THE STATUS OF AL-LI ALLOYS

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Abstract

Much progress has been made over the past few years in defining the physical and mechanical metallurgy of Al-Li alloys, in commercial alloy and process development, and in aerospace applications. Ten alloys are currently registered with the Aluminum Association. Seven of these have been registered in the last four years. The newer alloys have been optimized for the special needs of particular kinds of applications. Although in comparison with conventional alloys, their density advantage is small, the benefits from other characteristics are excellent. Key factors that affect the suitability of Al-Li alloys for many applications are discussed. Al-Li alloys have demonstrated ultra-high specific strength. Fracture toughness is sensitive to composition and quench rate. High resistance to fatigue crack growth is a major advantage in airframe primary structure. Anisotropy in most Al-Li alloys has an adverse effect on potential weight savings, but alloys with ancillary additions of Mn appear to be more isotropic. Al-Mg-Li alloys have high corrosion resistance. Important opportunities for further research and alloy development are highlighted.

Introduction

The First International Aluminum-Lithium Conference was held 14 years ago at Stone Mountain, GA, not far from the site of this 4th ICAA. A number of alloy and process development studies were being conducted at that time in response to the promise of a major increase in structural efficiency that would be possible with lower density and higher stiffness in Al-Li alloys. Enthusiasm over the potential of Al-Li alloys was tempered by the brittle behavior found in peak-aged alloys. Importantly, that first meeting set forth the challenge to develop an understanding of the mechanisms responsible for deformation and fracture in Al-Li alloys and to solve a number of other fundamental and engineering problems. The level of difficulty inherent in resolving the problems, together with the potential payoff from their solution, was an intoxicating mix that soon drew researchers from around the world, ultimately involving hundreds of people in industry, government and academia. Progress over the last 14 years has been at times a frustrating experience. Most everyone encountered road blocks along the path toward production applications. But, notable progress has been made, even though significant barriers remain - the challenge of new discovery with the promise of large payoffs in performance is still available in Al-Li research and development. This overview will focus on trends in alloy development and will discuss some of the special problems and benefits of Al-Li alloys.

Al-Li Alloys and Properties

A measure of progress in the field is the list of no less than 10 active Al-Li alloy compositions registered with the Aluminum Association, Table I [1]. Alloys 2090, 2091, and 8090 were the first alloys to be commercialized. They were developed to provide moderate-to-high strength and a distinct density advantage. Broad applications were hoped for by trading strength for toughness in the selection of age hardening practices as might be required for different product forms or applications. Thermal-mechanical processing to vary grain structure and composition variations within the registered limits were also used to optimize properties. The alloys were extensively evaluated by the aerospace community. Both trial applications and production applications were pursued aggressively at many companies. This experience highlighted major deficiencies that have severely limited the use of these alloys in production despite improvements in process control that were gradually introduced by the producers. Deficiencies include anisotropic properties; low toughness in high strength orientations and tempers; loss in toughness after thermal exposure; low stress-corrosion resistance in Al-Cu-Li-Mg alloys; poor formability and low ductility in unrecrystallized sheet and extrusions; low strength in the absence of cold work prior to aging; and high raw material costs. The development by Novamet of mechanically alloyed 5091, a moderate strength, non-heat treatable, powder metallurgy alloy offered promise for overcoming toughness, thermal stability, anisotropy, and corrosion problems. But, low resistance to fatigue crack growth made the material unsuitable for many applications [2].

