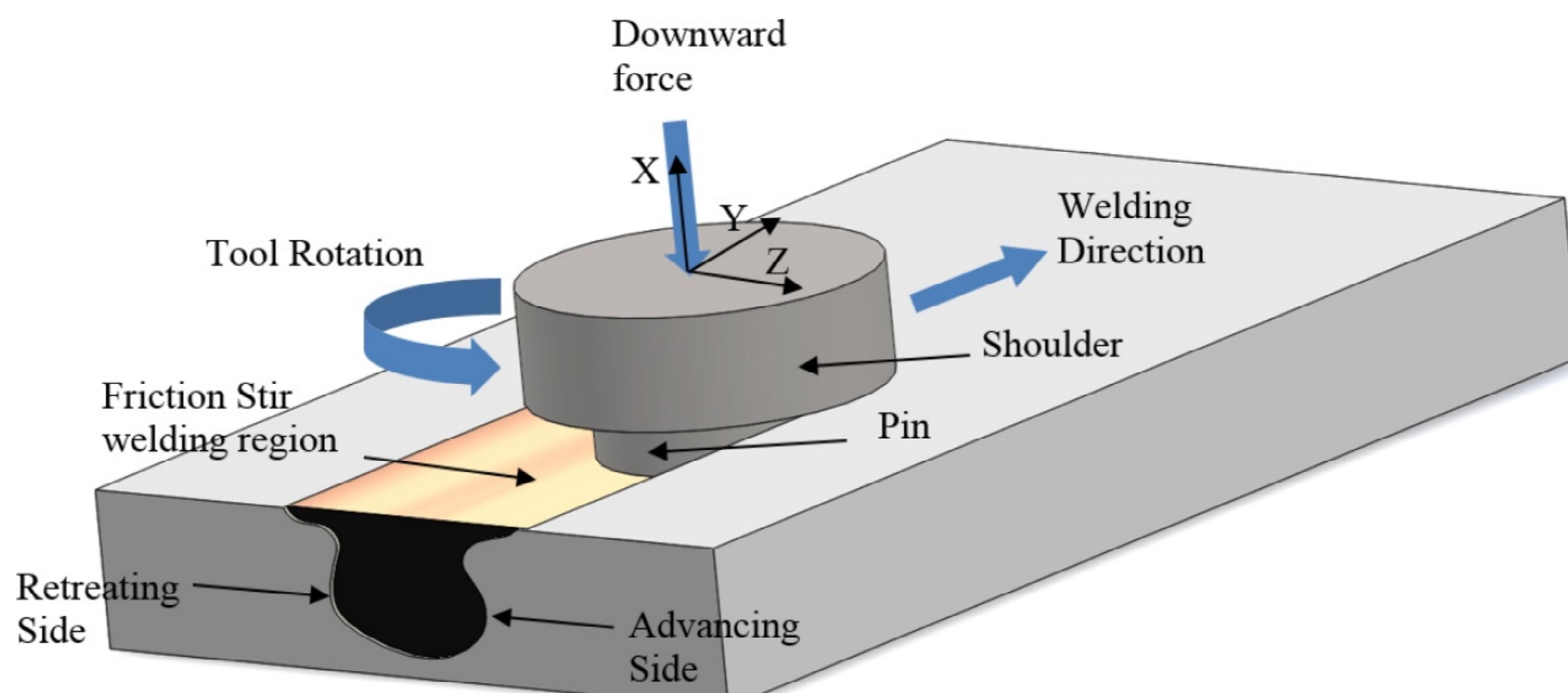
Similarly, hydrogen does not have the same effect on aluminium alloys as it does on carbon steels. Weld porosity occurs in the molten state due to the aluminum's high solubility for hydrogen. When aluminium strongly reacts with oxygen, an oxide of aluminium ( $\text{Al}_2\text{O}_3$ ) is formed. Since its density is high, it has possibility of producing weld inclusion as it might sink into the weld pool during welding. The oxide has a very high melting temperature (2050 °C) so it cannot be melted during welding. These stable surface oxides that are very strong and tough can be removed by either thoroughly wire brushing the joint area or by chemical methods [19,33].

