ALLOY DESIGN FOR OVERCOMING THE LIMITATIONS OF AL-LI ALLOY PLATE

E.S. Balmuth[1] and D.J. Chellman[2]
1. Lockheed Fort Worth Company, MZ 2853, P. O. Box 748, Fort Worth, TX 76101, USA
2. Lockheed Aeronautical Systems Company, Dept 73C3 Zone 150, Marietta, GA 30063, USA

Abstract

The low density, high elastic modulus, and high resistance to fatigue crack growth of Al-Li alloys have long promised significant weight savings in aerospace structures. However, the application of commercially available Al-Li alloys has been inhibited by a long list of deficiencies: Low fracture toughness; embrittlement after exposure to 65-135°C; anisotropic tensile and fatigue properties; through-thickness variability; and susceptibility to stress-corrosion cracking (SCC). Each of these problems have been overcome through optimized additions of major and ancillary alloying elements. Excellent property combinations and freedom from the above problems are possible without resorting to extraordinary processing practices. High fracture toughness, isotropic properties, thermal stability, and resistance to SCC, together with outstanding fatigue resistance, moderate strength, and advantages in density and modulus, have all been achieved in 2197 in thicknesses to 14 cm. The alloy design principles that have resulted in these advances are discussed.

Introduction

Major sections of small fighter and attack aircraft are fabricated from machined high-strength aluminum alloy plate. These include wing-carry-through bulkheads, frames, longerons, spars, and, until recently, wing skins. Fatigue loading is severe for these highly maneuverable aircraft. Fatigue cracks often initiate early in service at locations with unavoidable, intense stress concentrations. Consequently, parts for primary structure are largely sized by damage tolerance considerations. Thus, improved resistance to fatigue crack growth readily translates into weight savings. And, since the strength of parts that have cracks is more proportional to toughness than tensile strength, increased fracture toughness is also a direct benefit.

The Al-Li alloys that were developed and commercialized in the 1980's - 2090, 8090, and 2091 - all demonstrated significant advantages in fatigue crack growth resistance over conventional alloys typically selected for these applications - 2124, 7050, and 7475. Despite their low density, higher elastic properties, and good tensile properties, several deficiencies have precluded production applications of plate products in fighter and attack aircraft.

For the early Al-Li alloys in peak strength tempers, fracture toughness in the S-L orientation is typically $\sim 13\ MPa\sqrt{m}$ [1-4], less than half the typical values of conventional alloys. The brittle character of the thickness direction can result in cracking during manufacture [5] unless special care is exercised. Increasing part thicknesses to manage loads in the thickness direction and to prevent cracks initiated in other orientations from turning and propagating in an unstable manner can eliminate any potential weight savings in many applications.

For the early Al-Li alloys, an optimum combination of strength and toughness was developed by underaging to below peak strength. In this condition exposure to temperatures of 135-180°C results in hardening and a concurrent reduction in toughness. Additionally, in 2090 exposure to lower elevated temperatures of 65-135°C results in further strengthening. Increases in strength of more than 85 MPa were observed after 1000 hours at 107°C [6]. DSC patterns, Figure 1, show a large increase in endotherm 1, and eventually, a decrease in exotherm 2. Endotherm 1 is attributable to dissolution of both δ' and a less well defined metastable phase, T_1' [7], T' [8,9], or a transition phase [10]. A large, time dependent increase in the volume fraction of δ' is not expected, nor is it expected that δ' precipitation could be responsible for the sizable increase in strength. T_1 precipitation is detected by the decrease in exotherm 2, but this only occurs after more than 100 hours while half of the increase in strength developed in the first 100 hours. Thus, it appears likely that the strengthening observed under these conditions is due to precipitation of T_1' or T'. Losses in toughness accompanied this increase in strength in the initially underaged 2090. The strength increase was smaller in peak aged 2090, but the loss in toughness was severe after 1000 hours at 66°C [11]. In conventional alloys, thermal exposure generally results in an increase in toughness. Since many sections of fighter/attack aircraft are subject to aerodynamic heating, or heat from the engine, hot air ducts or other equipment, potential losses in toughness must be recognized in design.

