

Improvements of Mechanical Properties in Aluminum-Lithium Alloys

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Abstract

The desire for more efficient aircraft materials has fueled research of aluminum-lithium alloys. There have been, and still are, obstacles in the development of these alloys. The addition of lithium results in beneficial characteristics but also presents undesirable properties. Thermal stability and weldability are discussed, and experiments regarding anisotropy and corrosion resistance are analyzed. Possible solutions to problems are presented, as well as how more recent aluminum lithium alloys have lessened undesirable properties.

Introduction

Lithium is an excellent alloying element in aluminum for several reasons. First, it is the lightest known metallic element.¹ With an atomic number of three, only hydrogen and helium are lighter. With every 1% addition of lithium to aluminum, there is a 3% decrease in density in the alloy.² Because these alloys are significantly lighter than other aluminum alloys, they are of great interest to aerospace industries.

The addition of lithium also increases the elastic modulus of aluminum. The elastic modulus refers to the resistance of a material to deformation when it is stressed. With every 1% addition of lithium, the elastic modulus increases about 6%.² This is because lithium results in precipitation hardening in aluminum. Because of this increase in stiffness and strength, less volume of the material is needed for similar structural components. Since the density of the alloys is also reduced and less material is needed, the total weight of a component can be reduced.

Only eight elements exceed a solid solubility of 1% in aluminum. Lithium is one of these, and only 3 elements exceed its solubility.¹ Though lithium does have a tendency to burn if exposed to excessive heat or time when being alloyed, it is relatively easy to alloy with aluminum.¹

History of Aluminum-Lithium Alloys

Because of these benefits offered by lithium, much research has been directed toward aluminum-lithium alloys. Research of Al-Li alloys began in the U.S. and Germany in the early 1920s.³ Several patents were given during this time, with most of the patented

alloys having high lithium contents. However, the alloys had such poor performance properties, they were never used commercially.

No major developments were made with the alloys until the late 1950's, when the Alcoa Corporation patented the 2020 alloy. This alloy contained 4.5% Cu, 1.2% Li, .5% Mn, .2% Cd, with the remainder aluminum.⁶ Some important mechanical properties of the alloy, compared to other conventional alloys, are given in Table 1. The table shows the 2020 alloys surpassed many other aluminum alloys in the five properties analyzed.

Table 1 Comparison of Al-Li alloy 2020 to conventional aluminum alloys¹

Alloy and Temper	Tensile Strength, MPa	Yield Strength, MPa	Elong., Pct.	Shear Strength, MPa	Endurance Limit (500 x 10⁶ cycles), MPa
X2020-T6	579	531	3	338	159
2024-T86	517	490	6	310	124
7075-T6	572	503	11	331	152
7079-T6	538	469	14	310	152
7178-T6	607	538	11	359	152

The 2020 alloy was used commercially by the Navy in the RA-5C Vigilante Mach 2 aircraft wings and stabilizers.³ The alloy had a lower fracture toughness than other aluminum alloys, yet it performed well on these aircraft. The 2020 alloy was also evaluated for other applications on aircraft but failed to meet requirements, resulting in no other commercial use. The 2020 alloy and the previous patented alloys are called the first generation aluminum-lithium alloys.

Interest in Al-Li alloys diminished for several decades until the 1973 oil crisis, when high fuel prices forced the airline industries to purchase fuel-efficient aircraft.¹ Again the possibilities of aluminum-lithium alloys were researched. Between 1980 and 1987, four international conferences regarding Al-Li alloys were held.¹ This research led to the second generation of alloys, including 2090, 2091, and 8090, among others.

The second generation alloys certainly had improved mechanical properties when compared to the first generation alloys. However, the properties still could not meet most aircraft specifications in thermal stability, corrosion resistance, anisotropy, and weldability, the properties discussed in this paper.

The 8090 alloy, the most successful of the second generation, was used in EH101 helicopters in Europe.⁴ The uses of the alloy in the helicopter in its various product forms are given below in Table 2. As the application column of this table illustrates, the alloy was used in significant structural components. Generally, if any second generation aluminum-lithium alloys were used in aircraft besides the EH101 helicopter, it was only for non-structural, light duty application.

Table 2 Application of Al-Li alloy 8090 products in the EH101 helicopter⁴

Product form	End use condition	Substitute for	Application
Sheet T81	Solution heat treated, quenched, controlled stretched and precipitation heat treated to an underaged condition	AA6068-T6 (BS L113) AA2024-T3 (BS L109) AA2024-T4 (BS L110)	– Forward fuselage lower structure, cabin side, outer skins – Rear fuselage skinning and stringers – Instrument panels, consoles, avionics cabinets – Gearbox fairing substructure – Sundry sheet metal parts, including superplastically formed sheet
Sheet T621	Re-solution heat treated by the user (for enhanced cold formability), quenched and precipitation heat treated to an underaged condition (same ageing parameters as for T81 temper)	AA6082-T6 (BS L113) AA2024-T4 (BS L110)	
Sheet T8	Solution heat treated, quenched, controlled stretched and precipitation heat treated to near peak aged condition	AA2014A-T6 (BS L157, L159, L165, L167)	
Sheet T6	Superplastically formed components	AA2024 (Assemblies) AA2007 (SPF parts)	
Extruded sections and tube T8511	Solution heat treated, quenched, controlled stretched and precipitation heat treated to a near peak aged condition	AA7075-T74511 (BS L160)	– Numerous standard profiles, e.g. T sections, C sections, F sections, cruciform sections – Hollow seat tracks and floor beams – Square cross-section tubes for instrument racking, conduits for cables and ladders – Over 40 different profiles used, mostly as 7000 mm lengths which are incorporated lengthwise in the main cabin
Die forgings T852	Solution heat treated, quenched, controlled stretched and precipitation heat treated to a near peak aged condition	AA7010-T7451 (plate to DTD 5130A)	– All structural frames in main cabin machines from AA8090 cold compressed die forgings. These include side frames, roof frames, intercostals and sides of main undercarriage box. A total of 16 different forging configurations are made from which 38 different components are machined per aircraft

After the 1990's, a third generation of Al-Li alloys were developed. Just as the second generation alloys built on the first generation, the third generation sought to resolve issues with the second generation. Table 3 lists alloys of all three generations, as well as their composition and developer. The differences between the second and third generation alloys will be pointed out and discussed below, after some of the issues with the second generation are analyzed.