Table I. Registered Composition Limits, weight percent

Alloy	Li	Cu	Mn	Mg	Ag	Si	Fe	Cr	Zn	Zr	Ti	Al
2090	1.9-2.6	2.4-3.0	0.05	0.25	-	0.10	0.12	0.05	0.10	0.08-0.15	0.15	Rem.
2091	1.7-2.3	1.8-2.5	0.10	1.1-1.9	-	0.20	0.30	0.10	0.25	0.04-0.16	0.10	Rem.
2094	0.7-1.4	4.4-5.2	0.25	0.25-0.8	0.25-0.6	0.12	0.15	-	0.25	0.04-0.18	0.10	Rem.
2095	0.7-1.5	3.9-4.6	0.25	0.25-0.8	0.25-0.6	0.12	0.15	-	0.25	0.04-0.18	0.10	Rem.
2195	0.8-1.2	3.7-4.3	0.25	0.25-0.8	0.25-0.6	0.12	0.15	-	0.25	0.08-0.16	0.10	Rem.
X2096	1.3-1.9	2.3-3.0	0.25	0.25-0.8	0.25-0.6	0.12	0.15	-	0.25	0.04-0.18	0.10	Rem.
2097	1.2-1.8	2.5-3.1	0.10-0.6	0.35	-	0.12	0.15	-	0.35	0.08-0.16	0.15	Rem.
2197	1.3-1.7	2.5-3.1	0.10-0.5	0.25	-	0.10	0.10	-	0.05	0.08-0.15	0.12	Rem.
5091*	1.2-1.4	-	-	3.7-4.2	-	0.20	0.30	-	-	-	-	Rem.
8090	2.2-2.7	1.0-1.6	0.10	0.6-1.3	-	0.20	0.30	0.10	0.25	0.04-0.16	0.10	Rem.

*1.0-1.3 C, 0.2-0.7 O

Special characteristics like high fatigue crack growth resistance, superplastic formability, stable tensile properties after long-term thermal exposure, good weldability, good strength and toughness at cryogenic temperatures, and good corrosion resistance in atmospheric exposure testing were studied in depth with an eye to some important specialty applications, somewhat apart from general aerospace applications. With these promising capabilities in mind, alloy development goals were reformulated in the mid-1980's around the specific needs of particular kinds of applications. This round of alloy development was able to benefit from and build on the much firmer base of composition-microstructure-property relationships that evolved after the early Al-Li alloys became widely available. Most notable of the alloy development programs were the development of the Weldalite® family of high strength alloys; the development of a thick-section plate alloy; and optimization of low density, weldable Al-Mg-Li alloys. Interestingly, except for the Al-Mg-Li alloys, the newest alloys have placed diminished emphasis on low density in favor of other characteristics.

The Weldalite® development effort was led by Dr. Joseph R. Pickens at Martin Marietta Laboratories. His team defined property goals especially for cryogenic tankage in launch vehicles. The aims were good weldability and very high strength both in as-welded and in heat treated conditions. Four alloys in the Weldalite® family have been registered, 2094, 2095, 2195, and X2096, varying primarily in Cu content. These are Al-Cu-Li-Zr alloys with nominal additions of 0.4 Mg and 0.4 Ag. They have nominal Li concentrations of 1.0 to 1.6%, well below the 2.0 to 2.4% levels that were typically employed in the earlier alloys. Tensile strengths as high as 727 MPa were readily demonstrated in extruded bar [3]. The high strength levels were attributed to copious T_1 precipitation associated with the relatively high Cu/Li ratio, nucleated with the aid of the Mg and Ag additions which also enable coprecipitation of other metastable phases. Furthermore, the reduction in stress corrosion resistance with the addition of Mg is overcome with the simultaneous addition of Ag. Strength and toughness property optimization was conducted with thorough and systematic studies of the effects of varying solute concentrations. Figures 1-2 are results from the surveys on the independent effects of Li and Cu on strength [3,4]. These results, plus successful development of production-scale processing practices, detailed welding and cryogenic property studies, and part fabrication trials and validation testing has led to a major commitment in NASA's Lightweight Shuttle Tank program [5].

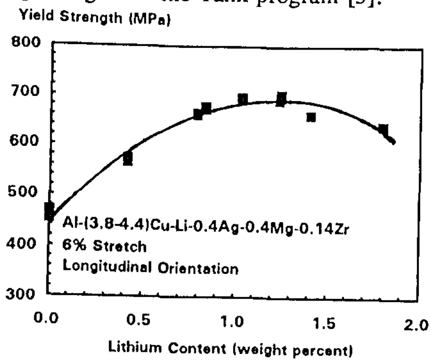


Figure 1. Effect of Li Content on Peak Strength Weldalite® Extrusions.

