Diploma Thesis

Evaluation of High Strength Al-Li and Al-Sc Alloys for the use in Cryogenic Launch Vehicle Feed Lines

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Graz, April 2014

Acknowledgement

An dieser Stelle bedanke ich mich bei allen, die mich bei der Erstellung dieser Diplomarbeit unterstützt haben!

Allen voran bei meinem Betreuer Rudi Vallant, der den Kontakt zur Firma Magna Steyr hergestellt und mir dadurch die Durchführung dieser Diplomarbeit erst ermöglicht hat, und mir während der Erstellung der Arbeit stets mit Rat und Hilfe zur Seite gestanden ist. Selbstverständlich auch beim Projektverantwortlichen bei Magna Steyr, Kurt Irnberger und allen Mitarbeitern, die an dem Projekt beteiligt waren und mich tatkräftig unterstützt haben.

Auch bedanken möchte ich mich bei meinen Kollegen aus dem Büro bei Magna Steyr, Karl-Hans und Oliver, die zwar nicht direkt in dieses Projekt involviert waren, aber trotzdem durch anregende Diskussionen und so manchen hilfreichen Hinweis zum Gelingen dieser Arbeit beigetragen haben.

Außerdem bei allen Mitarbeitern am Institut für Werkstoffkunde und Schweißtechnik an der TU Graz für die herzliche Aufnahme in die Institutsgemeinschaft und die fachliche Unterstützung die mir von allen entgegengebracht wurde. Ein besonderer Dank an Mustafa für die Hilfe im Kampf mit den Tücken des Textverarbeitungsprogramms.

Schließlich gilt mein ganz besonderer Dank meinen Eltern, die mir durch ihre moralische und auch finanzielle Unterstützung mein Studium erst ermöglicht haben.

Stefan Wakolbinger

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Graz, ………………………. ……………………………………..

Stefan Wakolbinger

Abstract

The take-off weight of a space launch vehicle influences the costs for the launch to a great extent. On the one hand, fuel can be saved by reducing the weight of the launcher; on the other hand, weight which is saved at the launch vehicle mass can be of use as additional payload. This is why reducing weight is quite important in developing future space launchers.

One way to contribute to this weight reduction is to replace the material of different components by ones of lower density without worsening properties of the parts. In best cases, the costs for a part decreases as well.

Since the beginning of space flight, aluminum alloys are used as material for structural parts. In this diploma thesis, the suitability of such alloys for the use as feed line material for launch vehicles is analyzed. As fuel for these launchers, liquid hydrogen and liquid oxygen are used. These substances exist at temperatures of 21 Kelvin, respectively 90 Kelvin, which causes special demands to a material.

In this thesis, particular attention is paid to Aluminum- Lithium and Aluminum- Scandium alloys, which were specially designed for aerospace applications, and show high strength at reduced density.

As starting point, a literature study was conducted, to determine the general suitability of the Aluminum alloys for the investigated purpose. Furthermore, potentially suppliers of the materials were consulted to gather information about actual availability of the alloys as well as guidance values according their costs.

Additionally, a comparison of weights was performed, to determine the influence of different material densities to the weight of the complete part. An FEM analysis was used to check the general suitability of the actual feed line design for Aluminum materials.

Finally, a utility analysis was conducted to weight and to combine the different properties of the different alloys. This way, the material was determined which brings out the best trade-off between the investigated options, and so is the best suitable one for our purpose.

Kurzfassung

Das Startgewicht einer Trägerrakete beeinflusst die Kosten für den Start wesentlich. Einerseits reduziert eingespartes Gewicht die benötigte Treibstoffmenge, andererseits, kann bei der Trägerrakete eingesparte Masse zusätzlich als Nutzlast mitgeführt werden. Bei der Entwicklung von zukünftigen Trägerraketen wird daher großer Wert auf die Reduzierung der Masse gelegt.

Dies erfolgt unter anderem in dem Bestreben, die Werkstoffe verschiedener Bauteile durch Materialien geringerer Dichte zu ersetzen, ohne dabei die Funktionsfähigkeit zu beeinträchtigen. Idealerweise ist das geänderte Bauteil zudem günstiger in der Herstellung.

So werden in der Raumfahrt seit ihren Anfängen Aluminiumlegierungen als Werkstoffe für Strukturbauteile eingesetzt. In der vorliegenden Diplomarbeit wird nun untersucht, ob sich Aluminiumlegierungen auch als Werkstoffe für Treibstoffleitungen von Trägerraketen eignen. Der Treibstoff für diese Raketen ist flüssiger Wasserstoff bzw. flüssiger Sauerstoff, der bei Temperaturen von 21 Kelvin bzw. 90 Kelvin vorliegt, was besondere Anforderungen an das Material stellt.

Besonderes berücksichtigt werden in dieser Arbeit Aluminium- Lithium und Aluminium-Scandium Legierungen, die speziell für den Einsatz in der Luft- und Raumfahrt entwickelt wurden und hohe Festigkeit bei gleichzeitig reduzierter Dichte aufweisen.

Beginnend wurde eine umfangreiche Literaturrecherche durchgeführt, um die grundsätzliche Eignung der Werkstoffe für den Einsatzzweck festzustellen. In weiterer Folge wurden Hersteller, und somit potentielle Lieferanten, für die Aluminiumlegierungen befragt, um Informationen zur tatsächlichen Verfügbarkeit und Lieferbarkeit zu erhalten, sowie Richtwerte für die Kosten der Materialien zu erheben.

Weiters wurde ein Gewichtsvergleich erstellt um den Einfluss von Legierungen verschiedener Dichte auf die Bauteilmasse darzustellen, sowie mit Hilfe einer FEM Analyse die Eignung des gegenwärtigen Leitungsdesigns für Aluminiumwerkstoffe überprüft.

Schließlich wurde eine Nutzwertanalyse ausgearbeitet, um die verschiedenen Eigenschaften der unterschiedlichen Legierungen zu gewichten und zusammenzufassen, und so das Material zu finden, das den ausgewogensten Kompromiss zwischen den verschiedenen Merkmalen darstellt und damit am besten für den Anwendungsfall geeignet ist.

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1 Introduction

In the year 2003, the European Space Administration (ESA) started the Future Launchers Preparatory Program (FLPP). Aim of this project is to help determine how Europe can maintain and strengthen its independent access to space in the long term. To do so, FLPP conducts system studies and research activities to bring up new technologies which are capable of delivering high performance and reliability, while reducing operational costs at the same time.

The major fields of the project include

- **Launchers -** various launch vehicle systems concepts are developed, and technologies required to make them possible are identified. On this basis, the decision for the character and design of the Next Generation Launcher (NGL) will be made.
- **Intermediate eXperimental Vehicle (IXV) -** a test vehicle to flight qualify several re-entry systems and technologies for space applications from future launchers to human transportation. [1]

Magna Steyr Aerospace, located in Graz, Austria, already manufactures feed lines for the actual ESA Launcher, the Ariane 5 rocket. Now the company engages in developing new feed lines for the upcoming NGL as part of the FLPP project. The development follows the major goal of the new feed lines to be more lightweight and of lower costs than the actual ones.

To fulfill this task, Magna Steyr researches three different material options. The first one is to use Carbon Fiber Reinforced Plastics (CFRP), the second one is to employ polyimides and the third one is to make the feed lines out of an aluminum alloy. After a basic study about the three material options concerning their usability for the application and an evaluation of their suitability as well as some actual material tests, a tradeoff between the three options is performed to find the most promising one with what the further development is pursued.

The basic study of the material option “aluminum alloys” was put out by Magna Steyr to the Graz University of Technology to be conducted as a diploma thesis, which the present work represents.

The thesis should determine the general suitability of aluminum alloys for the use in cryogenic feed lines, with emphasis on Aluminum-Lithium and Aluminum-Scandium alloys, which were especially developed for aerospace applications and stand out by high mechanical strength properties while maintaining low density.

1.1 Objective and Scope of the thesis

This diploma thesis was commissioned by Magna Steyr Aerospace to the Graz University of Technology, Institute for Material Science and Welding, to research the suitability of aluminum alloys for the use as material for cryogenic feed lines for space launch vehicles.

The objective of the work was to determine if aluminum alloys are applicable as material for cryogenic launch vehicle feed lines for the transport of liquid oxygen and liquid hydrogen. Special emphasis should be placed to aluminum- lithium alloys as well as aluminum-scandium alloys, which were developed for aerospace applications, where good mechanical properties coupled with low density at the same time are crucial. Additional, a tradeoff should be performed, to assess which one of the aluminum materials is most suitable for the regarded application, and thus is sent to the next level tradeoff between the different material groups of aluminum alloys, CFRP and polyimides.

Performing this task, at first a literature review concerning aluminum alloys in general and aluminum- lithium alloys and aluminum- scandium alloys in particular was conducted to gather information, and see if the materials are suitable for the intended purpose at all. Furthermore, more detailed information about some specific alloys which seemed to be promising after the first review was searched in literature. As a reference point on what to look for, a set of material requirements was given by Magna Steyr.

To deepen, verify and widen this background knowledge, in a next step manufacturers of aluminum alloys were contacted via telephone, email and also in personal. The information gathered this way were very interesting and helped on conducting this thesis a lot.

Additionally, a FEM analysis was executed to determine, if the actual line design is suitable for the use of aluminum materials. Also a comparison of weights was conducted, to identify the actual influence of different material densities to the line weight, which was strongly emphasized by the commissioning company in the first place.

Finally, to find the best choice of the aluminum alloys, a utility analysis was performed. The properties concerned in this analysis were basically given by Magna Steyr, but differed to the list of requirements given as starting point. As a result of the utility analysis, one material was chosen which was put into the continuative decision process by Magna Steyr.

1.2 Feed Lines for Rocket Propulsion Engines and Parts considered in this Thesis

In a space launch vehicle like the Ariane 5 rocket, plenty of different feed lines are built in. Sizes differing from small lines like control pipes for shift valves with diameter of about 20mm or even smaller, to fuel lines for the lower stage rocket propulsion engine with a diameter of about 180mm. Basically, this thesis should cover the suitability of aluminum for feed lines used in general, but when specific values were needed, a fuel line for an upper stage engine with diameter of 90mm as shown in Figure 1-1 was used as reference. In the left picture, an upper stage of an Ariane 5 rocket is shown. The right picture shows the feed line as it is delivered by Magna Steyr. The left line without thermal insulation, the right one with the thermal insulation attached.

As can be seen on the picture, the reference line consists of a straight tube, a bent tube, two flanges and two compensators which are located underneath the blue fixation cages. The fixation cages are a transport securing device and are not attached during operation. Purpose of the compensators is to balance longitudinal and angular movements in the line.

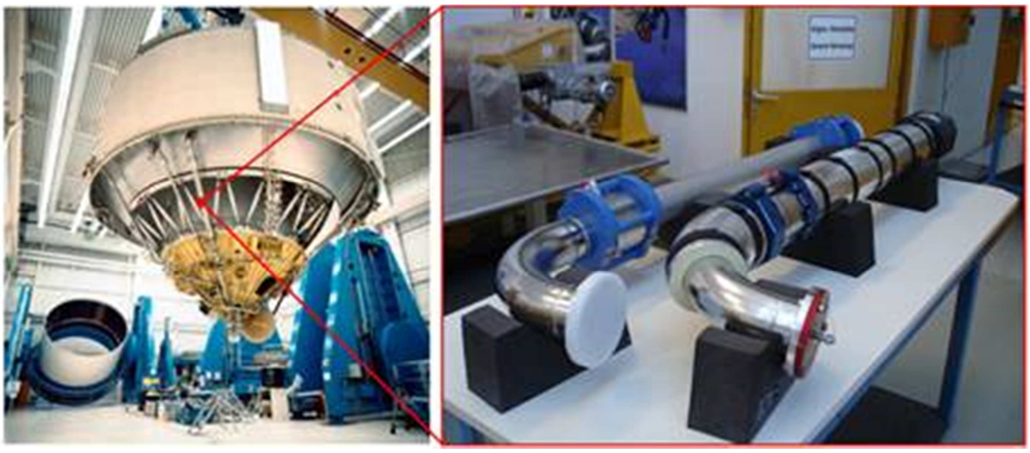


Figure 1-1 Fuel line of Ariane 5 upper stage engine, picture by Magna Steyr

This diploma thesis deals with the tube parts and the flanges of the feed line. Compensators are not considered in the first place.

Presently, the feed lines are made of an austenitic stainless steel. Straight parts are made of longitudinal seam welded and calibrated tubes, while the bent tube parts are manufactured out of two deep drawn half shells which are welded together. The flanges are milled out of the solid. For joining the parts, tungsten inert gas welding method is used. Compensators are bought in by a different company.

2 Literature Review- Materials Overview

In this chapter, a general overview about aluminum alloys and the aluminum alloy groups of the Al-Li system and the Al-Sc system and their potentials and shortcomings is given. Characterization of specific materials out of these groups is given in the chapters later on.

2.1 Classification of Aluminum Alloys

In general, aluminum products are arranged in two major groups. Wrought alloys and Cast alloys. Within these groups, the alloys are grouped by means of their main alloying elements. [2]

2.1.1 Wrought alloy series

According to the aluminum association, wrought aluminum alloys are designated by a four digit number with the first digit indicating the main alloying element. This system is used most in Europe and the United States. There is also a Russian designation system, which differs from the one named above and should not be confused with this, as it also uses four digit numbers, often prefixed by the numeral 0. [2]

2.1.1.1 1xxx series

The 1xxx series contains aluminum of a pureness of 99.00% or higher. Especially used for applications in the chemical or electrical fields. Alloys are characterized by high thermal and electrical conductivity, superior corrosion resistance and excellent workability on one hand, but low mechanical properties on the other hand. Strain hardening may enhance strength slightly. 1xxx alloys are used e.g. for reflectors, electrical conductors, packaging foil or decorative trim. [2]

2.1.1.2 2xxx series

The main alloying element in 2xxx aluminum alloys is Copper. Additional, there are several other alloying elements present in smaller amounts. To obtain optimum properties, these alloys need solution heat treatment. In this condition, mechanical properties are comparable to those of low carbon steels or even sometimes exceed them. Sometimes precipitation heat treatment (aging) can increase mechanical properties further. By this procedure yield strength is enhanced, but elongation behavior worsens. Tensile strength is not effected to a great extent.

2xxx alloys do not have as good corrosion resistance as most other alloys. Under certain conditions, they may also be affected by intergranular corrosion. To overcome this drawback, sheets of those alloys usually are clad with high purity aluminum or with an alloy of the 6xxx series to provide galvanic protection and so increases the resistance to corrosion of the core material.