### 5.1. Friction stir welding

Friction stir welding has been considered as the most significant development in metal joining of the past decade. FSW, a solid-state, hot-shear joining process, was developed by The Welding Institute (TWI) in 1991 [37]. It is regarded as a green technology because of its energy efficiency, environment friendliness and versatility. Use of FSW has gained a prominent role in the production of high-integrated solid-phase welds in 2000, 5000, 6000, 7000, Al-Li

series aluminium alloys and aluminium matrix composites. The FSW process progresses sequentially through the pre-heat, initial deformation, extrusion, forging and cool-down metallurgical phases. Fig. 8 shows the schematics of friction stir welding. The welding process begins when the frictional heat developed between the shoulder and the surface of the welded material softens the material, resulting in severe plastic deformation of the material. The material is transported from the front of the tool to the trailing edge, where it is forged into a joint [38,39]. Consequently, the friction stir welding process is both a deformation and a thermal process occurring in a solid state; it utilises the frictional heat and the deformation heat source for bonding the metal to form a uniform welded joint - a vital requirement of next-generation space hardware [40]. In FSW, several thermo-dynamical process interactions occur simultaneously, including the varied rates of heating and cooling and plastic deformation, as well as the physical flow of the processed material around the tool. Throughout the thermal history of a friction stir weld, no large-scale liquid state exists [38,39,41]. Table 4 shows the advantages of FSW over the conventional welding process.

Aerospace industries benefit from the innovative manufacturing developments, such as friction stir



**Fig. 8.** Schematics of the friction stir welding process.

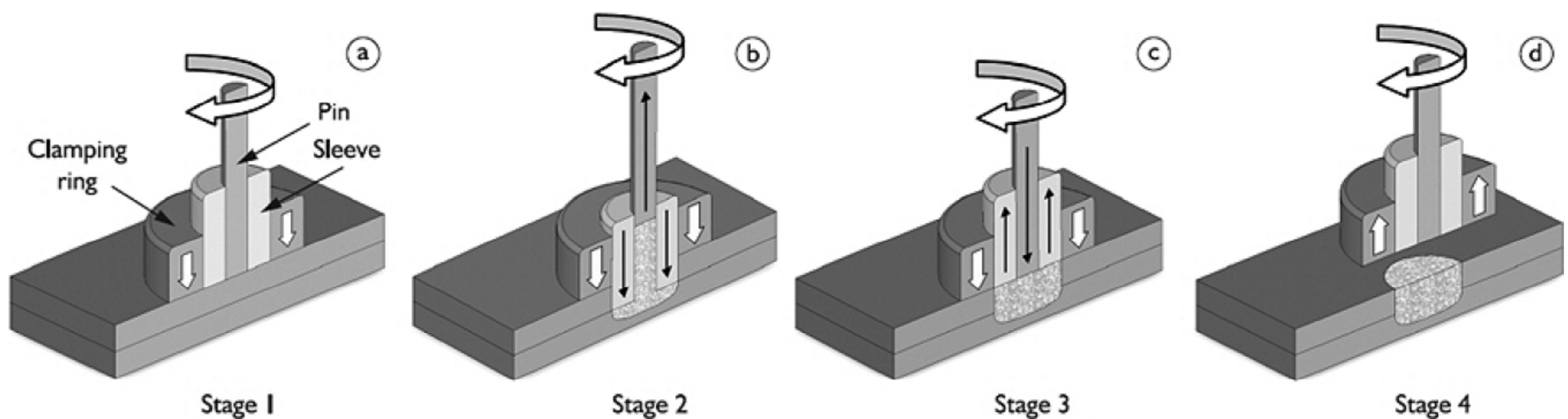
**Table 4.** Benefits of the FSW Process, modified from [38].

Metallurgical Benefits	Environmental benefits	Energy Benefits
<ul style="list-style-type: none"> <li>• Solid Phase Process</li> <li>• No loss of alloying elements.</li> <li>• Low distortion</li> <li>• Good dimensional stability and repeatability</li> <li>• Excellent mechanical properties in the joint area.</li> <li>• Fine recrystallized microstructure.</li> <li>• Absence of solidification cracking.</li> <li>• Replaces multiple parts joined by fasteners.</li> </ul>	<ul style="list-style-type: none"> <li>• No shielding gas required for materials with low melting temperature.</li> <li>• Eliminates solvents required for degreasing.</li> <li>• Minimal surface cleaning required.</li> <li>• Eliminates grinding wastes.</li> <li>• Consumable materials saving.</li> <li>• No harmful emissions.</li> </ul>	<ul style="list-style-type: none"> <li>• Improved Materials use (e.g. joining different thickness) allows reduction in weight.</li> <li>• Decreased fuel consumption in lightweight aircraft, automotive, and ship applications.</li> <li>• Only 2.5% of the energy needed for a laser weld.</li> </ul>