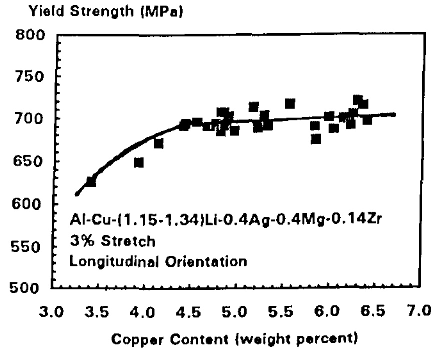


Figure 2. Effect of Cu Content on Peak Strength Weldalite® Extrusions.

The thick plate development effort was initiated by a team from General Dynamics Fort Worth Division (now Lockheed Fort Worth Company), Lockheed Aerospace Systems Company, and Reynolds Metals [6]. Initially, the focus of the effort was to demonstrate good, thermally stable toughness in the thickness direction with strength and corrosion resistance comparable to 2124-T851, plus a modest density and modulus advantage. The principal applications of interest were fighter/attack aircraft bulkheads and wing substructure. 2097 and 2197 met all of the property goals. As had been hoped, the lower Li content, δ'-free alloy, demonstrated the same kind of high resistance to fatigue crack growth that had been found in alloys with higher Li, Figure 3 [7]. Since fatigue crack growth resistance is the most important design criteria for these particular applications, the performance benefits are excellent despite the modest density advantage. Much lower anisotropy and through-thickness variability were also found, probably due to the role of the Mn addition in texture development. This development effort is more fully discussed elsewhere in this conference [8].

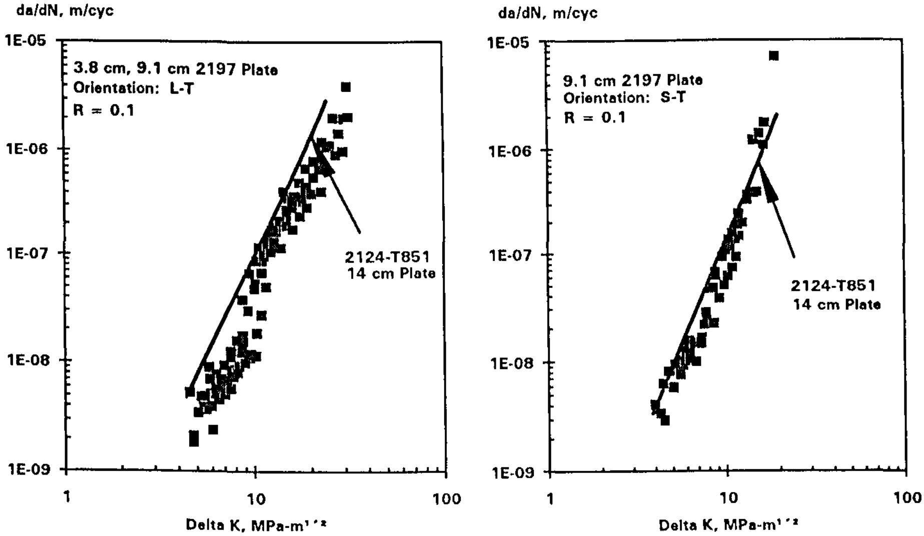


Figure 3. Constant Amplitude Fatigue Crack Growth Rates For 2197 Tested in 3.5% NaCl Compared with 2124 Tested in Sump Tank Water.