Alloys of the 2xxx series are suitable for structural parts where strength to weight ratio is crucial. They are used e.g. for truck an aircraft wheels, vehicle suspension parts, aircraft skins and fuselage. Also for parts which require good strength at temperatures up to 150°C. Some 2xxx alloys have excellent machinability, but apart from some exceptions they have limited weldability by conventional welding methods. [2]

2.1.1.3 3xxx series

In this alloys, manganese is the major alloying element. Compared to pure aluminum, they have about 20% higher strength. 3xxx alloys are generally not heat treatable. Manganese is used only in a few alloys, as it can be added to aluminum only up to a limit of about 1.5%. 3xxx alloys are widely used for universal applications where good workability is needed at medium strength. Examples would be beverage cans, cooking utensils, storage tanks, traffic signs or architectural applications like roofing, siding or furniture. [2]

2.1.1.4 4xxx series

Silicon is the main alloying element in this alloy series. It is added in quantities up to 12% to lower the melting range without producing brittleness. Most of the alloys are not heat treatable. 4xxx series alloys are used as welding wire and as brazing alloys, where a low melting point is required. The silicon containing alloys change color to dark grey when anodic oxide finishes are applied, so they are in demand for architectural applications. Specific alloys have low coefficient of thermal expansion and good wear resistance and so are used for engine pistons. [2]

2.1.1.5 5xxx series

In 5xxx series, the major alloying element is magnesium. It produces medium to high strength work hardenable alloys, also in combination with manganese. Magnesium is way more effective as a hardener than manganese and also can be added in larger amounts. 5xxx series alloys are well weldable and have good resistance to corrosion in marine atmospheres. At operating temperatures above 65°C stress corrosion cracking can be an issue at alloys containing more than 3.5% magnesium. Applications of this alloy series are e.g. decorative trim, cans, household appliances, boats and ships, crane parts, cryogenic tanks and automotive structures. [2]

2.1.1.6 6xxx series

These alloys contain both magnesium and silicon to form magnesium silicide (Mg2Si) which makes the alloy heat treatable. The alloys have good weldability, formability, machinability and corrosion resistance at medium strength. Due to heat treatability, parts may be formed in T4 temper, and afterwards strengthened to T6 temper by precipitation heat treatment. Applications are e.g. bicycle frames, transportation equipment and welded structures. [2]

2.1.1.7 7xxx series

Major alloying element is zinc, which is added in amounts of 1 to 8%. When it is coupled with a small amount of magnesium, it results in heat treatable alloys of medium to very high strength. Usually, also copper, chromium and other elements are added in small amounts. High strength 7xxx alloys have only low resistance to stress corrosion cracking and so often are used in an overaged temper for a better balance of strength, corrosion resistance and fracture toughness. Applications of these alloys are airframe structures, mobile equipment and highly stressed parts. [3]

2.1.1.8 8xxx series

Alloys of the 8xxx series contain a several different elements. For use in aircraft, space structures and cryogenic applications, alloys containing lithium have been developed. [4]

2.1.2 Cast Alloy series

Aluminum cast alloys designations are not international standardized. The most common designation system is the one of the Aluminum Association which is consists of a three digit number, followed by a decimal point and the number 0, 1 or 2.

Designations in the form xxx.0 define composition limits for castings. Designations in the form xxx.1 and xxx.2 name composition of specific alloys in remelt ingot form, suitable for foundry use.

- 1xx.x Controlled unalloyed compositions
- 2xx.x Aluminum alloys containing copper as the major alloying element
- 3xx.x Aluminum- silicon alloys also containing magnesium and/or copper
- 4xx.x Binary aluminum- silicon alloys
- 5xx.x Magnesium as major alloying element
- 6xx.x Not in use
- 7xx.x Aluminum alloys containing zinc as major alloying element. Usually also containing other elements
- 8xx.x Aluminum alloys containing tin as major alloying element
- 9xx.x Not in use [4]

2.2 Strengthening mechanisms in Aluminum Alloys

Aluminum itself is a rather weak metal. It gets its strength by alloying elements and several treatments.

Aluminum alloys are distinguished in heat treatable alloys and non-heat treatable alloys. Some alloys respond to phase solubility based thermal treatment like precipitation or age hardening, quenching or solution heat treatment. These alloys are designated heat treatable alloys. On the other hand, some alloys only respond to work hardening through mechanical reduction, mainly in combination with different annealing processes for property development. These alloys are designated non-heat treatable alloys.

Heat treatable alloys are those that can be hardened by a controlled cycle of heating and cooling. Usually, the 2xxx, 6xxx and 7xxx alloys belong to this group of solution heat treatable alloys. This means, they can be strengthened by heating and following quenching. An additional strengthening by cold working, a controlled deformation at room temperature, might be possible. Heat treated conditions of aluminum alloys are called T-tempers.

Strength increase by heat treatment is quite high. For example aluminum alloy 2024 has in fully annealed condition an ultimate yield strength of about 186 MPa. By heat treatment, cold working and natural aging, this can increase by about 250% to 483 MPa.

On the other hand, formability is affected in the other direction with heat treatment. Usually, aluminum alloys are best formable in the softest O temper.

The other group of alloys which do not respond to an heat treatment but only can be strengthened by cold work, are called the non-heat treatable alloys. These are the 1xxx, 3xxx, 4xxx and 5xxx alloys. The initial strength of these alloys is provided by the hardening effects of their alloying elements. Additional strength can be added by cold working, a deformation at room temperature which induces strain hardening. Strain hardened conditions are usually named H-tempers.

Strength increase created by cold work is significantly in non-heat treatable alloys. For example the ultimate tensile strength of aluminum alloy 3003 is increased from about 110MPa in annealed condition to about 200MPa in strain hardened temper H-18 [2]

2.2.1 Temper designations of aluminum alloys

Just like the alloy designations, the appellations of the temper conditions are widely agreed in the western world, even if they are not codified in international engineer standards. The temper designations elaborated by the different aluminum producers are registered at the Aluminum Association [5] and commonly accepted.

The temper designation of an aluminum alloy follows the alloy designation and basically consists of an individual capital letter. If subdivisions of tempers are required, they are indicated by one or more digits following the letter. These digits identify specific sequences of treatments that produce specific combinations of characteristics of the aluminum product. If a further specification is desired, more digits are added. [2]

Temper designations are as following:

- F- As fabricated, no special treatment is applied, no mechanical property limits.
- O- Anealed condition, this designation applies to wrought products which are annealed to obtain lowest strength.
- H- Strain hardened, this products have been strain hardened, with or without additional thermal treatment to reduce strength. The H is always followed by two or more digits described later in detail.
- W- Solution heat treated, designation for an unstable temper, only used for alloys whose strength naturally changes over month or years after heat treatment. Further specification necessary.
- T- Solution heat treated, applies to alloys whose strength is stable within a few weeks after heat treatment. The T is always followed by one or more digits described later in detail.

Designations for Strain Hardened Products:

- H1- Strain hardened only, after strain hardening, no further thermal treatment is applied. Digits after H1 indicate the degree of strain hardening.
- H2- Strain hardened and partially annealed, these products were strain hardened to more than the desired strength, and then strength is reduced by annealing to the desired level. The digits after H2 indicate the degree of strain hardening that remains after annealing.
- H3- Strain hardened and stabilized, the products are strain hardened and mechanical properties are stabilized by a low temperature treatment or as a result of heat introduced during fabrication. Usually, ductility is improved by stabilization.

Designations for Heat Treatable Alloys:

- T1- Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition. These products are not cold worked after an elevated temperature shaping process and mechanical properties are stabilized by room temperature aging.

- T2- Cooled from an elevated temperature shaping process, cold worked and naturally aged to a substantially stable condition. These products are cold worked specifically to improved strength after cooling from a hot working process like extrusion or rolling.
- T3- Solution heat treated, cold worked and naturally aged to a substantially stable condition. Mechanical properties are stabilized by room temperature aging.
- T4- Solution heat treated and naturally aged to a substantially stable condition. These products are not cold worked after solution heat treatment, mechanical properties are stabilized by room temperature aging.
- T5- Cooled from an elevated temperature shaping process and artificial aged. These products are not cod worked after an elevated temperature shaping process; mechanically properties are improved by precipitation heat treatment.
- T6- Solution heat treated and artificial aged. The products are not cold worked and mechanical properties are improved by precipitation heat treatment.
- T7- Solution heat treated and overaged or stabilized. These products are precipitation heat treated beyond the point of maximum strength to achieve special characteristics like resistance to stress corrosion cracking od corrosion.
- T8- Solution heat treated, cold worked and artificial aged. Strength is improved specifically by cold working after solution heat treatment and mechanical properties are improved by precipitation heat treatment.
- T9- Solution heat treated, artificial aged and cold worked. Cold working is applied after precipitation heat treatment to improve strength.
- T10- Cooled from an elevated temperature shaping process, cold worked and artificial aged.

Specific variations of the ten major temper grades are assigned by additional digits. [2]

2.2.2 Strengthening mechanisms

In aluminum alloys, different mechanisms are employed to increase properties like strength, hardness, resistance to wear, creep, stress relaxation or fatigue. These mechanisms depend, among others, on alloying elements, microstructures of solidification, thermomechanical history, heat treatment and cold working. To a large extent, these factors depend on whether the alloy belongs to the heat treatable or the non-heat treatable alloys.

2.2.2.1 Non-Heat Treatable Alloys

In non-heat treatable alloys, strengthening bases on solid-solution formation, second phase microstructural constituents, dispersoid precipitate and strain hardening. This applies mainly to alloys of the 1xxx, 3xxx, 4xxx and 5xxx groups.

For those elements that form solid solutions, the strengthening effect increases with difference in the atomic radius of aluminum and the alloying element. Manganese would be an example of an alloying element that works highly effective in this way.

Strength and hardness is also increased by increasing volume fractions of intermetallic compound phases (second phase constituents) formed by elements with relatively low solid solubility like iron, nickel, titanium, manganese or chromium. These second phase constituents are formed during solidification or by precipitation in the solid state during postsolidification heating.

Additions of manganese or chromium allow the formation of complex precipitates that inhibit grain growth and also assist in grain refining during rolling. This process involves the formation of a supersaturated solid solution, which is produced by rapid solidification and cooling during casting of the ingots. When the ingots are reheated for wrought processing, the supersaturated metastable solid solution causes solidstate precipitation of complex phases. These phases do not enhance strength itself, but they produce finely divided and dispersed particles that inhibit recrystallization and grain growth during subsequent heating.

Strain hardening by drawing, cold rolling or stretching also increases strength in non-heat treatable alloys very effective. This increase in strength is on the expense of reduction of formability and ductility.

2.2.2.2 Heat Treatable Alloys

In heat treatable alloys, also precipitation and ageing mechanisms contribute to mechanical properties. Heat treatment for precipitation strengthening includes a solution heat treatment at high temperature to maximize solubility, and afterwards quenching or rapid cooling to get a solid solution, supersaturated with solute elements as well as vacancies. The high strength is produced by finely dispersed precipitates which form during aging heat treatments. During the precipitation process, the saturated solid solution develops solute clusters, which causes a lot of strain due to size mismatch of solute and solvent atoms. These clusters stabilize dislocations as they trap or anchor them, and so considerably strengthen and harden the alloy.

Aging can happen naturally at room temperature over a time period of days or weeks (natural aging), or it is stimulated artificially by exposing the material to a temperature above room temperature (artificial aging), so metastable forms of the equilibrium precipitates of a particular alloy system are produced. These metastable precipitates remain coherent with the solid solution matrix and so contribute to precipitation strengthening. When further heated, the precipitate particles grow and convert to equilibrium phases which are not coherent. These processes soften the material and further lead to the annealed condition, which is the softest one.

In Table 2-1, some material properties and microstructural features which contribute to them are listed.

Table 2-1 Property microstructure relationships in aluminum alloys [6]

Property	Desired microstructural feature(s)	Function of feature(s)
Strength	Fine grain size with a uniform dispersion of small, hard particles	Inhibit dislocation motion
Ductility & toughness	Fine structure with clean grain boundaries and no large particle or shearable precipitates	Encourage plasticity and work hardening, inhibit void formation and growth
Creep resistance	Thermally stable particles within the matrix and on the grain boundaries	Inhibit grain boundary sliding and coarse microstructure
Fatigue crack initiation resistance	Fine grain size with no shearable particles and no surface defects	Prevent strain localization, stress concentrations, and surface slip steps
Fatigue crack propagation resistance	Large grain size with shearable particles and no anodic phases or hydrogen traps	Encourage crack closure, branching, deflection and slip reversibility
Pitting	No anodic phases	Prevent preferential dissolution of second phase particles
Stress corrosion cracking & hydrogen embrittlement	Hard particles and no anodic phases or interconnected hydrogen traps	Homogenize slip and prevent crack propagation due to anodic dissolution or HE

2.3 Influence of alloying elements on aluminum alloys

2.3.1 Copper

Aluminum-copper alloys containing 2 to 10% Cu, generally with other additions, form important families of alloys. Both cast and wrought aluminum-copper alloys respond to solution heat treatment and subsequent aging with an increase in strength and hardness and a decrease in elongation. The strengthening is maximum between 4 and 6% Cu, depending upon the influence of other constituents present. The properties of aluminum-copper alloy sheet in a number of thermal conditions are assembled in Fig. X. The aging characteristics of binary aluminum-copper alloys have been studied in greater detail than any other system, but there are actually very few commercial binary aluminum-copper alloys. Most commercial alloys contain other alloying elements. [3]

Aluminum- Copper alloys respond to solution heat treatment and subsequent aging with an increase in strength and hardness and a decrease in elongation. The strengthening maximum is between 4% and 6% Copper, depending on other alloying elements. [3]

Usually, commercial alloys of the Al-Cu-Li system contain about 1 to 2.5% Li and 2.5 to 5.5% Cu. Small additions of Zr, Mn or Cd are also common. The addition of copper decreases the solid solubility of Li in aluminum. [7]

2.3.2 Copper- Magnesium

Adding Magnesium to Aluminum- Copper alloys brings the possibility of solution heat treatment and quenching, and so an increase in strength. In some wrought material of this type, this increase in strength can come along with high ductility on ageing at room temperature. A further increase in strength can be reached by artificial aging, yet this brings also a loss in tensile elongation.

Already an addition of 0.5% Magnesium is sufficient to change the aging characteristics of Aluminum- Copper alloys. The Effect of strengthening of Mg additions can be maximized by cold working prior to artificial aging. In naturally aged materials, cold working can decrease the strengthening effect of magnesium addition. The effect of magnesium on the corrosion properties depends on the type of product.

2.3.3 Copper- Magnesium and other elements

Iron in concentrations as low as 0.5% lowers the tensile properties in heat treated condition if there is not enough silicon to tie up the iron to FeSi. In this case, Cu2FeAl2 is formed, which reduces the amount of Copper available for the strengthening mechanism. Silicon also forms Mg2Si with Magnesium which contributes to the age hardening process.

Silver improves the strength of heat treated and aged Al-Co-Mg alloys. Nickel increases strength and hardness at elevated temperatures but can lower tensile properties at room temperature.

Manganese alloys belong to the most important commercial alloys of the Aluminum Copper Magnesium system. In general, tensile and yield strength increases with amount of manganese and magnesium. The effect can be seen in the Figure, showing the tensile properties of an alloy containing 0.5% Mg. Cold working after heat treatment can increase strength furthermore. On the other hand, the addition of magnesium and manganese to the alloy causes a decrease in the fabricating characteristics and manganese lowers the ductility of the alloy. Therefore usually not more than 1% of this element is added to the alloy. [3]

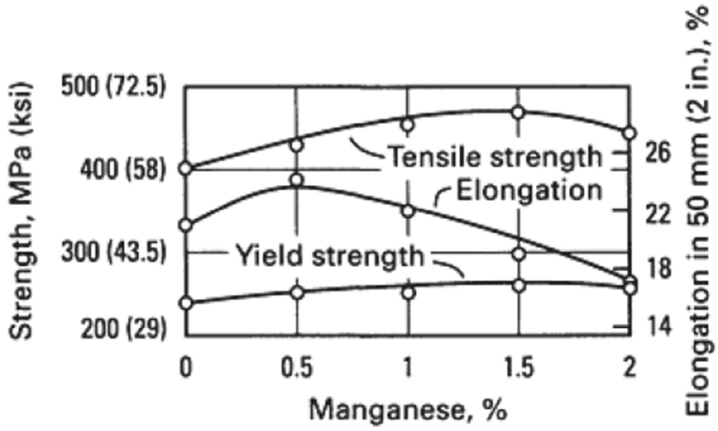


Figure 2-1 Effect of Manganese addition on Strength and Elongation [2]

2.3.4 Minor additions to Copper

Small amounts of several metals, specifically manganese, titanium, vanadium or zirconium, are known to raise the recrystallization temperature of Aluminum alloys. These alloys are known to have good welding properties. [3]

2.3.5 Magnesium

Magnesium is the main alloying element of the 5xxx aluminum alloy series. Usually, the amount of Mg does not exceed 5.5%, although the maximum solubility in aluminum would be 17.4%. Magnesium increases the strength of Aluminum without decreasing ductility too much. Alloys have good weldability and corrosion resistance. On the other hand, magnesium produces susceptibility to intergranular cracking and stress corrosion, as it precipitates at grain boundaries as Mg5Al3 or Mg5Al8, a highly anodic phase. [3]

2.3.6 Manganese

Strength increase from addition of Manganese works by solid solution or as finely precipitated intermetallic phase. There is no harmful effect on corrosion resistance. Manganese has a small solid solubility in Aluminum, but it stays in solution when chill cast, so that most of the Manganese added is kept in solution. Manganese is added to increase strength and to control grain growth. An effect of Manganese is to rise the recrystellization temperature. As a disperse precipitate it is slowing recovery and inhibiting grain growth. Manganese increases the quench sensitivity of the alloys. The effect of Manganese to strength and elongation is displayed in Figure 2-1 [3]

2.3.7 Magnesium-Manganese

The Magnesium- Manganese system has high strength in the work hardened condition, good welding properties and high resistance to corrosion. Increasing amounts of one of these elements make the fabrication processes more difficult. A main advantage of combining this two alloying elements is that precipitations of magnesium is more general throughout the structure when manganese is added. For a needed increase in strength, the addition of manganese allows a lower content of magnesium and ensures a more stable alloy. [3]

2.3.8 Iron

Iron has a high solubility in liquid Aluminum and a very low one of about 0.04% in solid state. Hence, the amount of Iron exceeding this value appears as an intermetallic second phase, as well as in combination with Aluminum, but also often in combination with other elements.