Table 3 Three Generations of Al-Li alloys: Compositions and Developers⁵

	Li	Cu	Mg	Ag	Zr	Sc	Mn	Zn	Approximate Date
1st generation									
2020	1.2	4.5					0.5		Alcoa 1958
01420	2.1		5.2		0.11				Soviet 1965
01421	2.1		5.2		0.11	0.17			Soviet 1965
2nd generation (Li ≥ 2 pct)									
2090	2.1	2.7			0.11				Alcoa 1984
2091	2.0	2.0	1.3		0.11				Pechiney 1985
8090	2.4	1.2	0.8		0.11	0.17			EAA 1984
01430	1.7	1.6	2.7		0.11				Soviet 1980s
01440	2.4	1.5	0.8		0.11				Soviet 1980s
01450	2.1	2.9			0.11				Soviet 1980s
01460	2.25	2.9			0.11	0.09			Soviet 1980s
3rd generation (Li < 2 pct)									
2195	1.0	4.0	0.4	0.4	0.11				LM/Reynolds 1992
2196	1.75	2.9	0.5	0.4	0.11		0.35 max	0.35 max	LM/Reynolds 2000
2297	1.4	2.8	0.25 max		0.11		0.3	0.5 max	LM/Reynolds 1997
2397	1.4	2.8	0.25 max		0.11		0.3	0.10	Alcoa 1993
2198	1.0	3.2	0.5	0.4	0.11		0.5 max	0.35 max	Reynolds/McCook 2005
2099	1.8	2.7	0.3		0.09		0.3	0.7	Alcoa 2003
2199	1.6	2.6	0.2		0.09		0.3	0.6	Alcoa 2005
2050	1.0	3.6	0.4	0.4	0.11		0.35	0.25 max	Pechiney 2004
2060	0.75	3.95	0.85	0.25	0.11		0.3	0.4	Alcoa 2011
2055	1.15	3.7	0.4	0.4	0.11		0.3	0.5	Alcoa 2012

Except for aerospace, the use of aluminum-lithium alloys is not practical in many applications. The alloys are very expensive to produce, so the cost can be justified only when significant savings are involved or reduction of weight is necessary. NASA has

utilized the third generation alloy Weldalite 2195 for a U.S. Space Shuttle external fuel tank.² The reduced density was the primary reason for its use, but high strength was also needed, which the alloy provided.

If the alloys could be commercially used in aircraft, the savings in fuel consumption would financially help both the industry and passengers. Significant progress has been made in the development of the alloys, but the high standards of the aerospace industry continue to hinder their use. However, because of the considerable benefits offered by aluminum-lithium alloys, research will continue, and aircraft manufacturers may eventually use them to replace conventional aluminum alloys.

Issues with AL-Li Alloys

Several issues prevent widespread use of aluminum-lithium alloys as an aerospace material: thermal stability, corrosion resistance, anisotropy, and weldability.

Thermal Stability

Thermal stability, or the ability of a material to maintain its mechanical properties when aged, is one such issue.⁶ Aerospace applications have stringent regulations for thermal stability because of the fluctuating temperatures the materials encounter. There is no desire to increase the risk of flying by using a structural material that changes properties when it is in use.

All aluminum alloys have some thermal instability, but aluminum-lithium alloys tend to be more prone to it. Because lithium is relatively soluble in aluminum, a solid solution is formed. However, this solid solution is usually supersaturated and can easily decompose into a second phase (Al_3Li) when work-hardened or aged.⁷ When the solid solution decomposes, the properties of these alloys change, as shown in Figure 1. The graph in Figure 1 shows how the ultimate rupture strength, yield strength, and ductility in percent elongation change with time as the material (sheet Al-Li alloy 1464) is aged at 85°C. Both the yield and ultimate tensile strength increase with the low temperature aging, while the ductility decreases due to decomposition into a precipitation hardening phase.⁶

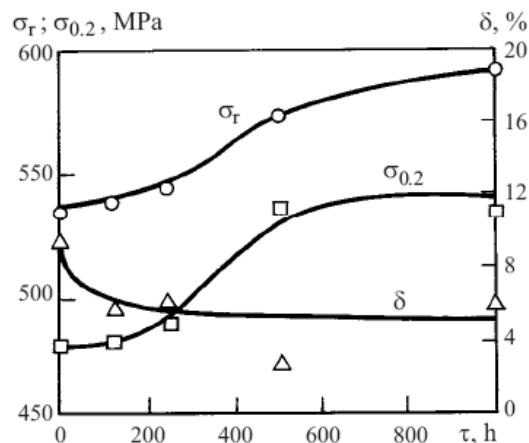


Figure 1 Ultimate rupture strength (σ_r), yield strength ($\sigma_{.2}$), and %EL of 1464 when aged at 85°C⁶

This type of low temperature (70-100°C) aging can easily occur on a part that becomes warm when in use. A component can reach these temperatures simply sitting in the sun. In high speed and space aircraft, components near the engines can also absorb enough heat to reach these temperatures. Aerodynamic heating, or heating due to friction with the air, can also cause this aging.⁶