We should also recognize the use of Al-Mg-Li alloys in Russia. Alloy 1420 was developed in the early 1960's by a team led by I. Fridlyander [9]. It is a low density, low strength, weldable alloy and has been used in aircraft production since 1970. Welding practice development, begun in 1980, led to the development of a welded MIG-29 fuselage and cockpit. Somewhat higher yield strengths were demonstrated with the further addition of 0.2 Sc in alloys 1421 and 1423. Weight savings with the use of these alloys derive from the density advantage and greater joint efficiency, compared with mechanical fastening. The usual problem of low fracture toughness is mitigated in several ways - moderate toughness levels are attained at the low strength levels of these alloys; to meet structural strength requirements, the assemblies must be lightly loaded; and in welded structures, stress concentrations are minimized. The design philosophy and fabrication method contrast sharply with those in the West where the emphasis is on high strength alloys and highly loaded mechanically fastened assemblies. For this reason, until recently there has been relatively little work with Al-Mg-Li alloys by aerospace companies outside of Russia. Higher strength Al-Mg-Li alloys with high corrosion resistance are being examined for marine applications [10].

The development of 2097, 2197, and the Weldalite® alloys covers a wide range of applications for plate products. There remains a need for a sheet product with moderate strength, isotropic properties, high resistance to fatigue and fracture, adequate thermal stability, good formability, and good producibility, with advantages in density and modulus over conventional alloys. Advances in our understanding of Al-Li alloys should make this objective readily attainable.

Microstructure and Mechanical Behavior

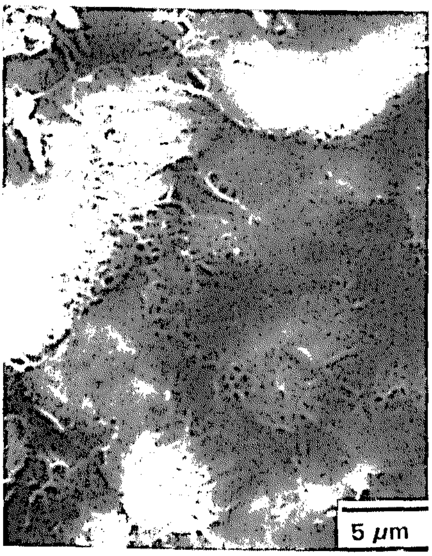
Fracture Toughness. Low fracture toughness has been the major deterrent to the use of Al-Li alloys since a number of potential 2020 applications were rejected in the 1960's. Process developments that assure low alkali impurity concentrations, low hydrogen levels, and controlled grain structures, plus compositions that minimize coarse constituent phases, have not attained a kind of holy grail - a high strength, high toughness, low density alloy. Studies have indicated that toughness is severely degraded by the nucleation and growth of coarse, Li-rich, equilibrium phases at grain boundaries. This tendency is aggravated by slow quench rates, high Li concentrations, high levels of other solute additions, high-angle grain boundaries, and longer aging times/higher aging temperatures, or extensive thermal exposure. Short-transverse fracture surfaces from 2124, 2090, 8090, and 2197 plate are shown in Figure 4. The S-L fracture toughness values for 2124 and 2197 were similar - 23-25 $MPa\sqrt{m}$. Toughness for the 8090 and 2090 samples was much lower. It is apparent that the toughness of 2124 is limited by the constituent particle volume fraction. The surface shows a large area fraction of brittle constituent particles separated by regions with a ductile, dimpled fracture mode. The intergranular and intersubgranular fracture surfaces of the low toughness 2090 and 8090 specimens show a large area fraction of marks that indicate the presence of coarse equilibrium phases. The elongated, crystallographic marks in 2090 are attributable to coarse T_1, while the more equiaxed marks in 8090 are probably due to T_B. In both cases the regions between the marks are relatively smooth, rather than dimpled. Smooth-surfaced, intergranular fractures are characteristic of alloys where δ' is present, owing to its role in restricting cross-slip. The 2197 surface has ductile dimples between the marks from the coarse particles. The area fraction of coarse particles was much less in the higher toughness 3.8 cm plate than the 9.1 cm plate. These results suggest that in the absence of δ', grain boundary precipitation is not as deleterious to toughness.

It has been shown that the problem of low toughness can be controlled with compositions formulated with lower solute levels [8]. Quench sensitivity studies have shed considerable light on the problem, modeling the drop in toughness with decreasing quench rate [11]. However, we lack sufficient information on the effect of individual solute element concentrations on quench sensitivity to formulate solute levels for even simple Al-Cu-Li alloys for specific thickness ranges with anything other than trial and error.