welding. FSW is the mainly used joining method for structural components of the Atlas V, Delta IV, and Falcon IX rockets as well as the Orion Crew Exploration Vehicle. Industries have started researching the applications of the FSW in new materials that are difficult to weld using conventional fusion techniques [6]. The seamless, stronger joints achieved with the FSW are used to join the tank and structural segments with fewer defects than possible using other arc welding. FSW has benefitted the aerospace industries tremendously as earlier joining methods were in-efficient and unreliable. For example FSW will perform an integral part in development of the Space Launch System's core stage, which will be powered by RS-25 engines (space shuttle main engines), at NASA [43]. In MMC's, the lack of thermodynamic balance between the metal and ceramic due to their difference in chemical and physical properties is the major cause for problems such as undesirable intermetallic-compounds (IMC) formation, uncontrolled solidification and micro-segregation or inhomogeneous distribution of reinforcement material. Joining these materials is a difficult process that involves formation of an undesirable phases (as molten Aluminium reacts with reinforcement), leaving a strength depleted region along the joint line during fusion welding. However FSW tries to solve these problems with its unique method of joining the materials. FSW stands out to be game changer in joining these materials, as welding occurs below the melting point of the work piece material, therefore the deleterious phases are absent. FSW is an effective method to join the MMC especially in the aerospace industries. Although rapid wear of the welding tool is a major problem due to large variation in hardness between the steel tool and the reinforcement material. Therefore effective

FSW tool material needs to be researched to counter the abrasive wear phenomenon. These tools include diamond coated tools, tungsten carbide and high speed steels. Hence effective monitoring to reduce the tool wears in FSW of MMC is essential to implement these materials in complex applications [5,6,44]. Many innovations in FSW have been made in NASA with its continuous research. For example in the original FSW, a keyhole or a small opening is formed when withdrawing the rotating pin which is a potential weakness in the weld therefore requiring an extra step to fill the hole during manufacturing. So engineers at NASA's Marshall Space Flight Centre developed an innovative pin tool that retracts automatically when a weld is complete and prevents a keyhole. Welds become stronger and eliminates the need for patching. The retracting pin also allows materials of different thicknesses and types to be joined together, increasing the manufacturing possibilities [44].

In the precipitation-hardened aluminium alloys (2xxx, 6xxx and 7xxx), reduction in strength occurs during FSW, in the heat-affected zone due to significant dissolution/coarsening of the precipitates [45]. Inorder to minimize this effect, experiments were conducted by submerging the work pieces in a liquid medium and the FSW was performed under specific environment. Several investigations have been carried out by rapid cooling of the FSW on different aluminium alloys. The texture analysis results suggested that the post-annealing effect, which frequently occurred after the FSW process, was remarkably restricted by the liquid CO<sub>2</sub> cooling thereby accelerating the refinement of the micro-structure. In the stir zone, the grain size decreased. As a result, a joint with an ultrafine grained structure and an excellent strength and matching ductil-



**Fig. 9.** Schematic representation of Friction stir spot welding. Reprinted with permission from Koen F. // INNOJOIN: Development and evaluation of advanced welding technologies for multi-material design with dissimilar sheet metals, (c) 2015 Belgian Welding Institute.

ity can be achieved by rapid cooling of FSW process. Although the substructure significantly enhanced the strength of the stir zone, the ductility was reduced [46,47].