The grain size of wrought products is reduced by Iron [3], but as well as Silicon it forms coarse constituents in 2xxx, 7xxx and 8xxx alloys, which leads to a lower fracture toughness and has harmful effects on fatigue crack initiation and fatigue crack growth resistance. So to achieve a good balance of strength, fracture toughness and fatigue growth resistance, low content of Iron and Silicon, tight control of composition and a good understanding of the complex phase diagrams are necessary. [6]

2.3.9 Zirconium

In the range of 0.1 to 0.3%, Zirconium additions are added to form a fine precipitate of intermetallic particles to inhibit recovery and recrystallization. A number of alloys use zirconium additions to increase the recrystallization temperature and to control the grain structure in wrought products. [3]

Zirconium is one of the most common small additions in commercial Al-Li alloys. The interaction between Al, Li, and Zr during precipitation from the supersaturated solid solution affects the properties and structure formation of commercial Al-Li alloys to a great extent. Most effort in research of the Al-Li-Zr system is made concerning the metastable phase formed during rapid solidification, cubic Al_3Zr, and during decomposition of the supersaturated solid solution, cubic Al_3Zr and Al_3Li. As already trace amounts of Zr cause the formation of primary Al3Zr particles, Zirconium is a promising grain refiner. The solubility of Zr in Al is considerable decreased as Lithium is added to the alloy. [7]

Experiments conducted with two alloys similar to 2090, differing only in the content of Zr, and examining its influence concerning fatigue strength showed, that strength increases remarkable with the content of Zr, as this element works as a grain refiner [8].

Figure 2-2 shows that fatigue strength of Al-Li-Cu-Mg-Zr alloys increase, when the temperature is decreased.

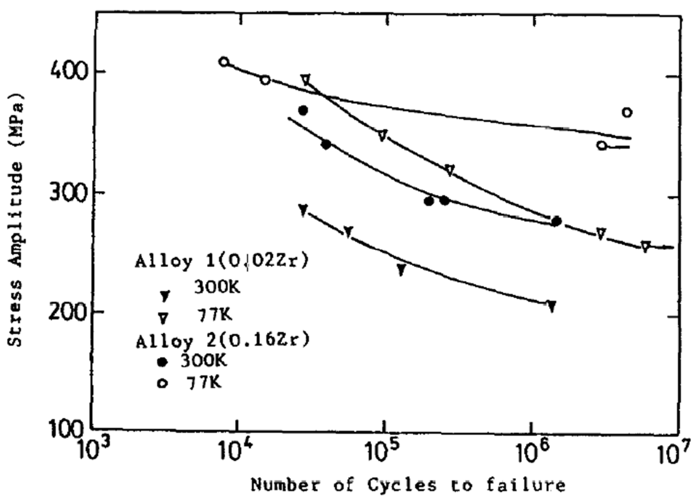


Figure 2-2 Fatigue curves of Al-Li-Cu-Mg-Zr alloys fatigued at 300K and at 77K [8]

2.3.10 Scandium

Inhibition of recrystallization, scandium increases the recrystallization temperature of aluminum to more than 600°C. Scandium additions of 0.2 to 0.6 weight % are most effective, in strengthening. [9]

The effect of Scandium is described in detail in the corresponding chapter.

2.4 Aluminum-Lithium Alloys

Alloying Lithium to Aluminum is a response to the demand of light, stiff and high-strength materials in aerospace, aircraft and automotive industries. This kind of alloys is under development since the 1950s. Lithium is the lightest metallic element. Each weight percent of it added to aluminum decreases its density by 3% and increases the modulus of elasticity by 5-6%. Also tensile strength increases with the addition of Lithium almost linearly. Aluminum-Lithium alloys show excellent fatigue and cryogenic properties. In Table 2-2 typical physical properties of aluminum-lithium alloys are listed. [7] [10]

Table 2-2 Typical physical properties of selected aluminum-lithium alloys [10]

Property	2090	2091	8090
Density, g/cm^3 (lb/in.^{3})	2.59 (0.094)	2.58 (0.093)	2.55 (0.092)
Melting range, °C (°F)	560–650 (1040–1200)	560–670 (1040–1240)	600–655 (1110–1210)
Electrical conductivity, %IACS	17–19	17–19	17–19
Thermal conductivity at 25 °C (77 °F), W/m · K (Btu · in./ft^2 · °F · h)	84–92.3 (580–640)	84 (580)	93.5 (648)
Specific heat at 100 °C (212 °F), J/kg · K (cal/g · °C)	1203 (0.2875)	860 (0.205)	930 (0.22)
Average coefficient of thermal expansion from 20 to 100 °C (68 to 212 °F), μm/m · °C (μin./in. · °F)	23.6 (13.1)	23.9 (13.3)	21.4 (11.9)
Solution potential, mV(a)	−740	−745	−742
Elastic modulus, GPa (10^6 psi)	76 (11.0)	75 (10.9)	77 (11.2)
Poisson's ratio	0.34	...	...

(a) Measured per ASTM G 60 using a saturated calomel electrode

2.4.1 Development of high strength Al-Li alloys for aircraft and space applications

Aluminum Lithium Alloys are in service since the 1950s. Since then, remarkable improvements in the properties of these alloys have been made. Not only strength, probably the most obvious performance indicator, also durability properties like corrosion and fatigue resistance as well as damage tolerance values like residual strength and fatigue crack growth have enhanced. These often determine the size and weight of an aircraft or spacecraft component. [11]

2.4.1.1 First generation alloys

Concerning time of development, Al-Li alloys are commonly divided in three generations. Materials developed before the 1970 are called first generation alloys. Although first trials of adding Lithium to Aluminum are reported already in the 1920s, the first application in aircrafts was in 1958, as 2020 plate material was used in American Navy airplanes. In the following years, also Russia developed Al-Li alloys like 01420 and 01421, which have been used in Russian aircraft building. [11]

2.4.1.2 Second generation alloys

Second generation alloys are called the ones engineered in the 1970s and 1980s. At this time, the aim of developing new alloys was to replace existing wrought material gauge by gauge, with the objective of reducing weight by finding materials of lower density. These efforts were made by American and European as well as Russian companies. Alcoa for example developed alloy 2090 in different tempers for extrusion, plate and sheet material, which was aimed on replacing aluminum alloy 7075. French company Pechiney focused on finding replacements for 2024 sheet and thin plates, and developed alloy 2091. Also The British Aerospace Establishment developed a substitute for alloy 2024 and manufactured alloy 8090. This material was in different tempers also used for space applications.

Russia made their own versions of these new alloys and developed for example 01430, which is similar to 2091, 01440 which is like 8090, or 01450 and 01460 which are similar to alloy 2090.

The second generation Aluminum-Lithium alloys in general show a concentration of Lithium of more than 2 percent. Although this amount provides quite low density, which was the focus of their development, it also brings some characteristics which are undesirable in the aerospace engineering.

On the plus side, these alloys showed a density reduction of about 7% to 10%, higher modulus of elasticity of about 10%to15% and lower fatigue growth rates, which means a higher fatigue life.

On the downside, fracture toughness is lower in short-transverse direction, plane stress fracture toughness/residual strength is lower and the tensile properties in general show highly anisotropic behavior. [11]

2.4.1.3 Third generation alloys

To overcome these shortcomings, in further developments since the 1990s, the content of lithium was reduced to about 0.75% to 1.8%. Alloys developed were 2195, 2196, 2297, 2397, 2198, 2099, 2199, 2050, 2060 and C99N. These materials were researched and developed for aircraft and space applications. They are referred to as third generation alloys. In Table 2-3, the nominal composition of some key Al-Li alloys are listed. [11]

Table 2-3 Nominal Composition of Key Al-Li Alloys [11]

	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

Design principles in development of 3rd generation alloys

With deeper Understanding of the influence of the chemical composition and the microstructure on mechanical and corrosion properties, optimization of alloying elements and thermo mechanical processing was possible. In developing the 3rd generation alloys, following alloying elements were involved.

- Li and Mg for density reduction and solid solution and precipitation strengthening
- Cu and Ag for solid solution and precipitation strengthening
- Zn for solid solution strengthening and corrosion improvement
- Zr and Mn for recrystallization control and texture
- Fe and Si as impurities affecting fracture toughness, fatigue and corrosion
- Ti as a grain refiner during solidification
- Na and K as impurities affecting fracture toughness.

Precipitates involved in strengthening are Al_2CuLi (T_1), Al_3Li (δ') and Al_2Cu (θ'-type). Addition of Mg and Ag leads to formation of precipitates that are isomorphous and isostructural with the T_1 phase, where Mg substitutes Li, and Ag substitutes Cu. This leads to Al_2(Cu-Ag)(Li-Mg) stoichiometry and atomic arrangements. The θ'-type precipitates are thought to be isomorphous and isostructural to the θ' precipitates in the Al-Cu system. To control texture and recrystallization in wrought products, in most 3rd generation Al-Li alloys form Al_3Zr and $Al_{20}Cu_2Mn_3$ dispersoids. Fe forms Al_7Cu_2Fe, an insoluble crystal structure in the presence of Cu. As this phase affects fracture toughness and fatigue adversely, it is minimized as possible.

Strength and fracture toughness is highly improved by cold deformation like stretching, cold rolling, and so on, prior to aging. This is because cold deformation refines the precipitate microstructure and reduces precipitation at grain boundaries during aging. The strengthening and toughness increasing effect of cold work prior to aging is due to the propensity of T_1 phase to nucleate at dislocations. The cold work increases the number of T_1 precipitates by about two orders of magnitude. [11]

2.4.1.4 Classification concerning main alloying elements

There are three main groups; commercial Aluminum-Lithium alloys are roughly divided in. Al-Cu-Li alloys as e.g. 2090, 2020 or VAD23 (Russian designation), Al-Mg-LI alloys like 01420 (Russian) and Al-Li-Cu-Mg alloys like 2091, 8090, Weldalite049, 01441 (Russian) or 1464 (Russian). Most Al-Li alloys also contain other small additions like Zr, Ag, Sc or Cd. It should be kept in mind, that most of these alloys were developed for aerospace and military applications, so the exact and complete compositions are rarely published as they are considered confidential. In Figure 2-3 Classification of Al-Li Alloys Figure 2-3 a classification of Al-Li alloys concerning their main alloying elements is shown. [7]

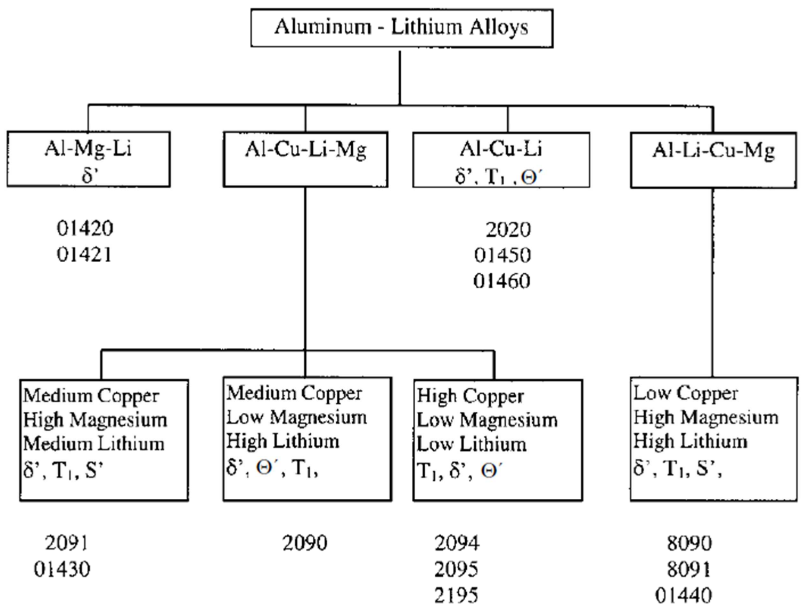


Figure 2-3 Classification of Al-Li Alloys [12]

2.4.1.5 Strengthening mechanisms in Al-Li Alloys

To get a better understanding of the influence of chemical compositions, an overview of the microstructural mechanisms of Al-Li alloys is given.

Precipitations which are involved in strengthening are, Al_2CuLi (T1), Al_3Li (δ') and Al_2Cu (θ'). The addition of Mg and Ag leads to precipitations of the same kind as T1 (isomorphous and isostructural), where the Ag atoms substitute the atomic positions of Cu, and Mg atoms substitute the atomic positions of Li. Thus, the stoichiometric and atomic arrangement is Al_2 (Cu-Ag)(Li-Mg). The θ' precipitation is thought to be of the same kind as the θ' precipitation in the Al-Cu system. The dispersoids, which form in most established wrought Al-Li alloys to control recrystallization and texture, are Al_3Zr and $Al_{20}Cu_2Mn_3$.

Table 2-4 shows an overview of precipitations, appearing in different Al-Li alloys. [12]

Table 2-4 Precipitations in Al-Li Alloys [12]

Precipitate	Stoichiometry	Crystal structure	Alloys
δ	AlLi	B32 (cubic)	01420, 01421, 01430, 01440, 01450, 01460, 2090, 2091, 2094, 2095, 2195, 8090, 8091
δ'	Al_3Li	L12 (ordered fcc)	
Θ'	Al_2Cu	Tetragonal	01450, 01460, 2020, 2090, 2094, 2095, 2195
Θ	Al_2Cu	bct (C16)	
T_1	Al_2CuLi	Hexagonal	01450, 01460, 2020, 2090, 2094, 2095, 2195, 8090
T_2	Al_6CuLi_3	Icosahedral, group M35	2020, 2091
T_B	$Al_{15}Cu_8Li_2$	fcc (C1)	2020
S'	Al_2CuMg	Orthorhombic	01430, 01440, 2090, 2091, 2094, 2095, 2195, 8090, 8091
S	Al_2MgLi	Cubic	01420, 01421
α'	$Al_3(Zr_{1-x},Li_x)$	L12 (ordered fcc)	01420, 01421, 01430, 01440, 01450, 01460, 8090, 8091, 2090, 2091, 2094, 2095, 2195
β'	Al_3Zr	L12 (ordered fcc)	
β'_{Sc}	$Al_3(Zr_x,Sc_{1-x})$	L12 (ordered fcc)	01421, 01460

Fe impurities form an Al_7Cu_2Fe crystal structure when Cu is present, an insoluble constituent phase. As this phase affects fatigue behavior and fracture toughness in a disadvantageous way, the content of Fe is tried to be minimized during development of alloys. Up to date Al-Li alloys contain Fe impurities as low as 0.1% or even less.