Zakharov presents several potential methods for increasing the thermal stability of aluminum-lithium alloys.⁷ First, the content of lithium can be decreased. Doing this reduces the degree of supersaturation of lithium in the solid solution. This is beneficial because it results in the solid solution having more stability and less decomposition into a second phase containing Al_3Li . This phase results in precipitation hardening and therefore a drastic change in properties. Reducing the lithium content is the most effective method, but when the lithium content is decreased, the density is increased and the specific strength and modulus of elasticity of the alloy decrease. These three properties are the reasons for the development of aluminum-lithium alloys, so decreasing lithium content too much defeats the purpose of creating the alloys in the first place. The “first generation” of aluminum-lithium alloys had lithium contents from 1-2%, while most of the second generation alloys have lithium contents above 2%. Because of this, the second generation alloys tend to have less thermal stability than the first generation.⁷

Another method involves the heat treatment of the alloys. If the supersaturated lithium is taken out of the solid solution during manufacturing, then it cannot decompose during the use of the material. Since less decomposition into the second phase can occur during use, the mechanical properties will change less, and the thermal stability is increased. To get the supersaturated lithium to decompose during the manufacturing process, it is best to allow the metal to cool slowly from the aging temperature instead of quenching, allowing the Al_3Li phase to form.⁷ This improves the thermal stability, but the increase in the second phase decreases the ductility and fracture toughness of the material, which can be an issue and needs to be accounted for.

Corrosion Resistance

Corrosion resistance is a second critical factor in the development of aluminum-lithium alloys. First generation Al-Li alloys were susceptible to exfoliation corrosion.² However, the issue was improved with the second generation alloys. Exfoliation corrosion usually occurs along grain boundaries and results in “leafing” and pitting of the surface of the material, as shown in Figure 2. From a side view, exfoliation corrosion looks like flaky pie crust.

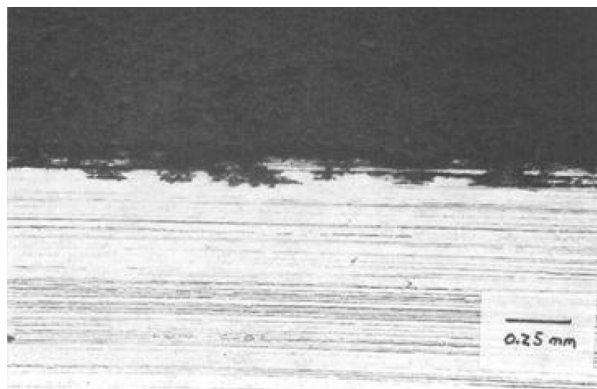


Figure 2 Side view of exfoliation corrosion⁸

Several tests are used to determine corrosion resistance. Laboratory tests include EXCO, MASTMAASIS, and SO_2 Salt Fog, which provide results quickly. The other method involves leaving the materials in varying environments over long periods of time, usually for years. Typically, these tests are performed aboard ships or near coastal areas. A study done by James Thompson uses both lab methods and shipboard exposure to evaluate the corrosion resistance of aluminum-lithium alloys.⁸

Thompson Experiment

Test Materials

The tested aluminum-lithium alloys were 2090-T8E41 and 8090-T851. For a comparison, the conventional aluminum alloy 7075 was tested in both the T651 and T7351 tempers. The received plates were 3 in. by 6 in. The plates were machined down to 1/10 thickness and 1/2 thickness, resulting in a step in the plate. The thickness and hardness of the plates of these materials are given in Table 4. After the plates were machined down, they were degreased with solvent, etched in sodium hydroxide for 3 minutes, rinsed in water, and dried with compressed air.

Table 4 Dimensions and hardness of tested specimens⁸

Material	Plane	Thickness		Hardness, Rb	Conductivity, %IACS ^a
		in.	mm		
7075-T651	T/0	1.00	25.4	91 90	32.0
	T/10	0.90	22.9		33.8
	T/2	0.50	12.6		
7075-T7351	T/0	1.00	25.4		39.9
	T/10	0.90	22.9		39.2
	T/2	0.50	12.6		
2020-T651	T/0	0.84	21.3	89 89.5	19.8
	T/10	0.77	19.6		20.2
	T/2	0.40	10.2		
2090-T8E41	T/0	0.50	13.0	86.5 89	17.1
	T/10	0.45	11.4		17.1
	T/2	0.25	6.5		
8090-T851	T/0	1.80	45.7	77 78	19.9
	T/10	1.64	41.6		20.0
	T/2	0.90	22.8		

Shipboard Exposure Procedures

Corrosion tests were performed on two different aircraft carriers and environments. The *U.S.S. Constellation* was traveling in the Western Pacific and Indian Oceans from February through September 1991. This included the monsoon season in that area. The *U.S.S. John F. Kennedy* was in the Mediterranean Sea for eight months. Weather reports measuring temperature and relative humidity were collected hourly on both ships.

One plate of each material was mounted onto cadmium-coated and painted steel racks using nylon bolts, nuts, and washers, to avoid contact with another metal. The rack placed the plates at a 45° angle, with the steps facing upward. These racks were attached to the radar towers about 9 feet above the deck.

Laboratory Testing Procedures

Of the corrosion tests mentioned, the EXCO corrosion test is the quickest, but does not imitate any typical environment. It involves submerging the material into nitric acid for 48 hours. In order to isolate the test just to the surface of the plate, a coat of beeswax was put on the edges.

The MASTMAASIS corrosion test intermittently sprays a solution containing acetic acid and sodium chloride. The test was done at 49°C and a 6 hour cycle was repeated. The cycle was 3/4 hr. of spray, 2 hrs. of drying, and a 3 1/4 hr. soak in the solution. This test was performed for four weeks and pictures were taken every week to analyze corrosion progress.

The SO₂ salt fog corrosion test is the closest imitation of a shipboard environment. The sulfur dioxide mimics the exhaust from fuel-burning ships and the salt spray represents ocean water spray. Sulfur dioxide is an acidifying agent because it forms sulfuric acid with water. The aluminum plates were mounted on acrylic racks in a testing chamber at 35°C and fogged with a sodium chloride spray and an injection of sulfur dioxide. The test took four weeks and pictures were taken every week.⁸

Results and Discussion

After all of the tests were completed, the plates were evaluated with a rating system specified by ASTM. This rating is not numerically measurable and involves the inspection of how severely corroded a material is. As this can insert opinion into the evaluation of the corrosion, eight judges were used. The results are in Table 5, which includes a key to interpret the abbreviations.