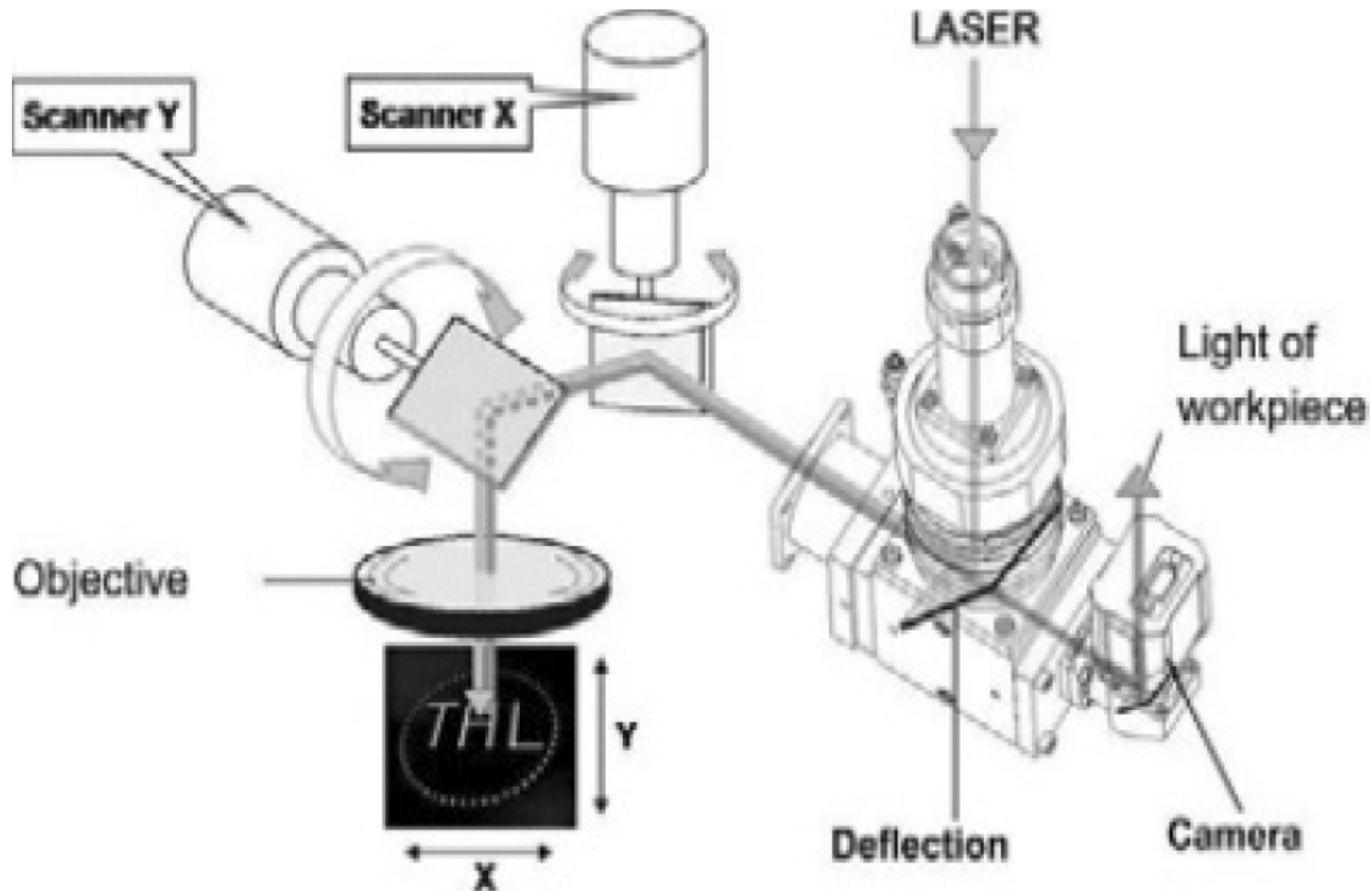
Reverse Dual Rotation – Friction Stir Welding (RDR-FSW) is a variant of conventional friction stir welding (FSW) process. RDR-FSW supports very low welding loads and improved weld quality. The total torque exerted on the workpiece by the tool is reduced. The overheating problems are significantly reduced by this process. The peculiarity about this process is that the tool pin and the assisted shoulder are independent and so they can rotate reversely and independently during welding process. This promotes improved weld quality and low welding loads, by adjusting the rotation speeds of the tool pin and the assisted shoulder independently. In RDR-FSW, the reversely rotating assisted shoulder partly offsets the welding torque exerted on the workpiece by the tool pin. Therefore the total torque exerted on the workpiece by the tool is reduced. This simplifies the clamping equipment thereby lowering the size and the mass of the welding equipment. The problem of overheating or incipient melting can be avoided by optimizing rotational speeds of both the tool pin and assisted shoulder as the tool pin can rotate in a relatively high speed while the assisted shoulder can rotate in an appropriate matching speed. The effect of reverse rotation of tool pin and assisted shoulder is very limited on heat generation, however homogenous temperature distribution and lower torque on work piece is attained with the corresponding material flow pattern and the distribution of heat generation rate [48]. Experiment [49] conducted on 7050-T7451 aluminium alloy proved that RDR-FSW significantly reduced the peak temperature reached in the thermal cycle by decreasing the rotation speed of the assisted shoulder when compared to conventional FSW. Li and Liu [50] analysed the effects of welding speed on microstruc-

tures and mechanical properties of AA2219-T6 when welded by the RDR-FSW.