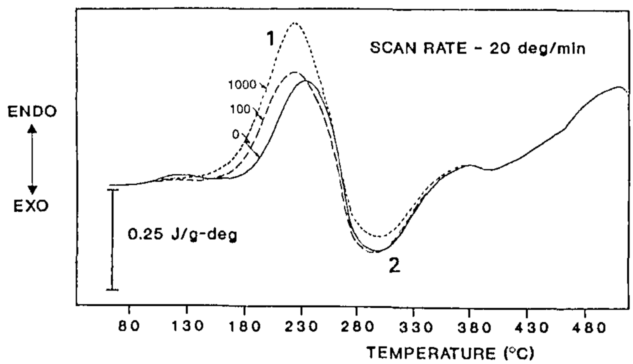


Figure 1. DSC Patterns for Unstretched 2090 Sheet Aged 24 Hours at 163°C and Exposed to 107°C for the Hours Indicated.

Tensile, fatigue, and fracture toughness are strongly affected by the intense crystallographic textures found in the early Al-Li alloys [12-14]. Texture leads to minimum strength at 45° from the rolling direction, near the surface; and minimum in-plane toughness in the T-L orientation at the midplane of the plate. Assuring fracture toughness comparable to the conventional alloys in the minimum toughness location by underaging results in minimum strength levels much below that of conventional alloys. The variability in properties due to texture complicates design, driving conservative assumptions, minimizing weight savings.

SCC resistance of the early Al-Li alloys is generally adequate for parts fabricated from thin plate where sustained ST stresses are minimal. However, the SCC resistance of 8090, 2091, and underaged 2090 plate [3,15,16] has been considered to be too low for aircraft parts made from plate thicker than ~2 cm. Their sustained stress capability in 3.5% NaCl alternate immersion testing is 100-170 MPa, while 2124 and 7050 have a sustained stress capability of more than 240 MPa.

The minimum requirements for applications of aluminum alloy plate in fighter/attack aircraft are: Moderate to high tensile properties; high fracture toughness in all orientations; stable properties after exposure to ~ 100-130°C; minimal variability in properties; high corrosion resistance; and consistent quality. The development of an Al-Li alloy having these qualities in thicknesses to 15 cm promises broad applicability in primary airframe structure and excellent weight savings derived from lower density, higher modulus, and especially, higher durability and damage tolerance.

Thermal Stability

The use of underaged tempers to achieve adequate fracture toughness promotes the tendency for increased strength and decreased toughness after thermal exposure. Aging to peak strength is required to eliminate this effect. To minimize embrittlement after exposure to slightly elevated temperatures (65-135°C), it is suggested here that the amount of solute remaining in solution after aging should be minimized. A low temperature final aging step can accomplish this, but aging times in excess of 100 hours may be required. In Al-Cu-X-Li alloys excess solute is associated with δ' - whenever δ' is present, a considerable amount of Li remains in solid solution. Choosing compositions for which δ' is not present after aging solves this problem - further precipitation of the Cu-rich strengthening phases will not occur during thermal exposure without a source of Li, either δ' or the solid solution. This choice is guided by the work of Silcock who illustrated the phases present after aging Al-Cu-Li alloys for 16 hours at 165°C [17]. The δ' phase is not found at lower Li concentrations.

The loss in strength with overaging is strongly retarded with increasing Mg content. This was apparent in the aging curves for a series of experimental Al-Cu-Mg-Li alloys with 0 to 2.2% Mg, investigated by Skillingberg [18]. To the extent that long aging times and/or subsequent thermal exposure may promote grain boundary precipitation which tends to reduce toughness while the loss in strength that accompanies overaging tends to increase toughness, it would be expected that there might be a trade in adding Mg for improved elevated temperature strength. However, overaging treatments of 100 hours at 182°C was found to have minimal effect on toughness, Table I.