Table 5 Results from corrosion tests. N = no attack P = pitting EA = slight exfoliation EB = moderate exfoliation EC = severe exfoliation ED = very severe exfoliation⁸

Alloy	Plane	Constellation	Kennedy	EXCO	MAST	SO ₂
7075-T651	T/10	EA	N-P	ED	ED	ED
	T/2	EC	EB	ED	ED	ED
7075-T7351	T/10	P	P	EA	P	EA
	T/2	P	P	EA	P	EA
2020-T651	T/10	P-EA	N-P	ED	P	P
	T/2	P-EA	N-P	ED	P	P
2090-T8E41	T/10	P	P	ED	P	P
	T/2	P	P	ED	P	P
8090-T851	T/10	P-EA	^b	ED	P	P
	T/2	P-EA		ED	P	P

Shipboard Results

The aluminum-lithium test materials aboard the aircraft carriers never corroded to above EB, or moderate exfoliation. Overall, the specimens on the *U.S.S. Constellation* had more corrosion than those on the *U.S.S. Kennedy*. This demonstrates that the monsoon conditions, including high temperatures, high humidity, and rough seas, have a significant effect on corrosion when compared to the less corroded alloys exposed in the more moderate Mediterranean climate. The warmer temperature could have increased the reactivity of the lithium in the alloy, resulting in more corrosion when in contact with salt water. The high humidity slowed the drying process, resulting in more exposure to salt water. It should be noted that on both ships, the second generation aluminum-lithium alloy materials had less corrosion than the non-lithium 7075 alloy in the T651 temper. Pictures of the 7075 alloy in both tempers and 2090-T8E41 from aboard the *U.S.S. Constellation* are shown in Figure 3. The 8090-T851 alloy had corrosion similar to the 2090-T8E41 alloy, so it is not included in the picture.

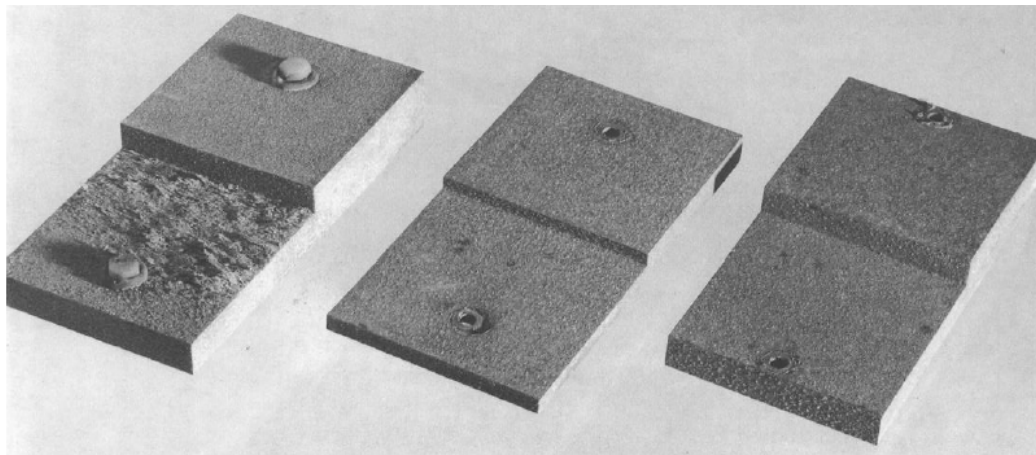


Figure 3 Pictures of 7075-T651(left), 2090-T8E41(middle), and 7075-T7351(right) after tests on board the *U.S.S. Constellation*⁸

Laboratory Results

The EXCO test is harsh and resulted in ED (very severe exfoliation corrosion) in all tested materials except the 7075-T7351 specimen. The results from this test give very little information on corrosion resistance, as no difference between the specimens could be determined.

Overall, the MASTMAASIS test did not result in corrosion as severe as the EXCO test. Only the 7075-T651 material had very severe exfoliation. Only pitting occurred in the other materials, a very mild corrosion in these tests.

In the most realistic test, the sulfur dioxide salt fog test, aluminum-lithium alloys clearly outperformed the conventional 7075 alloy. The 7075-T651 material again had very severe exfoliation corrosion whereas the 7075-T7351 material experienced only slight exfoliation. Neither of the Al-Li alloys experienced corrosion beyond pitting. The images of the 2090-T8E41 alloy from these three tests are in Figure 10.

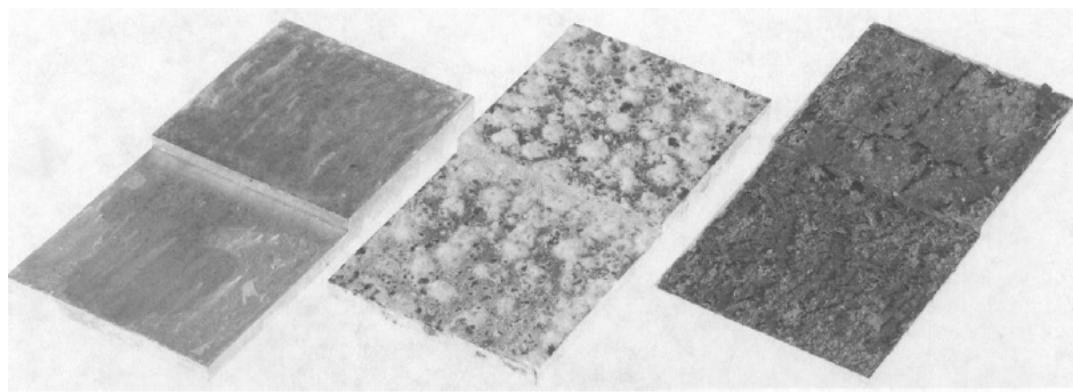


Figure 4 Pictures of 2090-T8E41 after salt fog (left), EXCO (middle), and SO₂ salt fog (right)⁸