Cold deformation like stretching, cold rolling or cold compression enhances strength and fracture toughness of the Al-Li alloy to a great extent, if done prior to aging. This is due to refinement of precipitate microstructures and inhibiting of precipitation at grain boundaries during aging. This effect is caused by the affinity of Al2CuLi (T1) phase to form at dislocations. By cold working before aging, the number of T1 precipitates is raised by about two orders of magnitude. [11]

Following, the strengthening phases in different kinds of Al-Li Alloys:

Al-Cu-Li alloys

The aluminum- lithium alloy designated alloy 2020 by the Aluminum Association, was the first commercial produced Al-Cu-Li alloy. It was produced by Alcoa in the 1950s. Advantages of alloy 2020 were high strength and low density as well as a high elastic modulus and very good corrosion properties. Due to these attractive advantages, the new material was used in high performance structures of military aircrafts. Essential drawbacks like low ductility and poor fracture toughness however lead to the ending of production of this alloy in the late 1960s.

Primary strengthening phases in alloy 2020 are partially coherent T1(Al2CuLi), θ'(Al2Cu) and TB(Al15Cu8Li2). TEM analysis showed that θ' precipitation is more prominent than T1 or T8. Nucleation of θ' is aided by cadmium, which also inhibits grain and precipitate growth by segregating at the boundaries of the matrix and the precipitations. Grain growth is also inhibited by manganese due to the forming of dispersoids (Al20Cu2Mn3).

The low ductility is assumed to be related to the formation of precipitate free zones (PFZs) due to heterogeneous precipitation of equilibrium phases at grain boundaries during aging. These regions are soft, so cracking occurs on their plastic deformation. Cracks propagate intergranularly in these phases. Another reason for low ductility is suggested to be meterstable coherent δ' (Al3Li) and partially coherent T1 precipitates which form on ageing. [12]

Alloys with high copper/ magnesium ratio

In alloys with high copper/ magnesium ratio, like the weldalite 049 type and alloy 2090, strengthening precipitates are θ', T1 and δ'. In addition to their role as grain refiner β' particles act as nucleation sites for θ'. T1 and θ' precipitations both require copper, so the formation of T1 occurs on the expense of the other one. The relatively high amount of copper added to this kind of alloys produces high strength on the one hand; on the other hand it results in a higher density of the alloy. [12]

Alloys with low copper/ magnesium ratio

Alloys like 2091 or 8090 have a low copper/ magnesium ratio. Therefore, Al2Cu (θ') is not a dominant precipitate. Instead of this, Al2CuMg phase (S') is formed mainly, and so strength is lower compared to the weldalite alloys. Due to the S', ductility and toughness is improved, but fatigue resistance is decreased. δ' is also found in these alloys. T1 competes with S' for the available Cu atoms and nucleation sites. Stretching or straining of the material prior to ageing provides more nucleation sites, and so prevents PFZs where no S' or T1 is present. [12]

Alloys of current development

As an example of 3rd generation Al-Li alloys, in 2099 and 2199 the following precipitates, dispersoids and elements are accountable for the properties:

- Strengthening: Al2CuLi (T1), Al3Li (δ'), Al2Cu (θ' type) and Mg
- Toughness control: Al2CuLi (T1), Al6CuLi3 (T2), Al3Zr (β') and Al20Cu2Mn3
- Recrystallization control: Coherent Al3Zr (β') dispersoids
- Grain size and texture control: Al20Cu2Mn3 dispersoids
- Fatigue improvement: Incoherent Al20Cu2Mn3 dispersoids and Al3Li (δ')
- Corrosion resistance: Zn

In Figure 2-4 Schematic precipitate microstructure in Al-Li 2099 and 2199 alloys, a schematic diagram of the precipitate microstructure can be seen.

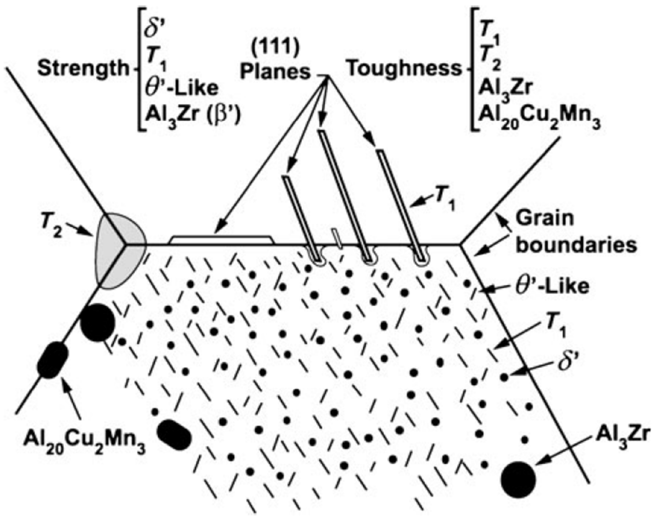


Figure 2-4 Schematic precipitate microstructure in Al-Li 2099 and 2199 alloys [11]

Figure 2-5 shows typical strengthening precipitates in 3rd generation Al-Li alloys in dark field TEM micrographs.

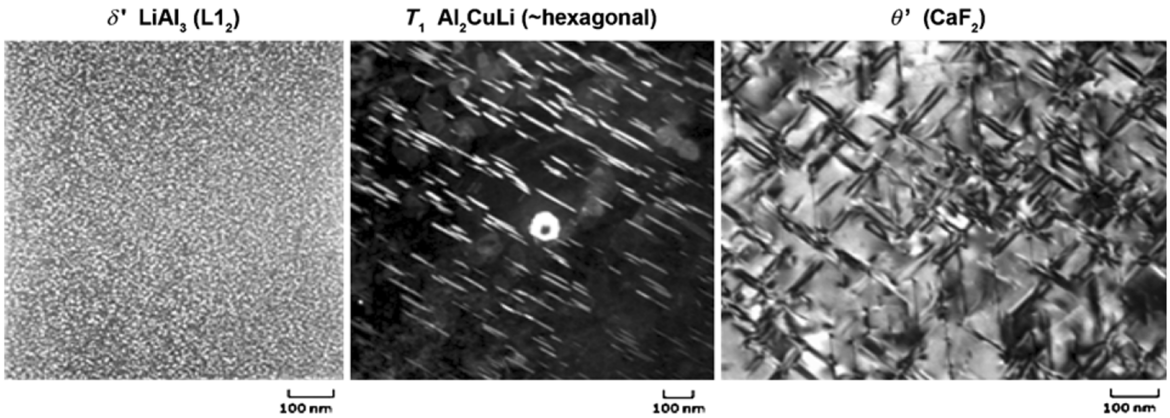


Figure 2-5 Strengthening precipitates in 3rd generation Al-Li alloys [11]

The crystallographic orientation of the grains and subgrains, the texture, is determined during forming processes like rolling or extrusion, and can be changed by thermo mechanical processes (TMP) like recovery or recrystallization annealing. This way, the desired microstructure of Al-Li alloy products can be controlled by TMP to be either recrystallized or unrecrystallized.

An example of thermo mechanical processing is shown in a generic fabrication map for Al-Li products in Figure 2-6. One can see the alternation of thermal processing and working processes. This treatment is called “Thermo Mechanical Processing”

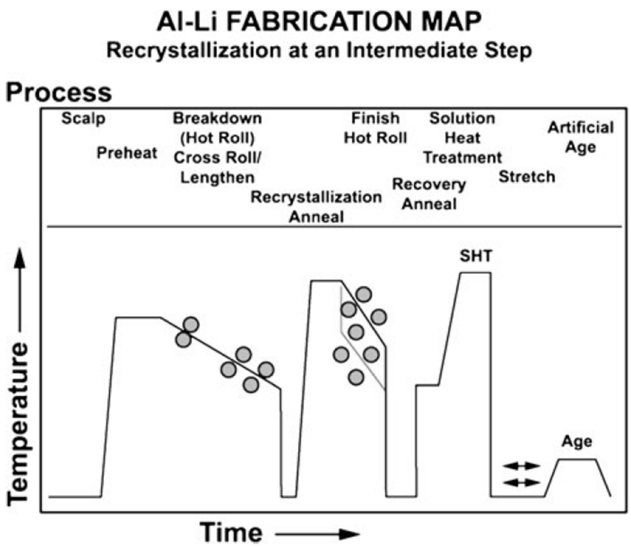


Figure 2-6 Generic fabrication map of Al-Li plate products [11]

Al-Li alloys are likely to form strong textures during forming, which leads to anisotropy in mechanical properties. Recrystallization annealing is needed, to perform recrystallazion in a separate step of procedure, so it does not occur during solution heat treatment, which leads to a final unrecrystallized microstructure with a moderate level of hot deformation texture.

As an example, Figure 2-7 shows optical micrographs of unrecrystallized alloy 2099 extrusions, unrecrystallized alloy 2099 and 2199 plate as well as recrystallized alloy 2199 sheet. [11]

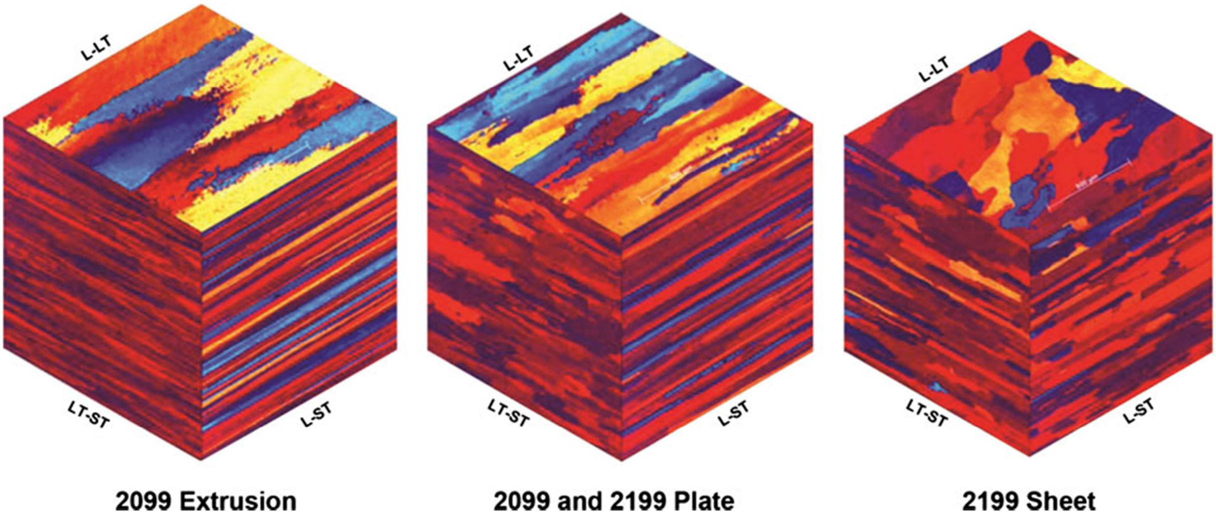


Figure 2-7 Optical micrographs showing an extruded product with thin, elongated unrecrystallized grains; a plate product with elongated unrecrystallized grains; and a sheet product with recrystillazed grains [11]

2.5 Aluminum- Scandium Alloys

2.5.1 Some basics about scandium

Scandium is a light metallic material with density of about 3 g/cm^3 and melting point of 1541°C. It is number 21 in the periodic system of elements and is counted in a wider range to the rare earth metals. [13]

Although this could be an attractive combination of properties for special high temperature and lightweight purposes, due to its limited availability and high price, it has almost no applications today. Fields, where scandium is used nowadays to some extent are as addition to metals in high intensity halide lamps, to adjust the light spectrum of the lamp to resemble sunlight, as dopant in laser technology and as alloying element in aluminum alloys. [13] There is no use of scandium known in its pure condition and the global use of scandium is very small at all. [14]

Even scandium is the 31st most abundant element on earth, there are no Sc resources where the element is explored in its pure condition. Scandium is extracted from enriched tailings of the production of metals like tungsten, uranium or aluminum, in which ores it is found in minor amounts. [14]

2.5.2 Alloying Scandium to Aluminum

When scandium is added to an aluminum alloy melt, this can be done ether in form of the pure element or in the form of a master alloy. Adding the pure element is technological feasible, but rather intricately and takes quite a time. When the element is added in gram size pellets to a melt of 800°C, it takes more than one hour to dissolve. This is due to the fact that a sequence of phase transformations has to take place before metallic Sc can dissolve in an aluminum melt of less than 1185°C. Additionally, metallic scandium is excessively expensive due to the rareness of the ores and the complicated extraction process.

It turned out, that scandium can dissolve in aluminum by reducing a Sc_2O_3 oxide directly to the melt. This oxide is by far less expensive than metallic scandium. Using these master alloys, the costs of adding scandium to an aluminum alloy could be reduced by an order of magnitude. Most common master alloys have a concentration of about 2% Sc, but the range offered goes up ti 20%. [14]

2.5.3 Influence of scandium on microstructure and properties of wrought aluminum alloys

The effect of Scandium in aluminum alloys is mostly linked to the Al_3Sc phase. Particles of this phase can form in a typical processing route under three conditions, which influences the properties of the alloy in a specific way.

- Formed in the melt during solidification after casting or welding, the Al_3Sc particles act as nuclei for α-Al and so lead to grain refinement.
- During high temperature processing in the range of 400°C to 600°C, like hot rolling, extrusion or homogenization, a dense distribution of Al3Sc particles, typically 20-100nm in size, is formed. These particles are reported to lead to good recrystallization resistance and enhanced superplasticity.
- Heat treatment of an alloy supersaturated in Sc in the range of 250°C to 350°C can lead to significant precipitation hardening. The size of the strengthening Al_3Sc particles is typically of about 2 to 6nm. [13]

2.5.3.1 Grain refinement

As in the sketch of the Al-Sc phase diagram in Figure 2-8 can be seen, there is a eutectic point at about 0.6% Sc and about 659°C. When an alloy melt with hypereutectic composition as the one marked with X is cooled down, the first phase that will form is Al_3Sc, whose lattice parameter is about the same as that of Al. The difference is only about 0.5%. Thanks to this similarities of the atomic structure, the Al3Sc particles work as nuclei for the solidification of aluminum crystals when the melt is cooled down further below the eutectic temperature. When Ti is added along with Sc, this effect is further enhanced. It leads to formation of Al3(Sc,Ti) particles, which are even more effective nuclei for aluminum during solidification. [14]

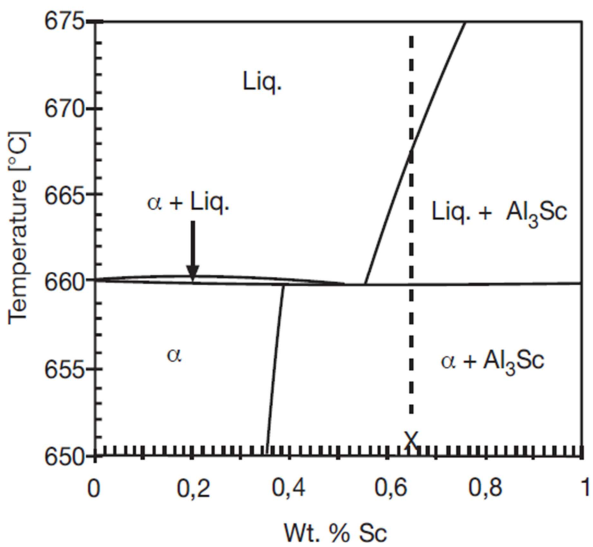


Figure 2-8 Sketch of the Al-rich side of the Al-Sc phase diagram. The symbol X indicates an arbitrary hypereutectic composition [14]

2.5.3.2 Grain structure control

At temperatures used for homogenization or solution heat treatment of common heat treatable alloys, also precipitation of Al_3Sc may take place. The particles formed at these temperatures, usually called dispersoids, are of too low number density to contribute to the alloy strength. However, they are very effective in impeding the grain boundary movement in the material. This way, they lead to a good resistance to recrystallization after forming processes like forging, hot rolling or extrusion. Such unrecrystallized materials show improved properties in strength, formability, ductility and corrosion resistance. Additionally, the dispersoids are effective in preserving a fine grain structure during superplastic forming. [14]