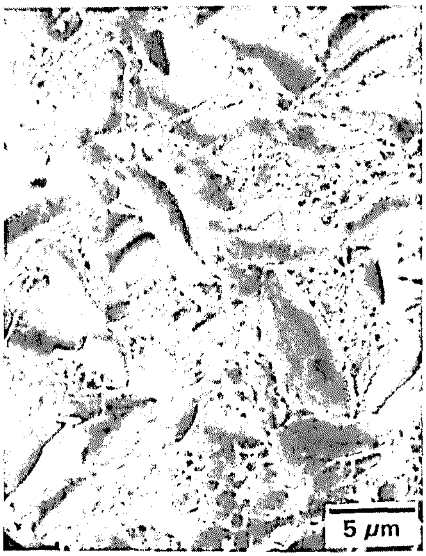
Fatigue Crack Growth Resistance. High resistance to fatigue crack growth is one of the most important benefits in Al-Li alloys. This is the case for simple δ'-strengthened Al-Li alloys, coprecipitation-strengthened Al-Li-Cu alloys, and δ'-free Al-Cu-Li and Al-Cu-Mg-Li alloys with higher Cu:Li ratios. Reversible planar slip, cyclic stability, and good toughness contribute to this behavior. Reversible planar slip results in rough fatigue fracture surfaces. This has suggested the further contribution of roughness induced crack closure effects. While crack closure theory is being reevaluated [12], phenomena often attributed to crack closure

(a) 8.9 cm thick 2124-T851 plate.

(b) 2090-T8E41 plate.



(c) 8.9 cm thick 8090-T8771 plate.



(d) 9.1 cm thick 2197-T861 plate.

Figure 4. Short-transverse fracture surfaces.

have been observed - greater advantages in crack growth rate at low R values, and accelerated crack growth rates for short cracks. Fatigue crack growth resistance in 8090-T8771 plate was shown to be sensitive to specimen orientations between L-T and L-45° due to the strong crystallographic texture and varying orientation of favored slip planes with specimen orientation [13]. Crack growth rates in 8090 were also found to be accelerated by thermal exposure due to both a loss in slip planarity with overaging and the reduction in toughness [14]. These effects could ultimately confound fatigue life predictions, however fatigue crack growth rates are fairly insensitive to orientation in the more isotropic, thick 2197 plate, and modest thermal exposures that do not severely degrade toughness or begin to reduce strength have little effect on fatigue behavior.

Anisotropy. Crystallographic textures in Al-Li alloys tend to be much more intense than in other Al alloys. The effects are greatest in unrecrystallized products, although there is a strong relationship between a recrystallized texture and the prior, unrecrystallized texture. The intense texture has strong effects on mechanical properties: tensile properties are 15% or more lower in orientations 45°-60° from the rolling or extrusion direction; low fracture toughness in the high strength orientations; higher fatigue crack growth rates in the low strength orientations; and variations in elastic properties. Variability in texture through-the-thickness in plate, and variations with extrusion shape, result in further variability in these properties. These effects have caused unexpected problems in production programs and can sharply reduce potential weight savings. The intense textures develop during working operations, but the role of Li is not understood. Process parameters have been designed to minimize the through-thickness variability in plate. However, controlled processing alone cannot be expected to develop a more randomized texture in higher strength, unrecrystallized alloys. The work with 2197, which contains ancillary additions of both Mn and Zr, has indicated much smaller levels of anisotropy. This suggests that Mn may reduce the intensity of the texture, but a more detailed study is needed.