Conclusion from Thompson Experiment

Most applications of aluminum-lithium alloys involve aircraft of some form. Many of these aircraft, especially military aircraft aboard aircraft carriers, will see saline environments. The shipboard tests in this experiment mimic these conditions. The only laboratory test that replicated shipboard exposure was the sulfur dioxide test. From these tests, it can be seen that susceptibility to corrosion has been reasonably resolved by the second generation Al-Li alloys. The results from this test show that the second generation alloys are actually more corrosion resistant than some of the widely used conventional aluminum alloys. Further development of these alloys should not need to consider corrosion resistance.⁸

Anisotropy

A third issue with the alloys is anisotropy. Anisotropy is the variance of mechanical properties of materials depending on how the material is oriented. In cold or hot rolled materials, the direction of orientation is in relation to the rolling direction.⁸ Because highly anisotropic materials are unpredictable, most industries have little interest in them. Aluminum-lithium alloys tend to have anisotropic behavior, complicating their use in the aerospace industry. An experiment conducted by Morrison and Allen looks into the anisotropy of strength and fracture toughness in two aluminum-lithium alloys.⁹

Morrison and Allen Experiment

Experimental Procedure

The Al-Li alloys of interest in this experiment were 8090-T8771 and 2090-T8E41. Two conventional aluminum alloys, 2024-T351 and 7075-T651, which are both widely

used in commercial airplanes, were also tested for comparison. The compositions of the aluminum-lithium alloys are given in Table 6. Their mechanical properties are given in Table 7; these were received from Alcoa Corporation, the provider of the materials. The material was rolled, although the exact amount or type of rolling work is not specified. The 8090-T8771 alloy plate was 12.5 mm thick, while the 2090-T8E41 plate was delivered in 15 mm plate.

Table 6 Composition of 8090 and 2090 Al-Li alloys tested in Morrison and Allen¹⁰

Material	Li	Cu	Mg	Fe	Si	Zr	Na
8090-T8771 12.5 mm plate	2.35	1.2	0.64	0.05	0.03	0.11	0.0005
2090-T8E41 15 mm plate (nom.)	1.9 - 2.6	2.4 - 3.0	≤0.25	≤0.12	≤0.10	0.08 - 0.15	-

Table 7 Mechanical properties of 8090 and 2090 Al-Li alloys tested in Morrison and Allen¹⁰

Material		0.2% Proof Stress MPa	UTS MPa	Elongation %	Toughness K _Q MPa√m
8090-T8771 12.5 mm plate	Longitudinal	508	555	5	31 (L-T)
	Transverse	479	548	8	28 (T-L)
2090-T8E41 15 mm plate	Longitudinal	559	595	5	-
	Transverse	586	617	7	-

The microstructures of the two plates are shown at 35x magnification in Figure 5. The 2090-T8E41 alloy had bands of unrecrystallized grains, while the 8090-T8771 alloy had flat elongated grains.

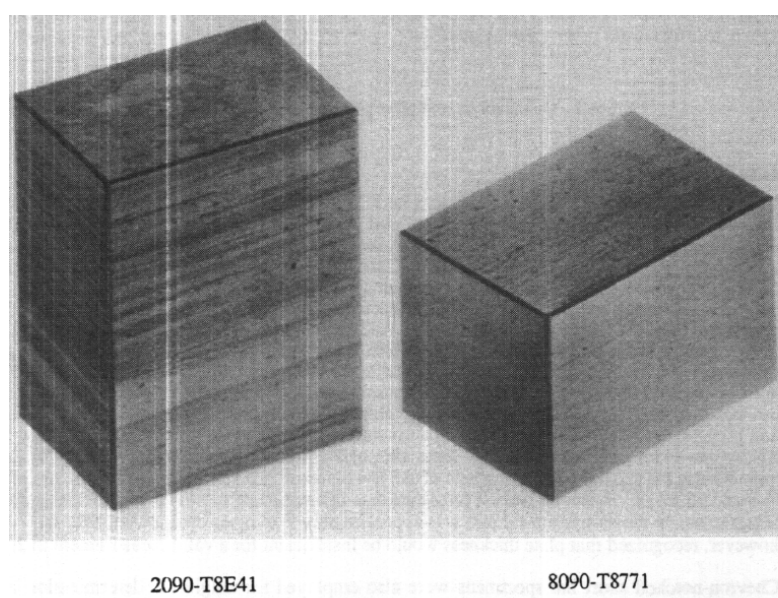


Figure 5 Microstructures of the Al-Li alloys¹⁰

For the tensile test, dogbone tensile pieces 6 mm thick, 13 mm wide, 6 mm wide at gauge length, and 25 mm long were cut out of the received plates. It was necessary to machine the plates down from their original thickness in order to have the specimens 6 mm thick. Two pieces were cut at each direction in relation to the rolling direction, starting at the longitudinal direction (0°) and moving clockwise at 30° intervals. This procedure is illustrated in Figure 6. The conventional aluminum alloys were cut only in the longitudinal and transverse (90°) direction, since less detailed data was desired from them. The specimens were then pulled using standard procedures at room temperature.