2.5.3.3 Precipitation hardening

In Figure 2-9, the solvus line of scandium in aluminum is shown. As there can be seen, the maximum solubility of Sc in Al is at about 0.38% However, by fast cooling during solidification it is relatively easy to obtain supersaturated solutions of Sc in Al. At cooling rates of 100°C/s, a 0.6% supersaturation can be achieved, and even supersaturation of more than 5% are possible by quenching the liquid melt at a cooled, rotating wheel. In supersaturated solution, the scandium may precipitate as finely dispersed Al_3Sc particles in temperature ranges of 250°C to 350°C. However, the hardness increase from Al_3Sc precipitation is significant, it is somewhat lower than what is normally associated with precipitation hardened alloys. Unfortunately it is not possible to combine the precipitation hardening of Al_3Sc with the usual precipitation hardening of heat treatable alloys of the 2xxx, 6xxx and 7xxx series. Figure 2-10 shows the temperature ranges of precipitation hardening for usual heat treatable alloys and for precipitation of Al_3Sc. It can be seen, that it is impossible to design a thermo mechanical process which obtains full precipitation hardening in the heat treatable alloys of the 2xxx, 6xxx or 7xxx alloys. So it might be more feasible to us scandium for precipitation hardening in the not heat treatable alloys of the 1xxx, 3xxx and 5xxx series. [14]

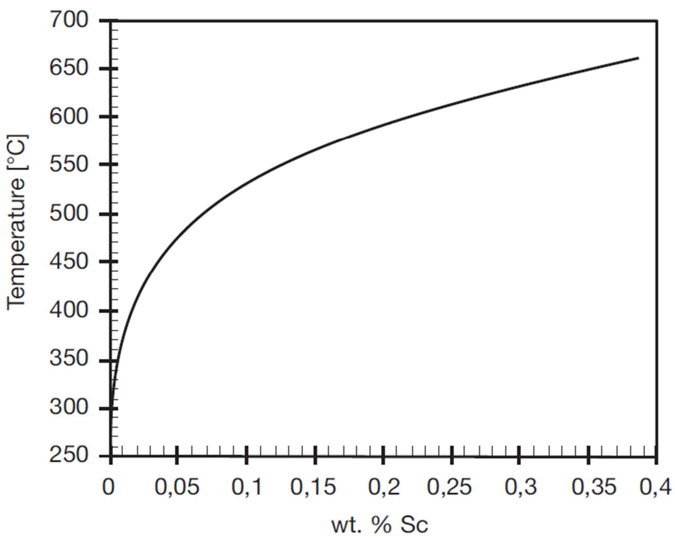


Figure 2-9 The solvus line of Sc in Al [14]

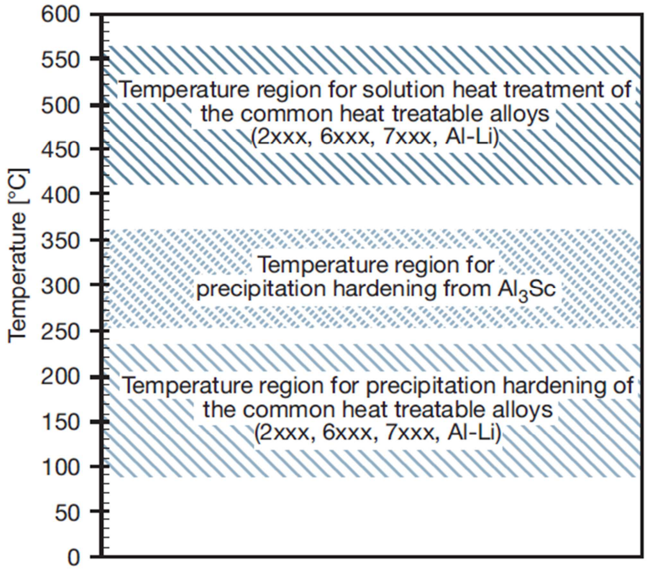


Figure 2-10 Typical temperature regions for solution heat treatment and precipitation hardening of the common heat treatable alloys, and for precipitation hardening from Al_3Sc [14]

2.5.3.4 Use of Sc containing Al alloys

The current use of Al-Sc Alloys is very limited. In the 1980s, some development of Al-Sc alloys took place in Russia, and some materials were used in parts of Russian cargo and military aircrafts. It is also claimed, that parts of the international space station are made of from alloys with Sc. [14]

In the western world, development in this field started about 10 years later, and Al-Sc alloys only find application in some sports equipment. For example, there is a series of baseball and softball bats, which are made of a scandium containing 7xxx alloy. The benefit of Sc in this field is to allow thinner gauges due to the improved yield strength, which gives a better "spring" effect of the bat. There are also some bicycle frames made of an Al-Sc alloy. Here also the benefit is a thinner wall thickness which makes the bicycle more lightweight. [13]

2.6 Alloying Scandium to Aluminum- Lithium Alloys

Scandium is known to have a grain refining effect and to reduce recrystallization in Aluminum alloys. In most applications, Scandium is added to Al-Mg alloys to increase their strength by precipitation of Al3Sc. This makes the Al-Mg alloys age hardenable, what they usually are not. Furthermore, some research has been done, to investigate the effect of Scandium additions to Aluminum- Lithium Alloys. In one experiment, Scandium was added in small amounts of 0.11% and 0.22% to an alloy, equivalent to 8090 aluminum wrought alloy. This amount was chosen, as from other experiments is known, that 0.1%Sc is sufficient to inhibit recrystallization in Al-Li alloys. As Zirconium is known to enhance the grain refining effect of Scandium, 0.1% to 0.14% Zr was added to all the investigated alloys. The materials were cast, forged and grain structure, age hardening behavior and tensile properties were investigated in comparison to the unmodified alloy.

Up to the casting level, there were also two alloys containing 0.42% respectively 0.84% Scandium analyzed. As Scandium levels exceeding 0.35% are reported to lead to coagulation of Sc containing precipitates during thermo mechanical processing, these alloys were not investigated further.

Figure 2-11 shows the as cast grain structure of the investigated alloys. It can be seen, that the grain size of alloys containing 0.11% respectively 0.22% Sc do not differ from the Sc free alloy. For high levels of Scandium, the grain structure is significantly finer.

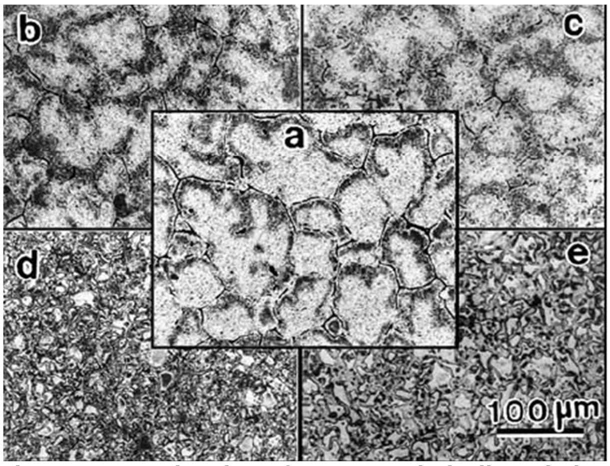


Figure 2-11Grain Size of as cast Al-Li alloys haing 0.1%Zr and 0%Sc (a), 0.11%Sc (b), 0.22%Sc (c), 0.43%Sc(d) and 0.84%Sc(e) [15]

In all the alloys, coarse prime particles were found. Analysis revealed these particles to be of the types Al-Sc, Al-Sc-Zr, Al-Fe-Sc-Cu and Al-Fe-Cu-Ni.

In forged condition, grain size was marginally smaller in the Sc containing alloys than in the base material.

Figure 2-12 Optical micrographs of forged and T8 heat treated alloy 8090 (a), 8090+0.11%Sc (b) and 8090+0.22%Sc (c) shows micrographs of forged and heat treated to T8 condition alloys 8090 (a), 8090+0.11%Sc (b) and 8090+0.22%Sc (c). Arrows mark primary particles present in the Sc containing alloys. The grain size of Scandium containing alloys is only slightly smaller.

Figure 2-13 shows transition electron micrographs of the investigated alloys, revealing that all alloys show a well developed subgrain structure, which confirms, that the grains are unrecrystallized. Even though the subgrain size of the Scandium alloyed material is finer, the amount of Scandium added seemed not to affect the subgrain size significantly.

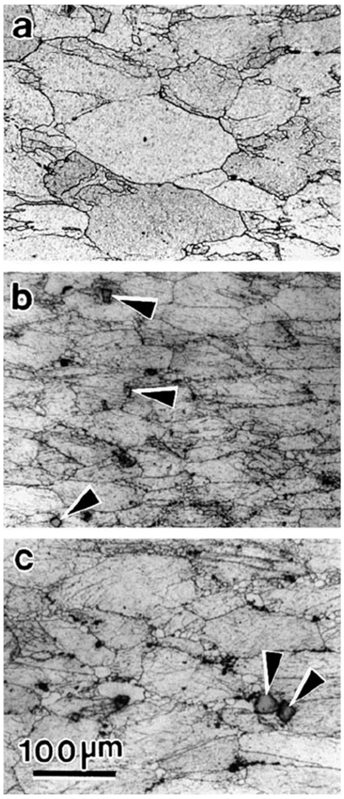


Figure 2-12 Optical micrographs of forged and T8 heat treated alloy 8090 (a), 8090+0.11%Sc (b) and 8090+0.22%Sc (c) [15]

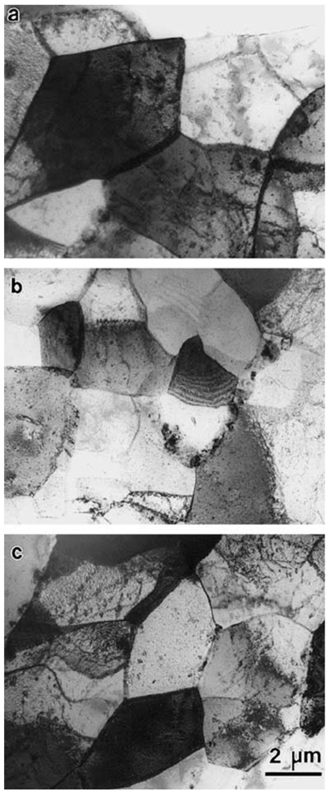


Figure 2-13 Transmission electron micrographs of alloy 8090 (a), 8090+0.11%Sc (b) and 8090+0.22%Sc (c) in T8 condition [15]

The experiment also showed a distribution of Al3Li and composite Al3Li, Al3(Sc,Zr) precipitates. The amount of the composite increased with the amount of Scandium added.

Looking at the results of the age hardening analysis, it can be seen, that hardness increased with increasing content of Scandium. As this gain is fairly uniform over the aging period, it can be concluded that the hardness raise due to scandium is independent from other precipitation reactions in the Al-Li alloy. The higher hardness of the Scandium modified alloys is probably caused by the finer subgrains and the greater amount of Al3(Sc,Zr) precipitates.

Figure 2-14 shows the hardness trend of the investigated alloys aged at three different Temperatures. As can be seen, the highest hardness was achieved by aging at 170°C. The qualitatively trend is similar for Scandium free and Scandium containing alloys.

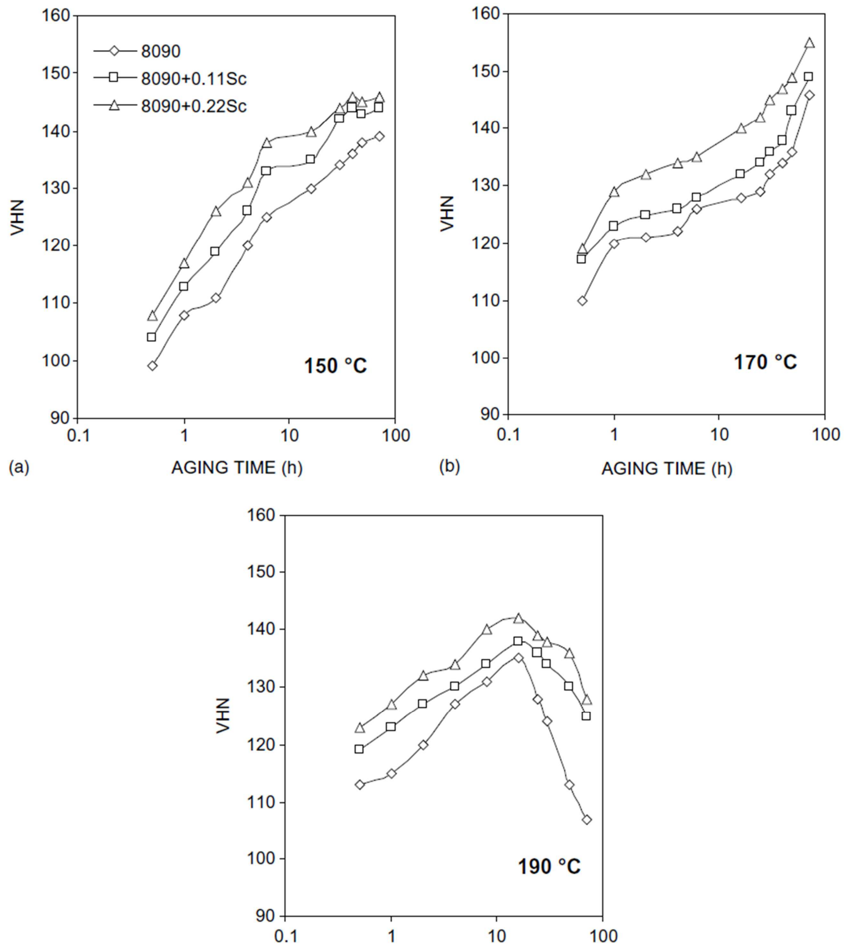


Figure 2-14 Hardening curves for the alloys 8090, 8090+0.11%Sc and 8090+0.22%Sc aged at different temperatures [15]

Measurement of tensile properties showed, that the Scandium modified alloys had slightly higher strength, but lower ductility compared to the base alloy. The improved strength is likely to be caused by the same effects as the increased hardness of the Scandium alloyed material. Finer subgrains and higher volume fracture of precipitates. The lower ductility is probably due to the coarse primary particles in the Scandium containing alloys. A higher amount of Scandium added would even lead to more primary particles and worsen the ductility of the material. [15]

2.7 Anisotropy- The effect of Directionality on Properties

Wrought aluminum products are, as the name indicates, mechanically worked after casting. The grain flow during this mechanical processing like forging, rolling or extrusion, leaves the grains of the material in a specific orientation which influences the properties of the material to a great extent. Figure X shows, how this orientations or planes usually are designated.

- L (Longitudinal): Parallel to major dimension or direction of working of section
- T or L-T (Long transverse): 90° to direction of working and parallel to width of section
- S or S-T (Short transverse): 90° to direction of working and parallel to thickness or minimum dimension of section

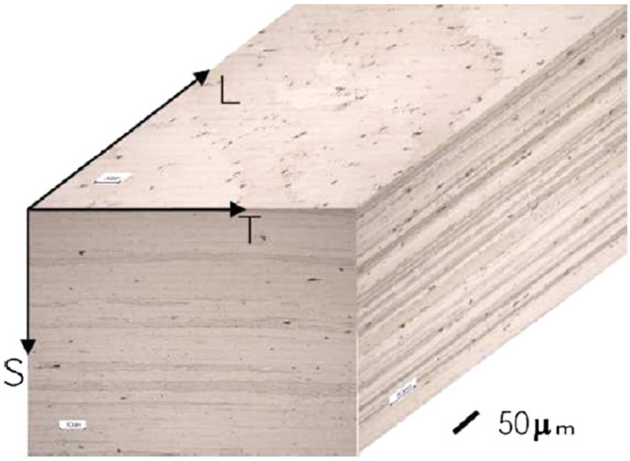


Figure X Pseudo 3D Image of the grain structure [16]

Typically, ultimate and tensile strength is highest in the longitudinal direction and lowest in the short transverse direction. Also other mechanical properties like fracture toughness, fatigue strength and elongation differ depending on test direction. But not only mechanical properties are affected by anisotropy, also other characteristics like the resistance to stress corrosion cracking are influenced by direction. In general, this effects are stronger in rather thick products, while in thinner sections, like sheets and thin plates, the difference in properties is not as distinctly.