Friction Stir Spot Welding (FSSW) is a green and sustainable variant of linear FSW, where no transverse movement occurs but uses a central pin, a surrounding sleeve, and an external plunger with independent movement at different speeds to fill the keyhole which is a major problem with conventional FSW. As shown in Fig. 9, the reciprocating parts carefully control the relative motion and applied pressure of the pin, sleeve, and plunger to refill the pin hole. This process offers greater alloy joining flexibility, significantly reduces energy consumption, lesser peripheral equipment, lower operational cost and lower weld distortion than Resistance Spot Welding (RSW) and has therefore been considered as a potential alternative for RSW and clinching, to fasten two metallic work pieces. Significant reduction in capital cost of up to 50% can be realized when compared to resistance spot welding [51].

## 5.2. Laser beam welding

Laser welding is a crucial joining technology to obtain welds with high depth-width aspect ratios, high quality, high precision and minimal distortion. LBW uses the radiant energy carried in a very small beam cross-section of particularly very high power density, to concentrate on the boundary surfaces of the two parts to be welded together. During the LBW a high-power laser beam is focused onto a metal surface, which melts and vaporize the metal under the focus creating a weld keyhole eventually generating a weld bead. A laser beam has comparably higher energy density than a typical plasma arc. LBW is a promising technology as welds with high degree of thermal efficiency, deeper penetration as a consequence of metal vaporisation in keyhole welding conditions, lower thermal distortion of the weld assemblies, higher welding speeds, narrower HAZ and



**Fig. 10.** Working principle of Remote Laser Welding, modified from [56] and [62].

better productivity are obtained compared to conventional welding process. However, the industrial implementation of the system is often perceived as a costly affair in the early days of its introduction due to its very low power conversion rates. But with recent developments in laser delivery techniques and resonator technology for CO<sub>2</sub>, solid-state fiber, and disk laser configurations has improved the quality of high power laser beams with good conversion efficiencies. CO<sub>2</sub> lasers generally have an electrical to optical conversion efficiencies approaching 20% with very good beam quality, high precision, high welding speed. Solid-state lasers supply beam powers around 10 kW to 50 kW while maintaining a high beam quality are available now in the manufacturing companies. Therefore, these lasers have a more compact footprint and much higher wall plug efficiencies than previous conventional lasers. The introduction of the fibre-optic delivery systems provided end-users with more flexibility in terms automation and compactness of the units. Laser welding of aluminium has great challenges as it involves several physical and chemical processes. For example aluminium has very low absorption rates due to its high reflectivity, which ranges between 0.86 and 0.90 for pure aluminium at laser wavelengths between 900 and 1,000 nm. Therefore very high specific energy is required in welding of aluminium. LBW is used for specialized operations where minimum heat-input and stress to the weld is required [53-58]. Several studies have been performed to understand the behaviour of AA 2024 welding using different laser power sources [59-61]. More focus has been shown towards analysing the effects weld-

ing AA 2024 thin sheets that are under 2 mm in thickness using Nd:YAG and CO<sub>2</sub> lasers and satisfactory results have been achieved [60].

Most laser welding configurations can produce long continuous welds but are most often used to produce a series of weld stitches. Weld stitching is a demanding process where RSW integrated with automated systems has dominated for quite long time. However now, RLW pose as a tough competitor with the developments in the Laser delivery technology. The RLW can perform remote weld stitches with different size and orientation based on the design requirements of the parts, whereas RSW can produce a round spot weld nugget of a size determined by the gun tip size. Programmable focusing optic scanners are used to perform the remote operations without requiring neither the part nor the scanner to be moved and scanners are mounted to a robot in-order to extend the working envelope for larger parts. Fig. 10 shows the working principle and components involved in the RLW process. Significant reduction in cycle time can be achieved with RLW when compared to RSW, it is one of the primary motivations for factory owners to switch to RLW. Weld cycle time adversely affects the productivity of the manufacturing process. In case of RSW where several mechanical motions such as open gun, robot reposition to next weld site, close gun etc. are required between each electrical weld cycle and they significantly affect the lead time of the product. For example a typical Robotic RSW unit requires 3 seconds to complete a single spot weld. However a RLW unit has comparatively very fast welding speeds of several m/min. Additionally a considerable reduc-

tion in the deadtime between the welds can be achieved as small mirrors are required to be reoriented to point to the next weld avoiding any physical movement of weld gun to the next location [56,62]. Therefore RLW is comparatively a cost effective process in moderate and high volume usage applications, a productive process with two to five spots a second.