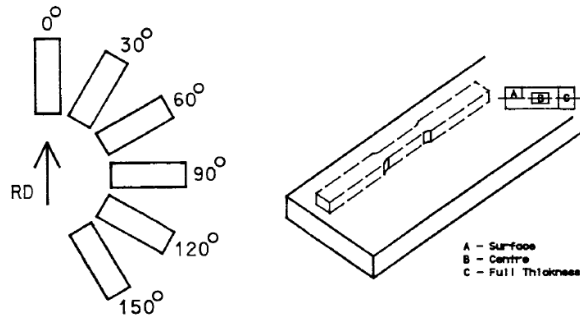


Figure 6 Directions tensile specimens were cut in relation to rolling direction (RD)¹⁰

The fracture toughness tests were done using a chevron-notched specimen and tested according to ASTM Standard E 1304. The fracture toughness specimens were cut in the same orientations as the tensile pieces, and four pieces in each direction were tested. This was to ensure that an average could be calculated to avoid the possibility of a severe data outlier. The pieces were 13mm square by 26mm long. They were chevron-notched as shown on the left side of Figure 7. Basically this was done by cutting out all but a triangle-shaped area that connected the specimen. The shaded triangle in the bottom view is the only area connecting the piece in the middle. The pieces were then pulled apart using the apparatus shown on the right side of Figure 7. The grips slowly pulled the piece apart, while the mouth opening gauge measured the displacement of the piece.

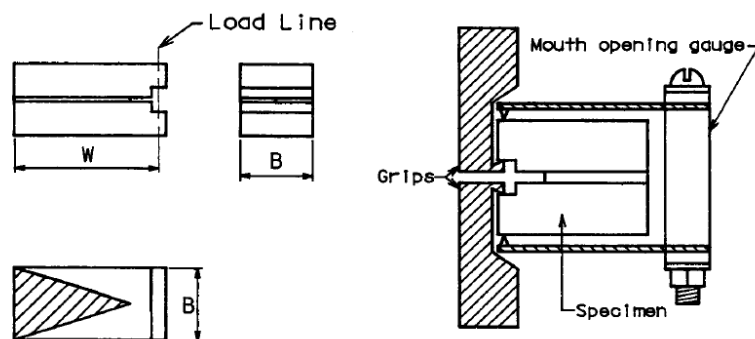


Figure 7 Profile of the fracture toughness specimen and testing apparatus¹⁰

Results and Discussion

Figure 8 contains the graph of the results from the Morrison and Allen tensile tests for both the 8090-T8771 and 2090-T8E41 alloys. Only the full thickness data points (triangles) need to be considered. For both alloys, the yield strength and ultimate rupture strength dipped at 60° and 120° from the rolling direction. The strengths were highest in the longitudinal direction (0°) and transverse direction (90°). The graphs illustrate the large amount of variance in strength which occurs in anisotropic materials. Overall, the 2090-T8E41 alloy was less anisotropic than the 8090-T8771 alloy.

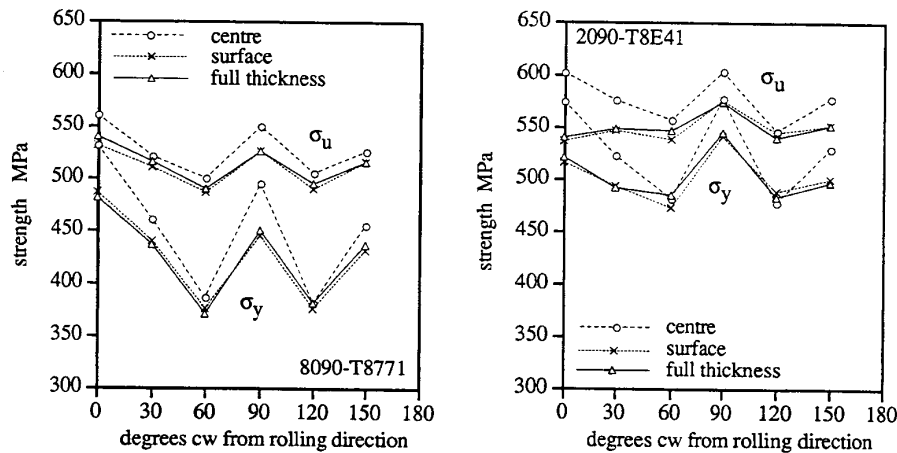


Figure 8 Ultimate tensile(σ_u) and yield strength(σ_y) of 8090 and 2090 Al-Li alloys as a function of orientation¹⁰

The graphs in Figure 9 relate percent elongation to rolling direction. The longitudinal direction experiences the least elongation, and the transverse direction had the second least ductility. The 60° and 120° directions had the most elongation, which corresponds to their reduced strength shown in the tensile tests.

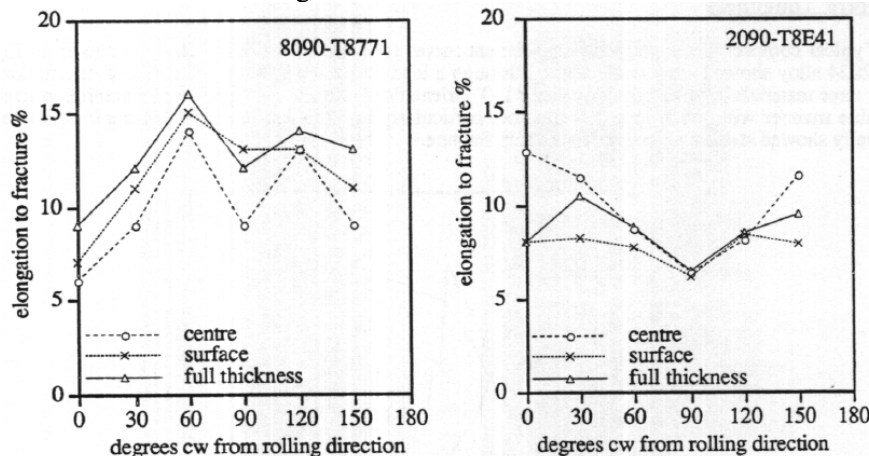


Figure 9 Percent elongation of 8090 and 2090 Al-Li alloys as a function of orientation¹⁰

The graph in Figure 10 shows the results from the fracture toughness tests. The 8090 alloy had higher fracture toughnesses than the 2090 alloy, but the graph shows that the 8090 toughness values had a much larger span than the 2090 alloy. The 8090 alloy fracture toughness value dropped close to $10 \text{ MPa}\sqrt{\text{m}}$ in the transverse direction, while the 2090 alloy showed less variance in toughness values. This means that the 2090 alloy is also less anisotropic in fracture toughness than the 8090 alloy.