For non heat treatable alloys, formability (related to strength) is often more important than absolute strength, so in tables, properties are generally specified in the longitudinal direction. For heat treatable alloys, strength is usually of greatest importance, so property values are given in transverse direction most times. [2]

In Table 2-5 the effect of anisotropy in properties can be seen at an example.

Table 2-5 Low temperature fracture toughness ofaluminum alloy plate [2]

Alloy and condition	Room temperature yield strength		Specimen design	Orientation	Fracture toughness, K_{Ic} or $K_{Ic}(J)$ at: 24 °C (75 °F)		−196 °C (−320 °F)		−253 °C (−423 °F)		−269 °C (−452 °F)	
	MPa	ksi			$MPa\sqrt{m}$	$ksi\sqrt{in.}$	$MPa\sqrt{m}$	$ksi\sqrt{in.}$	$MPa\sqrt{m}$	$ksi\sqrt{in.}$	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
2014-T651	432	62.7	Bend	T-L	23.2	21.2	28.5	26.1	...	...	...	...
2024-T851	444	64.4	Bend	T-L	22.3	20.3	24.4	22.2	...	...	...	...
2124-T851(a)	455	66.0	CT	T-L	26.9	24.5	32.0	29.1	...	...	...	...
	435	63.1	CT	L-T	29.2	26.6	35.0	31.9	...	...	...	...
	420	60.9	CT	S-L	22.7	20.7	24.3	22.1	...	...	...	...
2219-T87	382	55.4	Bend	T-S	39.9	36.3	46.5	42.4	52.5	48.0	...	...
			CT	T-S	28.8	26.2	34.5	31.4	37.2	34.0	...	...
	412	59.6	CT	T-L	30.8	28.1	38.9	32.7	...	...	...	...
5083-O	142	20.6	CT	T-L	27.0(b)	24.6(b)	43.4(b)	39.5(b)	...	...	48.0(b)	43.7(b)
6061-T651	289	41.9	Bend	T-L	29.1	26.5	41.6	37.9	...	...	...	...
7039-T6	381	55.3	Bend	T-L	32.3	29.4	33.5	30.5	...	...	...	...
7075-T651	536	77.7	Bend	T-L	22.5	20.5	27.6	25.1	...	...	...	...
7075-T7351	403	58.5	Bend	T-L	35.9	32.7	32.1	29.2	...	...	...	...
7075-T7351	392	56.8	Bend	T-L	31.0	28.2	30.9	28.1	...	...	...	...

(a) 2124 is similar to 2024 but with higher-purity base and special processing to improve fracture toughness. (b) $K_{Ic}(J)$.

2.8 Welding of Aluminum Alloys

Among others, welding is one of the most applied methods to join aluminum alloys. Welding of aluminum is generally well understood, but there are some issues which have to be thought of. In general, aluminum and aluminum alloys can be welded by all established methods like gas shielded arc welding, which is probably the most applied technique, but also resistance welding, laser beam welding, electron beam welding, friction welding or friction stir welding are used.

One thing which has to be thought of is the oxide layer which forms naturally at aluminum surfaces or is increased electrochemically. This oxide melts at about 2050°C which is much higher than the base alloy. If the oxide is not removed, it will result in incomplete bonding. Thinner oxide layers can be removed ether by a flux or by the gas welding arc, thicker oxide layers must be removed mechanically. As the use of fluxes can lead to further problems concerning corrosion, inert gas arc welding which removes the oxide layer without a flux, has found wide acceptance. [2]

To evaluate the weldability of an aluminum material at all, four factors are to be considered.

- Weld joint efficiency, the degradation of mechanical properties
- Porosity formation
- Susceptibility to cracking during solidification of the metal
- Resistance to corrosion [12]

Weld joint Efficiency

In general, heat treatable aluminum alloys show lower tensile strength and ductility in the as welded condition. Improvements can be accomplished by modifying the composition and microstructure of the weld fusion zone by proper selection of filler metals and welding parameters. The thermal cycles in the heat affected zones however can cause complex metallurgical reactions and changes in mechanical properties of the optimal heat treated base material. So, also the heat affected zones experience a reduction in mechanical properties. Unfortunately, the HAZ properties cannot be easily recovered without a complete solution heat treatment and aging, which often is not possible especially in large and complex parts. As a result of this, the as welded properties of the heat affected zones are often the limiting factor concerning weld efficiency.

As welded joint efficiencies in AL-Li alloys range from about 50% to 80%, while joint efficiencies can go up to 100% for weldments which are solution annealed and aged after welding. Electron beam welding method produces better joint efficiencies than gas tungsten arc welding methods which are due to the narrower fusion zone and heat affected zone. The joint efficiencies of different welding methods are compared in Figure 2-15. **Fehler! Verweisquelle konnte nicht gefunden werden.**In Table 2-6, mechanical properties in weldments of different alloys are listed for comparison. [12] [2]

Table 2-6 Mean tensile properties of Weldalite 049, 2090 and 2219 weldments with conventional and Weldalite filler [2]

Base metal/filler	Temperature(a)	Thickness mm	Thickness in.	Postweld temper	Weld position	Ultimate tensile strength MPa	Ultimate tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation, %, in 25 mm (1 in.)	Elongation, %, in 50 mm (2 in.)
VPPA square butt weldments(b)											
2219/2319	RT	9.5	0.375	As-welded	60° horizontal	273	39.6	140	20.4	7.9	4.6
2219/049	RT	9.5	0.375	As-welded	60° horizontal	283	41.1	154	22.3	7.1	4.7
2219/049	RT	5.8	0.230	As-welded	60° horizontal	325	47.1	161	23.4	9.0	5.0
2090/2319	RT	13	0.500	As-welded	Vertical	252	36.5	156	22.7	8.6	4.7
2090/049	RT	6.5	0.255	As-welded	60° horizontal	285	41.3	147	21.3	7.1	3.8
049/2319	RT	9.5	0.375	As-welded	Vertical	274	39.8	248	36.0	1.5	1.0
049/049	RT	9.5	0.375	As-welded	60° horizontal	315	45.7	249	36.1	1.5	1.5
049/049	RT	9.5	0.375	Naturally aged for 800 h	60° horizontal	372	54.0	290	42.1	3.0	...
VPPA weldments of extruded plate(c)											
049/049	175 °C (350 °F)	9.5	0.375	As-welded	...	287	41.6	188	27.3	5.4	...
049/049	RT	9.5	0.375	As-welded	...	372	54.0	290	42.0	3.0	...
049/049	−195 °C (−320 °F)	9.5	0.375	As-welded	...	413	59.9	360	52.2	1.9	...
049/049	−253 °C (−423 °F)	9.5	0.375	As-welded	...	505	73.2	427	61.9	1.7	...

(a) RT, room temperature. (b) All fractures occurred in the heat-affected zone. (c) 100 × 9.5 mm (4 × 0.375 in.) plate. Source: Martin Marietta Manned Space Systems

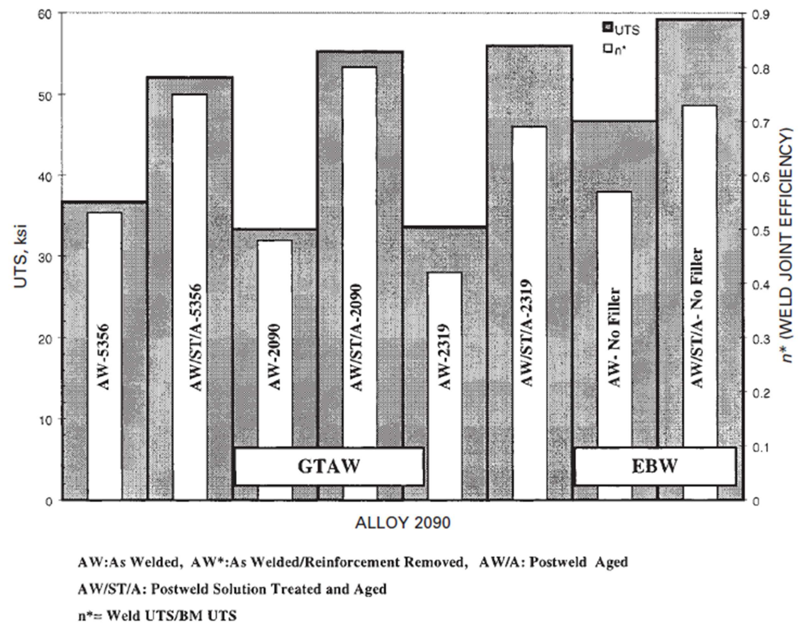


Figure 2-15 Weld joint efficiency for alloy 2090 using various processes and filler metals [12]

Porosity Formation

Another problem in welding aluminum alloys is the solubility of hydrogen, which dissolves rapidly in molten aluminum. In solid aluminum, hydrogen has almost no solubility which leads to porosity in the weld. High temperatures of the weld pool allow a large amount of hydrogen to be dissolved, and when the pool solidifies, the solubility of hydrogen is greatly reduced. Hydrogen which exceeds the solubility limit forms gas porosity. Hydrogen is formed by reactions of hydrogen containing substances at the hot surface or the welding arc. So any source of hydrogen like moisture, residues of lubricants must be eliminated. Electrodes must be stored in dry areas. [2]

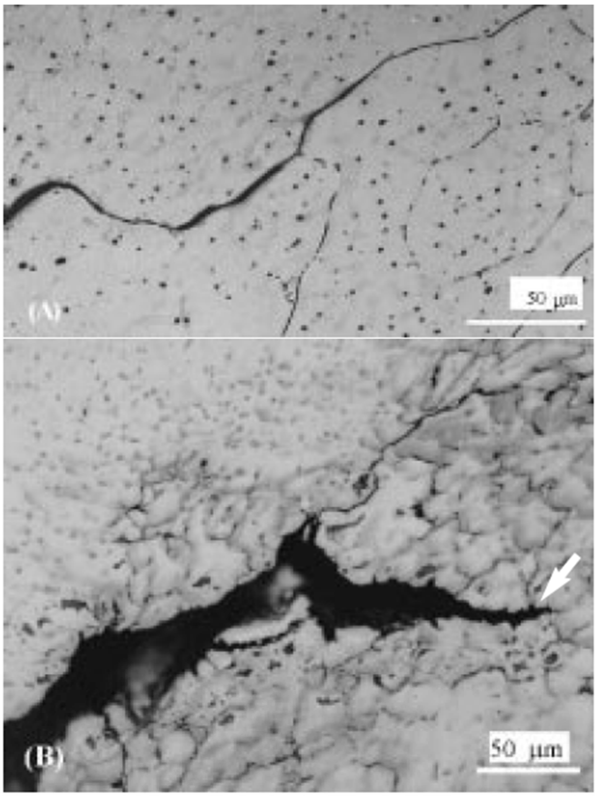
In Aluminum- Lithium alloys it was observed that Lithium containing compounds form in the surface layer which increases the level of moisture absorption relative to other aluminum alloys. The most effective method found to reduce weld fusion zone porosity was to remove the surface layer by chemical or mechanical milling. By removing at least 0.13mm at either side of a specimen, porosity was reduced significantly. Electron beam welding and laser beam welding methods also produced welds of low porosity. [12]

Weld Cracking

Due to the high coefficient of thermal expansion of aluminum, therefore its big change in volume during solidification, in combination with the large solidification temperature range, weld cracking is a concern which has to be thought of. Especially in the heat treatable alloys, two kinds of cracking have to be respected. [2] [12]

Solidification cracking, or hot cracking, occurs along solidification grain boundaries when high levels of thermals tresses and shrinkage are present while the weld pool solidifies. Hot cracking occurs within the weld fusion zone and is affected by metal composition and weld parameters. Partitioning of alloy and impurity elements during solidification cause the formation of low melting liquid films along the boundaries which will crack if enough stress is imparted to the boundary. A picture of solidification cracks in alloy 8090 (A) and alloy 2195 (B) is shown in Figure 2-16. [2] [12]

Liquidation cracking occurs in the heat affected zone of heat treatable alloys, when eutectic phases or constituents with low melting point melt at grain boundaries during welding. If sufficient stress is present, tearing may happen. [2]



A alloy 8090; *B* alloy 2195; arrow *B* highlights tip of crack

Figure 2-16 Weld solidification cracking in two different alloys [12]

Non-heat treatable alloys are less problematic in welding due to the lack of precipitate forming elements which can lead to hot- or liquidation cracking. In addition joint efficiencies are higher because no coarsening or dissolution of precipitations can happen. [2]

Corrosion of Weldments

Many heat treatable alloys can be welded without reducing the resistance to corrosion. On the other side, welding creates residual tensile stresses and modifies the microstructure, so in some alloys the resistance to corrosion is lowered by welding. For corrosion mechanisms see section “Corrosion” in this chapter.

2.9 Metallic Materials for cryogenic use

In general, strength of metallic materials increase as temperature is lowered. Concerning fracture toughness, other than most types of steel, aluminum does not show a distinct ductile- brittle transition behavior as it is cooled down, so toughness is not lowered abrupt at a certain temperature. This makes it a good candidate for cryogenic applications. [2]

Some experiments [8] at specific Al-Li Alloys show, that also fatigue strength increases with decreasing temperature.

It also has been found, that Al-Li alloys show increased ductility and fracture toughness at lower temperatures than room temperature. Hence they seem to be an attractive material for cryogenic applications. Experiments carried out on an 8090 material of two different tempers, one leading to a homogenous distribution of S' and δ', and one leading to a dominant δ' microstructure, showed that fatigue resistance of both tempers were considerable enhanced at cryogenic temperatures compared to ambient temperature. The δ' microstructure presented higher fatigue resistance than the (S'+δ') microstructure at both ambient and cryogenic temperature. [17]

In general, most aluminum alloys show only little change in properties below zero. While yield and tensile strength may slightly increase, impact strength remains approximately constant and elongation decreases slightly. Compared to certain austenitic steels, the relatively low elongation may be a drawback of aluminum alloys. [18]

Figure 2-17 shows the thermal expansion of different materials at different temperatures.