Thermal Stability. Loss in toughness after thermal exposure has been a key problem inhibiting the use of the early Al-Li alloys in many airframe applications. While predictable loss in tensile properties during service has often been accommodated in design, a loss in fracture toughness is not as manageable. Initially, some effects were anticipated with the use of underaged tempers to achieve an optimum combination of strength and toughness. Some increase in strength and concurrent loss in toughness could be expected with further aging at temperatures above about 120°C. Overaging accompanied by the growth of equilibrium precipitates at grain boundaries could also be expected to adversely affect toughness. But, large increases in strength and decreases in toughness were found after long-term thermal exposure to temperatures as low as 66°C [15]. The microstructural changes responsible for this behavior have been poorly characterized, however, precipitation of the T_1' phase may be responsible for the mechanical property changes after exposure to the lower temperatures [8]. The use of peak-strength tempers and lower Li concentrations has been effective in minimizing the loss in toughness after thermal exposure.

Summary

While there have been a number of important applications of the early alloys, 2090, 8090, and 2091, many application trials were unsuccessful. Important advances have been made in recent years in the development and commercialization of new Al-Li alloys. These have been optimized for specific classes of applications. The success of these efforts is largely due to a more mature understanding of the relationships among chemistry, microstructure, and mechanical behavior. They have exploited particular attributes of Al-Li alloys at the expense of acceptable tradeoffs in other properties. Optimizing the properties of 2090, 8090, and 2091 with alternate heat treatments or grain structures has been a less effective approach for many applications.

Al-Li alloys have been the subject of intense study. Nevertheless, there are many unanswered questions. Some of these are discussed below:

1. Since quench sensitivity depends strongly on solute concentration, solute limits should be optimized for specific gages. The effects of varying solute levels on quench sensitivity must be determined to establish appropriate limits.

2. Mn additions appear to reduce the levels of anisotropy in Al-Cu-Li-Zr alloys. This may be due to more uniform nucleation of T_1 as a result of the role of the Al_6Mn dispersoid particles in homogenizing deformation in the cold work applied after quenching. Or, the Mn-containing particles may play some role in modifying texture development. The effects need to be better quantified and understood.

3. Thermal stability is an important issue for applications in high speed aircraft. Microstructural changes after both long-term and short-term exposures to a range of temperatures need to be better characterized for different kinds of Al-Li alloys.

References

1. "Registration Record of Aluminum Association Designations and Chemical Composition Limits," The Aluminum Association (1993).
2. M.A. Phillips and S.R. Thompson, "The Mechanical Property Data Base From an Air Force/Industry Cooperative Test Program on Advanced Aluminum Alloys," (Air Force Final Report WL-TR-94-4014, 1993).
3. J.R. Pickens et al., Aluminum-Lithium Alloys, ed. T.H. Sanders, Jr. and E. A. Starke, Jr. (Birmingham, UK: MCEP, 1989), 1397.
4. J.R. Pickens et al., Proc. of the 1994 Conf. on Advanced Earth-to-Orbit Propulsion Technology, Huntsville, AL, May 17-19, 1994, to be published.
5. Aviation Week & Space Technology, March 7, 1994, 22.
6. M.H. Skillingberg et al., Light-Weight Alloys for Aerospace Applications II, ed. E.W. Lee and J.J. Kim (Warrendale, PA, USA: TMS, 1991), 17.
7. E.S. Balmuth, "Fatigue Properties of Al-2.7Cu-1.5Li Plate," 1993 AIME TMS Annual Meeting, Denver, CO (1993).
8. E.S. Balmuth and D.J. Chellman, "Alloy Design For Overcoming the Limitations of Al-Li Alloy Plate," this conference.
9. I.N. Fridlyander et al., Aluminium-Lithium, ed. M. Peters and P.-J. Winkler (Oberursel, Germany: DGM Informationsgesellschaft mbH, 1992), 35.
10. L.S. Kramer et al., "Weldalite® 050 Al Alloy Variant For Torpedo Hull Applications," (Naval Surface Weapons Center Report TR 92-43, 1992).
11. J.T. Staley et al., Met. Trans. 24A, (1993), 2417.
12. N. Louat et al., Met. Trans. 24A, (1993), 2225.
13. X.J. Wu et al., Met. Trans. 25A, (1994), 575.
14. K.T. Venkateswara Rao et al., Met. Trans. 24A, (1993), 2233.
15. C.D. Buscemi and E.S.C. Chin, Microstructural Science 16, (1988), 221.