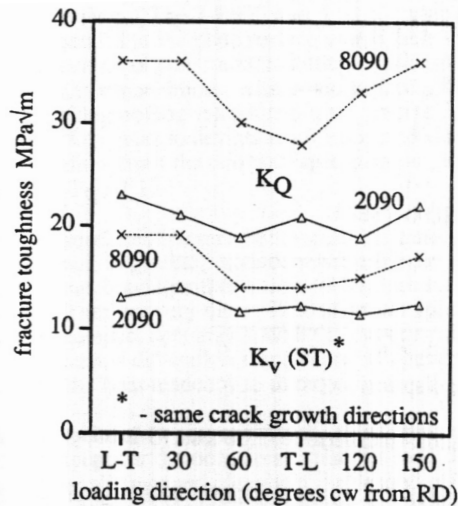


Figure 10 Fracture toughness values of 8090 and 2090 Al-Li alloys as a function of orientation¹⁰

Conclusions from Morrison and Allen experiment

This experiment exposes the issue of anisotropy in second generation aluminum-lithium alloys. The high degree of anisotropy in the 8090-T8771 alloy definitely would affect its application in industry. The 2090-T8E41 alloy had more acceptable anisotropic properties. Looking at some of the differences between the two alloys might suggest sources of anisotropy. The most drastic differences are in composition, as 2090 has less lithium and more copper, as shown in Table 6. There are also differences in content of trace element additions which are more difficult to analyze. These content differences result in different crystallographic textures and precipitate distribution, which affect anisotropy.¹⁰ Another possible source of anisotropy is heat treatment. The 2090 alloy was water quenched after a solution treatment, while the 8090 alloy was not. Also, the 2090 alloy was aged for less time. These differences result in different grain sizes and crystallographic textures, which are factors in anisotropy.¹⁰

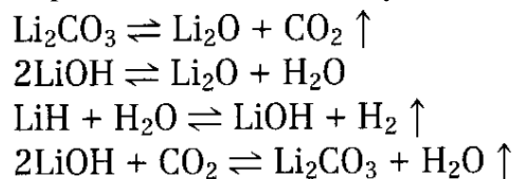
Weldability

The weldability of aluminum-lithium alloys is a fourth significant factor in their application in industry. Many methods of welding the alloys have been tested, including gas tungsten arc (GTAW), gas metal arc (GMAW), variable polarity plasma arc (VPPA), electron beam (EB), and laser beam (LB). None of these methods is flawless and all result in some degree of weakening of the welded joint and heat-affected zone (HAZ).¹¹ There are three reasons for this weakening. First, the heat results in the creation of pores in the HAZ. Also, aluminum-lithium welded joints have a high susceptibility to hot cracking, and the heat treatment of the joint and HAZ is altered by the high temperatures.¹¹

Porosity

Since lithium is a very reactive metal, the surface (as deep as .2 mm) of aluminum-lithium alloys can contain a large amount of various lithium compounds, including lithium carbonate, lithium hydroxide, and lithium hydride.¹¹ These compounds can decompose with heat and form different types of gases, shown in Table 8. If the gases created with the heat from welding are not able to escape the weld pool, they will form a pore inside the material. The bottom of the weld pool is very prone to this, as gases are not very mobile in that area.

Table 8 Lithium compounds found in Al-Li alloys and their decomposition¹¹



Since all of these compounds except lithium carbonate contain hydrogen, a general estimate of how much of these compounds are in the material can be made by measuring hydrogen content. The surface of the Al-Li alloys was found to have about five times as much hydrogen content as the center of the material.¹¹ This is illustrated in Figures 11 and 12. Figure 11 shows the microstructure of an Al-Li alloy from the side; the compounds near the surface are very visible. The graph in Figure 12 shows how the hydrogen content near the surface drastically increases, when compared to the rest of the material.

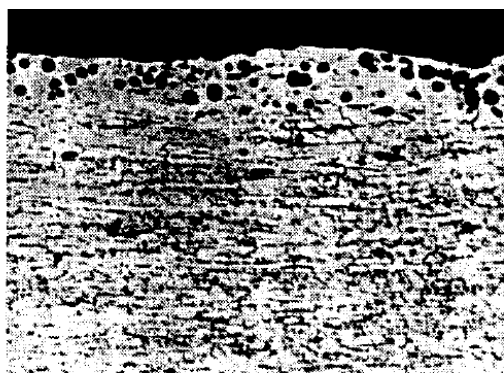


Figure 11 Side view of microstructure of Al-Li alloy 1420¹¹

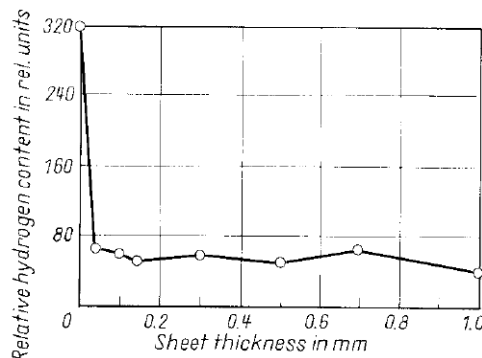


Figure 12 Relative hydrogen content dependence on depth in Al-Li sheet¹¹

To reduce the porosity of the welds, the surface (.2mm) of the material should be removed by either scraping or chemical etching, but this is not efficient.¹¹ The other option is to stir the weld pool to help expel the gases that form. This can be done with electromagnetic agitation or pulsating the welding arc. The variable polarity plasma arc (VPPA) welding method seems to do the best job in releasing gases.¹¹

Hot Cracking

The heat from the welding process exaggerates the somewhat brittle behavior of the alloys and causes the welds to crack.¹¹ Figure 13 shows a crack length contour map for several Al-Li alloys. The two axes represent magnesium and copper content of the alloy, and contour lines are drawn for specific crack lengths. Several aluminum alloys are also plotted to give an idea of their cracking susceptibility. As both copper and magnesium

content increase, the crack susceptibility decreases. However, both of these elements increase the density of the alloy, so only limited amounts can be added without overriding the density decrease given by lithium.