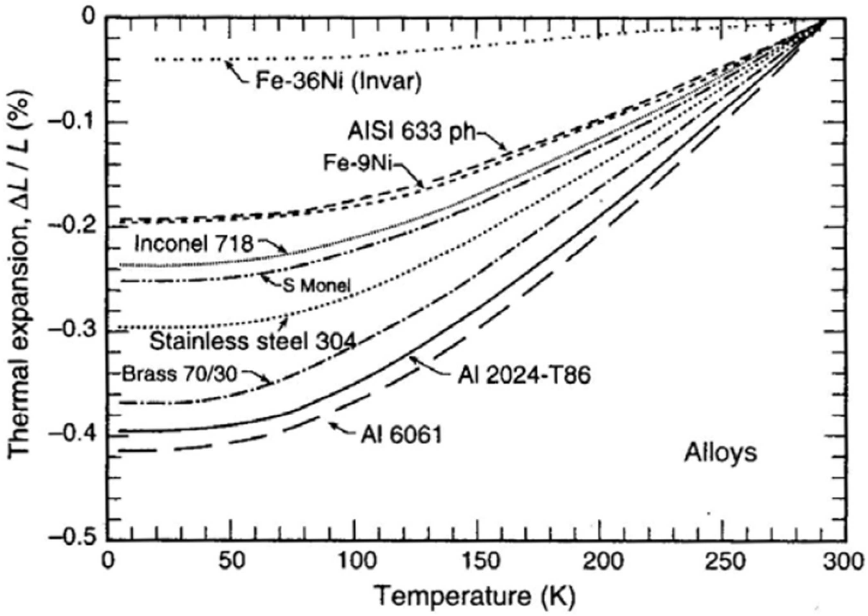


Figure 2-17 Thermal expansion of different materials [19]

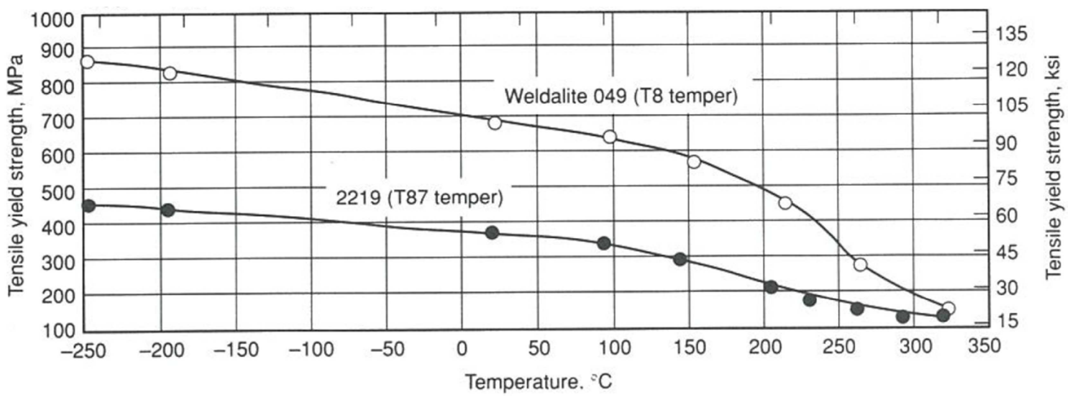


Figure 2-18 Yield strength comparison of an aluminum-lithium candidate alloy for cryogenic tankage applications with a conventional alloy [2]

Aluminum-lithium alloys show greater increase in strength than conventional aluminum alloys. Figure 2-18 shows a comparison between two different aluminum materials, one an Al-Li alloy, the other one a conventional alloy. [2]

Of different alloys evaluated at different heat treat conditions, aluminum alloy 5083-O had greater fracture toughness than the others. As temperature decreased, the fracture toughness of this alloy increased. Alloy 2219-T87 had the best combination of fracture toughness and strength both at ambient temperature and at -196°C. Alloy 6061-T651 had good fracture toughness at room temperature and at -196°C, but yield strength is lower than that of alloy 2219. [18]

2.10 Corrosion

Aluminum is considered to have an excellent corrosion resistance. It owes its status as one of the most utilized structural metallic materials to a great extent to the barrier oxide film, which is strongly bonded to the surface and reforms immediately in most environments if it is damaged. This barrier film is highly effective in protecting the material from corrosion, even if it is only 1nm thick when formed on a freshly machined surface exposed to air.

At normal atmospheres, the natural oxide film formed is about 20 to 200nm thick. It consists of two layers; the inner oxide, which is a compact amorphous barrier whose thickness is determined by the temperature of the environment but not by its composition (oxygen, dry or moist air), and the outer one, a thicker but more permeable film of hydrated oxide. Its thickness is determined by the hydrating potential of the environment. [2]

Due to this protective layer, extensive degradation is only seen when its protective effect is abolished due to low or high pH-values. Nevertheless, corrosion appears at aluminum materials in different modes, depending on alloying elements, condition of material or its measurements. Modes of corrosion are as following. [20]

Pitting Corrosion

In the passive range, corrosion of aluminum usually appears as random, localized formation of pits. The conditions, under which metals in the passive state are subject to corrosion by pitting are established by the pitting-potential principle. The pitting potential E_p is the potential in a particular solution, above which pits will occur and below which they do not. At potentials more active than E_p, where the oxide layer maintains it integrity, anodic polarization is easy and corrosion happens slow and uniform. Above E_p anodic polarization is difficult and the current density increases sharply. The oxide layer ruptures at weak points of the barrier and localized corrosion develops at this points. Liability to corrosion depends on alloying elements, if the alloy is heat treatable or not or on temper grade. Figure 2-19 shows pit density and pit depth compared for different alloy groups.

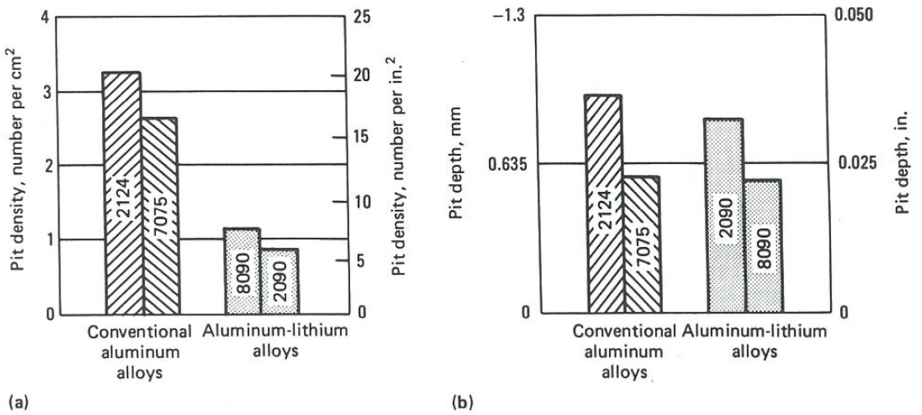


Figure 2-19 Pitting characteristics of selected aluminum and aluminum-lithium alloys exposed to an SO2 salt fog for 32 days. [2]

While acidic agents cause rather deep pits in aluminum materials, alkaline agents produce rather flat pits. Figure 2-21 and Figure 2-20 show examples of these two cases for pitting corrosion at an Al-Mg alloy. [20]

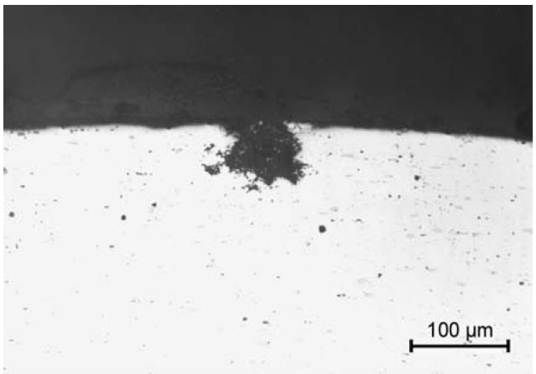


Figure 2-21 Example of deep pitting corrosion in AlMg alloy attaced by an acidic agent [20]

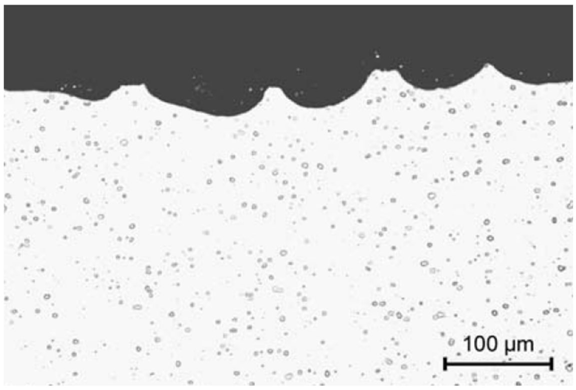


Figure 2-20 Example of flat pitting corrosion in AlMg alloy attaced by an alkaline agent [20]

Intergranular Corrosion

Intergranular corrosion is the selective attack of grain boundaries or regions close to them, but not of the grain itself. It is caused by potential differences between the grain boundary region ant the grain body. The exact location of the corrosion attack varies between the different alloy systems. In 2xxx alloys for example, it is a narrow band on either side of the boundary which lacks copper. in copper bearing 7xxx alloys, it is also the copper depleted zone at the grain boundaries, while in copper free 7xxx alloys, corrosion is located at anodic zinc and magnesium bearing constituents at the grain boundaries.

Although slight intergranular attack has been observed in aggressive environments, the 6xxx alloys are generally resistant to this type of corrosion. [2]

The sensitivity to intergranular corrosion is also influenced by alloy tempering. In Figure 2-22 and Figure 2-23, corrosion attack to an Al-Mg alloy of different tempering is shown.

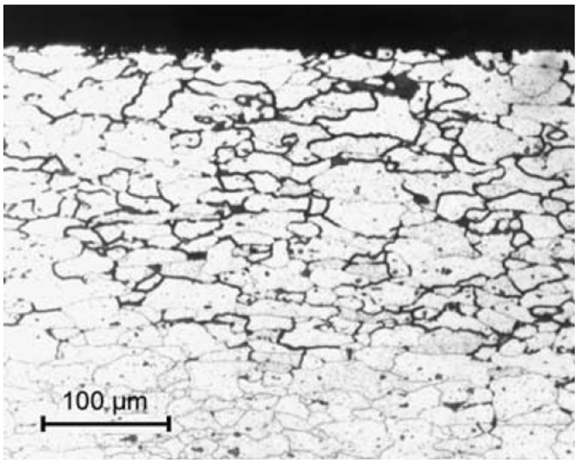


Figure 2-23 Example of intercrystalline corrosion in Al-Mg alloy [20]

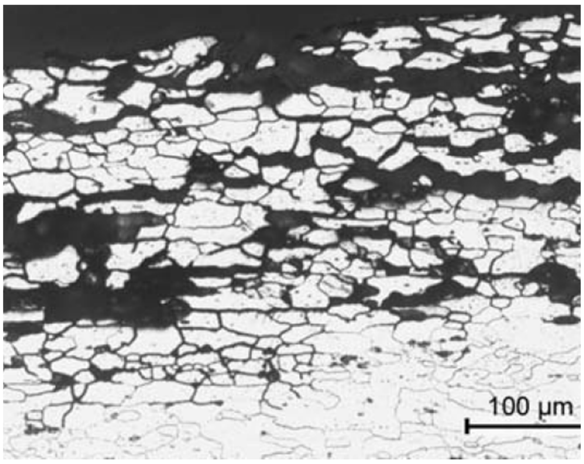


Figure 2-22 Example of intergranular corrosion in an Al-Mg alloy due to insufficient quenching rate at tempering [20]

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is defined as the coactive action of stress and a corrosive environment, which can lead to fracture of the material at a stress level lower than the macroscopic yield stress of the material. Also the fracture mode under corrosive environment can be different from that without SCC conditions.

Two mechanisms have been identified to be the major causes of stress corrosion cracking, anodic dissolution and hydrogen embrittlement. Of this two, hydrogen embrittlement is assumed to take the dominant role in aluminum and aluminum alloys. [21]

Only aluminum alloys which contain some amounts of soluble alloying elements like copper, magnesium, silicon or zinc are susceptible to stress corrosion cracking. As SCC is dependent on tempering, for most commercial alloys tempers have been developed which provide a high degree of immunity to stress corrosion cracking in most environments. As SCC happens characteristically intergranular, according to the electrochemical theory, this requires a condition along grain boundaries which makes them anodic to the rest of the microstructure, so corrosion happens just along them. These conditions are the same as in intergranular corrison. [2]

The other phenomenon which can lead to stress corrosion cracking is hydrogen embrittlement of critically oriented grain boundaries which are charged by tension stresses of a minimum amount. Hydrogen is formed by chemical reactions with a moist atmosphere at the surface and diffuses into the tension loaded grain boundaries quite fast. The sensitivity of the grain boundaries to hydrogen embrittlement is dependent on the alloying elements and the condition of the material. Unalloyed aluminum and various alloys are completely immune to stress corrosion cracking. An unrecrystallized wrought microstructure is less prone to SCC than a recrystallized one.

In a material sensitive to SCC, residual stresses and notch stresses can be sufficient to cause fracture even when no external loads are applied. Examples of such fractures are shown in Figure 2-24 and Figure 2-25. It can be seen that recrystallized microstructure and coarse grain structure is more susceptible to SCC than fiber shaped microstructure. [20]

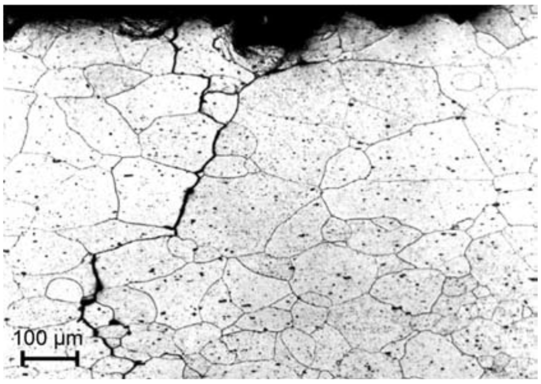


Figure 2-25 SCC in alloy 7020 showing intergranular fracture in recrystallized microstructure [20]

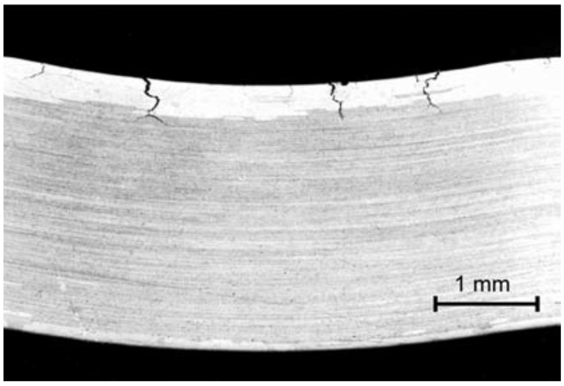


Figure 2-24 SCC in Al-Zn alloy showing intergranular fracture in recrystallized coarse grain zone [20]

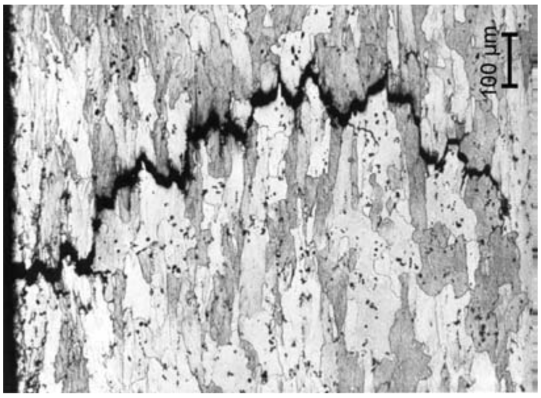


Figure 2-26 Intergranular corrosion in tension in Al-Cu alloy [20]

In Al-Cu alloys, corrosion fracture which is similar to SCC in Al-Zn alloys, can happen. Especially, when quenching conditions are suboptimal or gauges are too thick. This is intergranular corrosion, which was accelerated by tension stresses. An example is shown in Figure 2-26.

Hydrogen Embrittlement

As Hydrogen has a higher solubility in the liquid phase than in the solid one, gas porosity can form during solidification. The presence of specific impurities, such as sulfur compounds, can enhance the intake of Hydrogen. Other impurities, like beryllium, copper, tin and silicon decrease the hydrogen intake. In addition to primary porosity, hydrogen can also cause secondary porosity and blistering during heat treating. It can also play a role during grain boundary breakup in stress corrosion cracking. [3]

During melting or heat treating aluminum alloys, hydrogen is produced from reactions of water vapor. Blistering due to hydrogen is often associated with precipitates at grain boundaries or the formation of small voids. Other than in ferrous metals, in aluminum alloys it is more common to have a multitude of voids near the surface which coalesce to produce a large blister. Hydrogen diffuses into the aluminum lattice and gathers at defects.

Dry hydrogen gas is not harmful to aluminum alloys, however, in the presence of water vapor subcritical crack growth increases dramatically. The stress needed to crack an aluminum alloy decreases significantly in the presence of humid hydrogen gas. Crack growth is a function of permeability.