## 6. CONCLUSION

As long as the ballistic launch methods are used as means of transporting the cargo from earth's surface to orbit, the need for light weight structures will remain to be the foremost consideration in spacecraft's design. Similarly, airlines are concerned with energy consumption due to the significant rise in fuel cost. The vast majority of either the aircraft or the weight is derived from the structural components and fuel. Therefore the structural efficiency of the aircraft needs to be improved by reducing the aircraft's weight which translates into reduced fuel consumption and increased cargo. The best way to achieve the weight reduction is through the selection of lighter materials and the aerospace industries relies heavily on aluminium alloys for this purpose. Aluminium alloys have been the primary material choice in the structural parts of aerospace and marine sectors for more than 80 years. Aluminium appears to be a better choice because of their well-known mechanical behaviour, easiness with design, manufacturability and established inspection techniques.

The guiding consideration for the design of aircraft structures remains to be the proper choice of lightweight and strong materials. Aluminium possess a wide range of properties that allow them to be the best choice for aerospace applications. Also tailored Aluminium alloys, which best fits the requirements of aircraft industries, are manufactured by suitably varying the chemical composition and processed to obtain the best combination of properties. The Al-Cu alloys, which are high strength alloys, respond to heat treatment by age hardening and are used for high strength structural applications where the main design criterion is damage tolerance. These alloys are strengthened by the precipitation of the  $\text{Al}_2\text{Cu}$  and  $\text{Al}_2\text{CuMg}$  phases. The 2000 series alloys are used mainly in the wing and the fuselage sections of the aircraft. Development of the newer versions of these alloys provides improvement in fracture toughness, corrosion resistance, slower fatigue crack growth, improved weight savings and longer service lifetimes. The Al-Zn al-

loys which are high strength alloys, have been used to manufacture the upper wing skins, stringers and horizontal/vertical stabilizers. Of all the aluminium alloys the Al-Zn-Mg-Cu versions have proved to exhibit the highest strength. The 7000 series alloys have excellent combination of high strength, resistance to fatigue crack propagation, superior fracture toughness, resistance to stress corrosion cracking and superior damage tolerance. Introduction of the Al-Li alloys, tremendously improved the aero-structural performance of the aircrafts. The new Al-Li alloys along with the efficient structural design provide the options for improved structural performance for next generation aerospace applications. The third generation Al-Li alloys were developed to improve the shortcomings of second generation Al-Li alloys. This resulted in the development of light weight, high performance aluminium alloy. They were developed to compete with conventional aluminium alloys, carbon-fibre composites, and metal-matrix composites for aerospace applications, particularly in transport aircraft structures.

The demand of aircraft manufacturers for improved joining methods, which can reduce the weight of the aircraft, eliminate stress concentrations, reduce heat affected zones and improve joint efficiency, have resulted in the adoption of welding, bonding and extrusions for joining aircraft materials, replacing the use of rivets. FSW is one of the top choices for the aerospace joining applications. The seamless, stronger joints achieved with the FSW are used to join aircraft structures with fewer defects than possible using other arc welding. FSW stands out to be game changer in joining the aircraft aluminium materials, as welding occurs below the melting point of the work piece material, therefore the deleterious phases are absent. RDR-FSW solves the problems in FSW, therefore allowing very low welding loads and improved weld quality. The overheating problems and the total torque exerted by this process are reduced. Hence the clamping arrangements are either minimized or totally eliminated. FSSW process offers greater alloy joining flexibility, significant reduction in energy consumption, lesser peripheral equipment, lower operational cost and lower weld distortion than RSW and has therefore been considered as a potential alternative for RSW and clinching, to fasten two metallic work pieces. LBW is a promising technology as welds with high degree of thermal efficiency, deeper penetration, lower thermal distortion, higher welding speeds, narrower HAZ and better productivity are obtained compared to conventional welding process. Variants of the LBW process such

as Remote Laser Welding (RLW) allows the production of many weld stitches at a much faster rate than possible with robotic resistance spot welding.

Research focus on aerospace materials has been directed towards development of new materials that can meet the changing industrial needs. Aircraft aluminium alloys continue to evolve with the increasing demand from the aircraft manufacturers. From the high strength and lightweight aluminium alloys to the enormous application of nanotechnology, advancement in material technology is set to yield revolutionary results in materials capabilities. Development in materials directly reflects improvement in its properties. These material property improvements signifies reduction in material usage and scrapping, improved performance and improved life cycle of the aircraft.

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