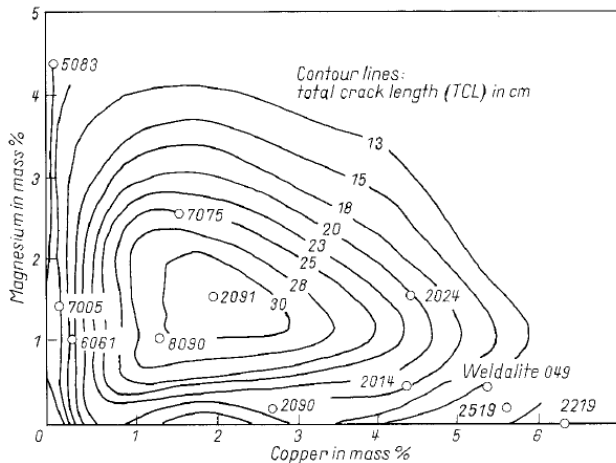


Figure 13 Crack length in relation to copper and magnesium content¹¹

The filler material used in welding also affects the crack susceptibility. Again copper content in the filler helps, and it is suggested that filler material should have not less than 12% Cu.¹¹ Popular filler materials also contain silicon, but the silicon reduces the ductility of the weld in Al-Li alloys, increasing cracking. Lithium has similar results to silicon when in the filler alloy, so it should be avoided in the filler. Overall, the filler should have high copper content, low silicon content, and no lithium content.¹¹

Weakening of Joints

Welding can reduce the strength of the heat affected zone (HAZ) up to 50%.¹¹ The heat from the weld often alters the thermal treatment of the material and basically anneals it. Figure 14 shows the HAZ of an Al-Li alloy after being gas-tungsten-arc welded. To reduce the width of the area that is heated during welding, a more precise welding technique is useful. Both electron beam (EB) and laser beam (LB) welding provide this. They use a very narrow, high power source to weld, and do not considerably heat the surrounding areas.¹¹

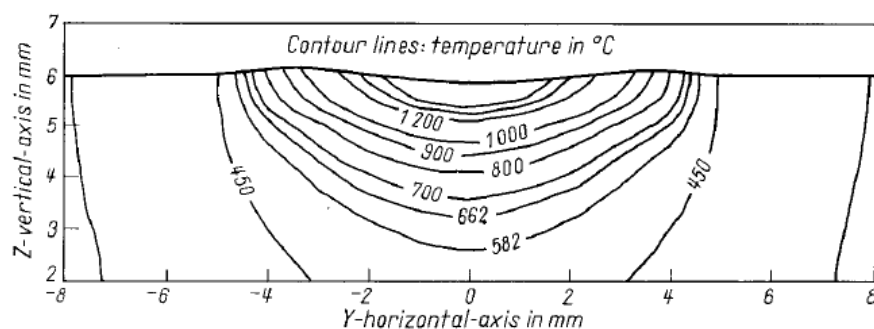


Figure 14 Distribution of heat nearby GTA weld¹¹

3rd Generation Alloys

The third generation Al-Li alloys includes the alloys developed from about 1990 to the present. These alloys built off the second generation alloys and improved many of the mechanical properties of Al-Li alloys. The four properties presented above are not the only characteristics that are considered. Two important others are fracture toughness and crack

deviation. The most important method in improving alloy characteristics is altering the composition of the alloy by increasing, decreasing, or adding alloying elements.^{5, 12}

By reviewing Table 3 in the Introduction, the general changes in composition between the generations can be seen. Since the properties of second generation alloys were discussed above, only a comparison between the second and third generations is needed to see how the third generation made improvements.

The most important composition change is in lithium. The lithium content is reduced considerably in the third generation alloys. This improves the anisotropy, fracture toughness, weldability, crack deviation, and thermal stability of the third generation.⁵ The maximum lithium content for the third generation is 1.8% in the 2099 alloy, and the optimal content is somewhere around 1.5%.⁵ Magnesium serves a similar purpose in aluminum as lithium. It decreases density and results in precipitation hardening.⁵ In the third generation, magnesium content was also decreased.

The copper content in the third generation did the exact opposite of lithium. Averaging all of the alloys listed in Table 3, the third generation had about a 1% increase in copper content over the second generation. Increasing the copper content does the same thing as decreasing the lithium content. Ductility is increased, resulting in better fracture toughness and crack deviation, and weldability and thermal stability are improved because of copper's heat tolerance.⁵ As magnesium does similar things as lithium in aluminum, silver additions result in similar properties as copper.⁵ None of the second generation alloys included silver, but 6 of the 10 listed third generation alloys contain silver additions.

Other trace element additions provide benefits to the alloys. Both zirconium and manganese are added to control the recrystallization and texture of the aluminum.⁵ Zirconium was added even in the first generation alloys and its content has stayed around .11% through all of the development. However, manganese was never included until the third generation alloys. An average of slightly over .3% is added to the third generation alloys. Even though the second generation alloys had reasonable corrosion resistance, improvements were still made. The addition of zinc increases strength and improves corrosion resistance, and the third generation alloys were the first to include the element.⁵

Conclusion

Aluminum-lithium alloys have been in development for over 90 years. The alloys have great potential in the aerospace industry, but strict regulations hold back their commercial use. The first and second generation alloys had substantial issues with mechanical properties, which resulted in very little use. The third generation alloys revised the second generation and have fewer mechanical property issues.

Because of the benefits and cost savings possible with the use of aluminum-lithium alloys, research and development will continue. Fine-tuning the composition and processing of the alloys will result in better alloys. If improvements continue to be made, aluminum-lithium alloys could replace conventional alloys completely.

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