Strength and Fracture Toughness

The Cu-rich phases, T_1 (Al_2CuLi), S′ (Al_2CuMg), and θ' (Al_2Cu), are primarily responsible for strengthening in Al-Cu-Mg-Li alloys. The plate-like T_1 phase is probably the most potent strengthening precipitate available for Al-base alloys. In Al-Cu-Mg-Li alloys, S′ usually

Table I. Effect of Overaging on 3.2 cm Plate

Alloy	Age hours/°C	YS - LT MPa	K_{Ic} - S-L MPa$\sqrt{m}$	Overage hours/°C	YS - LT MPa	K_{Ic} - S-L MPa$\sqrt{m}$
Al-3.0Cu-1.6Li	16/177	459	24.2	100/182	398	25.3
Al-2.7Cu-1.5Mg-1.3Li	80/177	459	22.7	100/182	453	21.5

coprecipitates with T_1, and the θ' phase may also be present when the Cu:(Mg + Li) ratio is sufficiently high. Very high strength levels are possible at low precipitate volume fractions. With the further addition of Ag, strength levels above 690 MPa have been attained in sheet [19]. Conversely, large volume fractions of the spherical δ' provide only a modest increase in strength. The first commercially available Al-Li alloys were formulated with solute levels near the limit of that which can be dissolved during solution heat treatment to achieve good combinations of strength and density. Elongated, unrecrystallized grain structures and texture contribute to strength, but in a directional manner. Because the Cu-rich precipitates often nucleate heterogeneously at dislocations, cold work after quenching is requisite for a uniform distribution of particles and an optimum combination of strength and toughness. Ashton [20] showed that most of the benefit was attained with a 3% stretch after quenching, but an additional increment of improvement in strength and toughness could be had with further stretching to 7%. At equivalent solute levels, cold work is equal to or more effective than alloying additions of elements like Cd, In, Ag, Sn [21,22], Mg or Zn [23-25] that also serve to promote T_1 nucleation and a more uniform distribution of the Cu-rich particles.

From the study by Skillingberg [18] of a series of Al-Cu-Mg-Li alloys fabricated as 1.5 cm plate, peak longitudinal yield strength for compositions within a limited range can be estimated with a simple empirical equation:

$$\text{YS (MPa)} = 6.89[9 + 11(\%\text{Cu}) + 9(\%\text{Mg}) + 4.3(\%\text{Li}) + 4(\%\text{Cu}\cdot\%\text{Li})] \tag{1}$$

Deformation and fracture in Al-Li alloys has been the subject of intense study over the last 20 years [26]. The effects of grain boundary precipitation and the results of quench sensitivity studies [2,27-29] are of particular interest in designing an alloy for thick plate. The quench sensitivity studies showed the tendency for precipitation of incoherent T_2 (Al_6CuLi_3) particles on high angle grain boundaries when quench rates were reduced. Furthermore, higher solute alloys were more quench sensitive [2,28], and that the quench sensitivity of toughness is much greater than that of strength. Grain boundary precipitates, T_2 in Al-Cu-X-Li and δ (AlLi) in high Li alloys, nucleate during quenching and may grow during aging. This leads to a considerable quantity of grain boundary precipitate, as well as the formation of an adjacent pfz. These features promote a low toughness, intergranular fracture mode.

Very low fracture toughness in the S-L orientation is characteristic of the early Al-Li alloy plate products. At high strength levels, in-plane toughness values are also generally too low for use in aircraft. To overcome the problem of low toughness in thick Al-Li plate, grain boundary precipitation must be minimized. An approach in alloy design to accomplish this is to reduce the total solute content - because of the strong relationship between strength and toughness, a lower solute alloy with a lower peak strength will have higher fracture toughness.

Since Al-Cu-X-Li alloys are capable of such high strength levels, leaner alloys can still be competitive with conventional alloys. And, as illustrated by Dorward [30], toughness is higher with lower Li concentrations. These reductions in solute reduce the thermodynamic driving forces for grain boundary precipitation, especially the Li-rich precipitates that are expected to be the most deleterious to toughness. Lower strength is not a desirable feature, but the advantages of higher toughness can make this an acceptable tradeoff.

Other factors that may affect toughness - coarse Fe- and Si-rich constituent particles, K and Na impurities, intense planar slip behavior when δ' is present, and hydrogen content - have also been the subject of earlier studies. Their relative contribution in a high toughness alloy without an intense texture remains unclear. However, S-L fracture toughness levels similar to premium conventional alloys have been demonstrated in alloys with lower solute concentrations, low Fe, Si and impurity concentrations, and commercial ingot metallurgy melting and processing practices developed for Al-Li alloys [1,31].

Corrosion Resistance

Susceptibility to SCC has been identified in Al-Cu-Mg-Li alloys. SCC resistance in these alloys is significantly improved with additions of either Ag [32] or Zn [3,16,33]. However, these additions are likely to increase quench sensitivity. Another approach is to eliminate the Mg addition altogether - Al-Cu-Li alloys demonstrate high SCC resistance in a peak strength condition, especially at lower Li concentrations. For the series of Al-Cu-Mg-Li alloys evaluated by Skillingberg [18], only the Mg-free alloy successfully passed alternate immersion SCC testing at a sustained stress of 240 MPa.

Anisotropy

During hot working, Al-Li-X-Zr alloys develop an intense texture at Li concentrations as low as 0.5 weight percent [34]. Thermomechanical processing to induce recrystallization alters the nature of the texture, but because of the strong relationship with the prior unrecrystallized texture, properties may remain highly anisotropic. The roles of Li and Zr in the development of texture are poorly understood, confounding the resolution of this problem. Fortunately, it

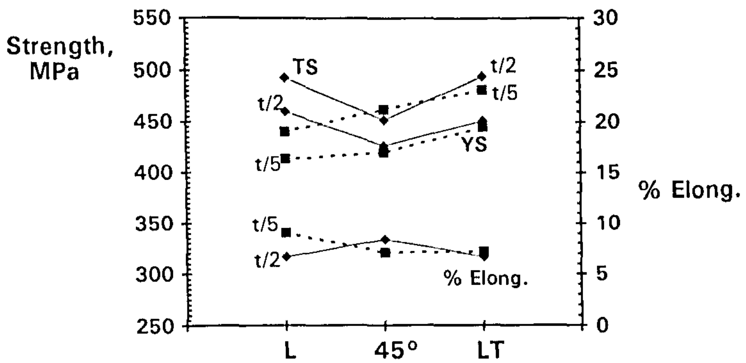


Figure 2. Variation in In-Plane Tensile Properties at the Mid-Plane (t/2) and Near-Surface (t/5) Locations for 3.8 cm Al-2.7Cu-1.5Li-0.3Mn-0.1Zr Plate.

Table II. Registered Composition Limits, Weight Percent

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Li	Zr	Ti	Al
2097	0.12	0.15	2.5-3.1	0.10-0.6	0.35	0.35	1.2-1.8	0.08-0.16	0.15	Rem.
2197	0.10	0.10	2.5-3.1	0.10-0.50	0.25	0.05	1.3-1.7	0.08-0.15	0.12	Rem.

was found in an Al-2.7Cu-1.5Li-0.1Zr alloy that the addition of 0.3% Mn reduces anisotropy to levels similar to those found in conventional aluminum alloys, Figure 2. Variation in elastic properties is also associated with an intense texture [35]. For the 3.8 cm plate illustrated in Figure 2, the variability in tensile modulus was 1%, compared with about 4% in 2090 plate. Mn additions result in the formation of incoherent Al_6Mn dispersoids which are believed to affect the development of substructure during hot working. There is likely a secondary benefit from the Mn dispersoids as they may homogenize slip during the stretch after quenching for a more uniform precipitate distribution.

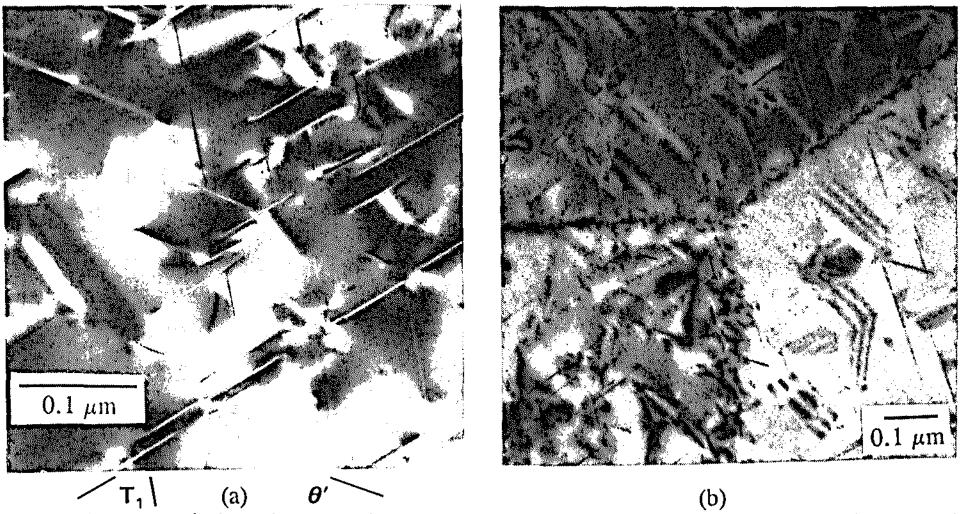
Alloy Design

A plate alloy with a nominal composition Al-2.8Cu-1.5Li-0.12Zr-0.3Mn was designed at Reynolds Metals Company to meet the needs of fighter/attack aircraft. The Li content of was selected to minimize density while avoiding the problems associated with the presence of δ'. The Cu content provides a strength level similar to 2124-T851 which is widely used in fighter/attack aircraft. Higher Cu concentrations would provide higher strength at the expense of toughness, especially in thick sections. A Mg-free composition was selected to avoid SCC susceptibility and to minimize quench sensitivity, although this is a tradeoff against better strength stability after thermal exposure. The ancillary Zr addition assures an unrecrystallized grain structure for optimum in-plane strength and toughness. Finally, the Mn addition reduces the tendency for the development of an intense crystallographic texture, minimizing anisotropy and through-thickness variability. As a relatively dilute, Mg-free composition this alloy has good ingot casting characteristics. High ingot recovery rates are expected.

Very similar alloys with this chemistry have been registered with the Aluminum Association as 2097 by Alcoa and 2197 by Reynolds, Table II. Typical properties for the 3.8 cm plate were illustrated in Figure 1. Strength and toughness properties of 14 cm plate have demonstrated the capability for exceeding the minimum requirements established for 2124-T851 [36]. Typical toughness values in the L-T and S-L orientations are 39 $MPa\sqrt{m}$ and 25 $MPa\sqrt{m}$, respectively. The microstructure of the 3.8 cm plate in Figure 3 shows a uniform distribution of T_1 particles, a smaller proportion of θ', freedom from coarse grain boundary precipitates and no pfz. No δ' was observed.

Status

Plate meeting the composition limits for 2097 and 2197 have been fabricated from production-scale 4500 kg ingots. Properties have been evaluated for 3.8, 9.1, 10.2, 13.2, and 14 cm thicknesses. The goals of good strength, S-L toughness above 23 $MPa\sqrt{m}$, high in-plane toughness, isotropic properties, resistant to SCC, and good thermal stability have all been demonstrated in extensive coupon testing. High resistance to fatigue crack growth was also determined. Additional damage tolerance and durability testing has been conducted under



(a) (b)

Figure 3. Transmission electron micrographs showing (a) T_1 and θ' matrix precipitates, and (b) grain boundaries with no pfz nor coarse, equilibrium precipitates (Courtesy of F.W. Gayle, NIST).

spectrum loading using both simple geometries and more complex structural subcomponents [37]. These have indicated fatigue crack growth rates 2-5 times lower than 2124, depending on test conditions. Bulkhead structures were fabricated from 9.1 cm plate from the first production-scale 2197 plate and assembled into a center-fuselage test component [38]. A new effort has been initiated at Lockheed Fort Worth Company under USAF sponsorship, leading to flight experience for fatigue-critical bulkhead segments in 1995 [36]. Elements of this program include the production of multiple lots of 14 cm 2097/2197 plate to provide producer confidence in being able to guarantee properties and quality; durability and damage tolerance testing; subcomponent static and durability testing; application studies; and replacement of a bulkhead section on a service aircraft.

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