As already mentioned in the section “stress corrosion cracking”, SCC is promoted by hydrogen embrittlement. Table 2-7 lists some observations of SCC in Al-Li-X alloys and proposed explanations due to effects of hydrogen. [12]

Table 2-7 Hydrogen embrittlement in Al-Li-X alloys [12]

Observations	Proposed hydride cracking mechanism
Presence of stable hydrides indicated by tritium release characteristics, by SIMS and by laser microprobe spectroscopy	Systems that form hydrides can be embrittled by hydrides
Discontinuous crack propagation in the absence of dislocation at crack tip	Diffusion of hydrogen to the region ahead of the crack tip to form hydride and its subsequent failure
Increased faceted appearance of the fracture surface with increased hydrogen precharging	Longer precharging times leads to enhanced hydride formation and enhanced embrittlement
Hydrogen interaction with the SGB and SSGB precipitates caused embrittlement	Hydrogen interacts with the grain boundary AlLi phase to form $LaAlH_4$ and the hydride can favourably nucleate at the SSGB
Intergranular fracture mode in SCC with very little microductility	Hydrogen interacts with AlLi to form $LiAlH_4$ at SGB
Ease of crack initiation at SGB and decrease in K_{ISCC} with aging or higher Li content	Hydrides formed from grain boundary AlLi act as crack initiators. Grain boundary AlLi amount increases with aging of higher Li content
Direct imaging of a brittle hydride	Strong support for the hydride crack mechanism

Exfoliation Corrosion

Wrought products of aluminum in certain tempers are subject to exfoliation corrosion. In this type of corrosion, attack happens along selective surface paths which are parallel to the surface. Layers of uncorroded aluminum are split apart and pushed apart by the voluminous corrosion products. As this type of corrosion can be detected quite easily already at an early stage and additionally is restricted in depth, it usually don’t leads to unexpected structural failure as SCC does.

Exfoliation corrosion usually occurs in products which have strongly directional structures and highly elongated grains form platelets which are quite thin compared to their length and width. Susceptibility to this type of corrosion results from aligned intergranular or subgrain boundary precipitations. Also from strata which differs slightly in composition. Exfoilation is not affected by stress or lead to stress corrosion cracking. Alloy groups, most susceptible to exfoliation corrosion are 2xxx and 7xxx alloys and some cold worked 5xxx alloys. [2]

3 Defining Requirements- A Starting Point

At the beginning of the Project, Magna Steyr provided a list of properties which should be considered while looking for a new material. These properties were split up in four groups as there were mechanical properties, chemical properties, properties of processability and costs.

Mechanical Demands

- High strength- high specific strength
- Low density
- High ductility
- Notch sensitivity
- Anisotropy

- Fatigue properties
- Applicability at cryogenic temperatures

Chemical Properties

- LOx, LH_2 compatibility
- Sensitivity to stress corrosion cracking
- General corrosion behavior

Factors of Processability

- Formability
- Weldability
- Machinability

Factors of Costs

- Material costs
- Manufacturing costs
- Availability

At Magna Steyr, there was already a document existing [22] concerning properties to be considered for the material tradeoff. These are the requirements that are used for the tradeoff between the material groups of aluminum alloys, CFRP and polyimides.

- Stiffness
- Density (<2.66 g/cm³)
- Specific Yield strength (Re/ρ) (~500- 800 MPa)
- Specific strength (Rm/ρ) (~500-1000 MPa)
- Low content of Fe, Si, K, Na
- Fracture toughness K1c
- Strength properties at cryogenic temperatures (LN2, LH2, LOX, down to 20K)
- Formability
- Stress corrosion cracking
- No ageing, cracking, chipping, flaking, peeling, delamination, etc. when subjected to environmental extremes (cryogenic temperatures, vacuum,…)
- Good low cycle fatigue
- Good resistance to creep
- Material should not be ITAR controlled
- Material should be available in Europe
- Annealing after processing necessary
- Low sensitivity to hydrogen embrittlement (base material, weld seems, HAZ)
- Chemical resistance to LH2, LOX
- Weldability (arc welding, FSW)

For the material comparison within the aluminum alloys, this requirement list is also used predominantly, but some adjustments have been made in coordination with Magna Steyr. For example some of these factors do not differ greatly between aluminum alloys, others were added.

The conclusive property list which was the basis for the final decision in the utility analysis can be found in the corresponding chapter.

4 Finding Material Options

4.1 Cambridge Engineering Selector (CES)

The first attempt to find possible material choices was to use a computer assisted tool which is utilized at the Graz University of Technology, the Cambridge Engineering Selector (CES EduPack 2013).

As there were no specific values given to start with, the selected material should just be "The best possible", the start of the project was a little tricky. As the major goal of the project was to make the feed lines more lightweight and less costly, it was decided to start with specific strength.

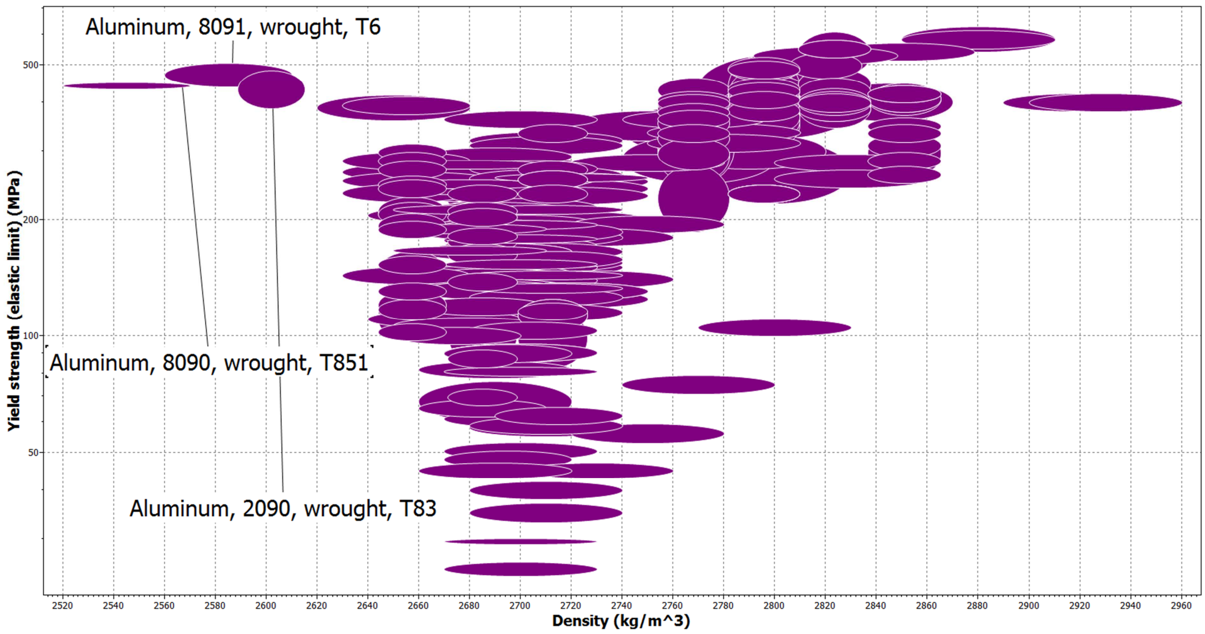


Figure 4-1 CES Plot of Aluminum Alloys

In a first attempt, in the Cambridge Engineering Selector, aluminum alloys were plotted in a diagram showing yield strength and density. As can be seen in Figure 4-1, the alloys with highest yield strength at lowest density really are the aluminum- lithium alloys. Unfortunately, the three alloys marked in the diagram are the only materials of this alloy system existing in the CES database, and there is no aluminum- scandium alloy at all. As it turned out later, the three Al-Li alloys existent in CES are not available any more.

As a consequence, the Cambridge Engineering Selector was not helpful in this project.

4.2 Selecting potential materials for the project

As the thesis project should emphasize on Aluminum- Lithium and Aluminum- Scandium alloys, the next step was to pick the corresponding alloys from the Aluminum Association Registration list [23] and to perform a literature review on them to see which ones of them are promising for the project. While carrying out this literature study, it came out which of them were already in use in comparable fields and on which ones data was available.

Additional alloys where selected as they emerged as possible options during the literature review.

The alloys, the literature study was started with were as many as 2195, 2090, 8090, 2098, 2196, 2050, 2099, 2199, 2198, 8091 2091, 2094, 2095, 2196, 2097, 2197, 2297, 2397, 8017, 8024, 8093 for the Aluminum Lithium alloys and 2023, 5024 for the Aluminum- Scandium alloys.

Of course, not all of them could be searched in detail, quite many of them fell out of scope quite fast due to lack of data. On the other hand, some other materials came along. The materials which were reviewed more in detail are described in the next chapter.

5 Characterization of specific materials

In the following chapter, some specific alloys which appeared to be promising during the literature review are described more in detail. The alloys listed in the “Baseline Materials” section, are materials which are known to be already in use in comparable fields like aerospace or space applications. (e.g. alloy 2219 and alloy 2195 were used as materials for the Space Shuttle fuel tanks)

Alloys listed in the “New Materials” section are materials which were quite new developed for aerospace applications, but are not known to be in use today in this field.

5.1 Baseline Materials

5.1.1 Alloys of the 7xxx series

Some of the alloys of the 7xxx series show highest mechanical properties of all aluminum alloys. Alloy 7075 for example has yield strength of about 550 MPa [24]. Drawbacks like the extreme sensitivity for weld cracks [2] and the susceptibility for stress corrosion cracking especially in the presence of hydrogen make these group of alloys unfeasible for the purpose this paper deals with.

5.1.2 AA5059

Alloy 5059, sold under the trade name ALUSTAR, belongs to the Aluminum Magnesium alloys and therefore is a non-heat treatable material. It was developed as an improvement of alloy 5083, which is a well-established material and used for shipbuilding for some decades.

The goal of developing the new alloy was to increase strength by at least 20%, while maintaining the high level of corrosion resistance or even enhance it. These goals were achieved by raising the content of Magnesium in the alloy to up to 6% and a special thermo mechanical process.

Mg is added to Al-Mg alloys to increase strength. Usually, not more than 4.5% Mg is added due to the gradually decrease in corrosion resistance which happens above this value. Anodic Al-Mg intermetallic particles precipitate at grain boundaries, causing the alloy to become susceptible to inter granular corrosion. This inter granular corrosion may also lead to pitting and stress corrosion cracking subsequently.

In this case, corrosion resistance was enhanced by addition of a controlled amount of zinc, which creates Mg-Zn intermetallics, which in combination with a specific thermo mechanical treatment will stay inside the grain and compensate for the electro-chemical imbalance. Also manganese and zirconium are added in controlled amounts to increase strength and delay the recrystallization process in the heat affected zone during welding and so to produce a fine grain structure. [25]

Alloy 5059, developed and patented by Aleris, is produced basically in two tempers. O/H111, which is applied for cryogenic tanks, and H131/H136, which is used for armor applications. (e-mail conversation with Thorsten Wehner, Manager Product Application, Aleris)

In O/H111 condition, the material shows a yield strength of 160 MPa, [26] which is the lowest, compared to the other investigated materials, but according to an FEM analysis conducted with the model of an existing reference line, this is sufficient. The material also fulfills the criteria of the minimum first eigenfrequency of about 100 Hz (see FEM pictures in appendix).

Table 5-1 shows minimum tensile properties of AA5059 compared to other Al-Mg alloys

Table 5-1 Base material tensile strength of Al-Mg alloys [26]

Alloy	Temper	Plate-thickness (mm)	Proof Strength Rp0.2 (MPa)	Ultimate tensile strength; Rm (MPa)	Elongation A (%)
5059 **) ALUSTAR ™ (AlMg5.2MnZnZr)	O / H111	< 20	160	330	24
5083 (AlMg4.5Mn0.7)	O / H111 H112	12.5 - < 50 12.5 - < 40	125 125	275 275	16 10
5049 **) (AlMg2Mn0.8)	O / H111 H112	12.5 - < 100 12.5 - < 25	80 90	190 200	17 10
5454 *) AlMg3Mn	O	2.9 – 76.2	83	214	18
5754 **) (AlMg3)	O / H111 H112	12.5 - < 100 12.5 - < 25	80 90	190 190	17 10

*) in acc. to ASTM B 209 (Tensile tested in L – direction)

**) in acc. to EN 485-3 (Tensile tested in LT – direction)

Mechanical properties of weldments of O/H111 condition material can be seen equal to base material. There is no necessity for a post weld treatment (Telephone conversation with Dr. Miermeister, Aleris). In higher strength conditions, properties of weldments decrease to that of O/H111 condition. Figure 5-1shows strength of MIG welded Plates in H321 temper with an AA5183 filler in after weld condition. [25]

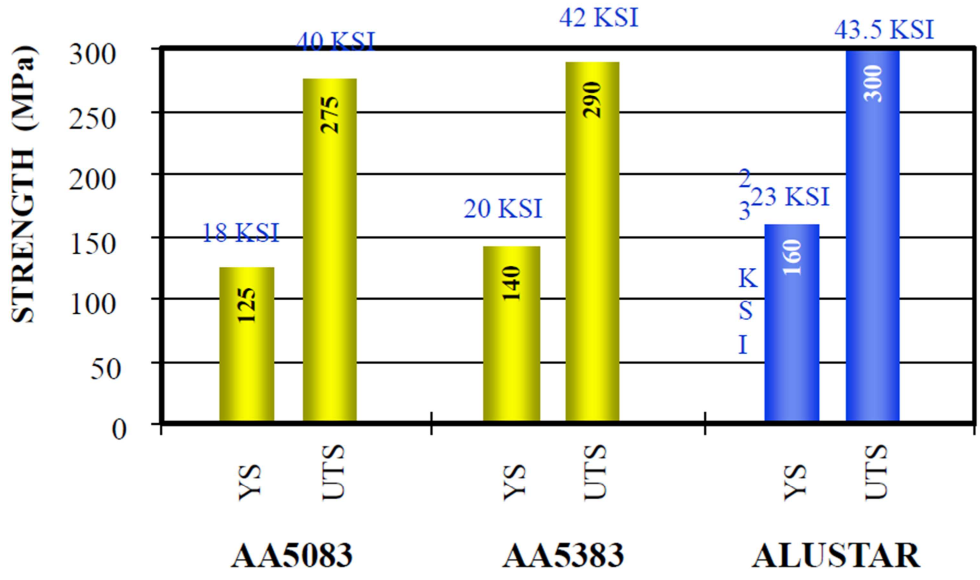


Figure 5-1 After weld strength of MIG welded plate [25]

There are tempers of higher strength like H131/H136 or H321, but this higher strength goes on the expense of elongation to break, which can be seen as an indicator for damage tolerance.

Table 5-2 shows minimum mechanical properties of Al- Mg alloys in H131 temper.

Table 5-2 Minimum mechanical Properties of armor materials [27]

Alloy	Temper	Specification*	Test direction	Plate thickness mm	in	Tensile strength R_m MPa	ksi	Yield strength $R_{p0.2}$ MPa	ksi	Elongation A %
AA 5083	H131	MIL-DTL-46027	L	6.35 - 12.67	0.250 - 0.499	310	45.0	241	35.0	8
		(table VI)		12.7 - 50.8	0.500 - 2.000	310	45.0	255	37.0	8
				50.83 - 76.2	2.001 - 3.000	303	44.0	241	35.0	9
EN AW 5083	H131	TL 2350-0004	LT	6.35 - 12.67	0.250 - 0.499	311	45.0	242	35.0	8
				12.7 - 50.8	0.500 - 2.000	311	45.0	256	37.0	8
				50.83 - 76.2	2.001 - 3.000	304	44.0	242	35.0	9
AA 5059	H131	MIL-DTL-46027	L	6.35 - 12.67	0.250 - 0.499	393	57.0	303	44.0	8
Alustar®		(table VI)		12.7 - 50.8	0.500 - 2.000	393	57.0	296	43.0	7
				50.83 - 76.2	2.001 - 3.000	344	50.0	289	42.0	8
EN AW 5059 Alustar®	H131	TL 2350-0004	LT	6 - 60	0.236 - 2.362	370	54.0	300	44.0	8
AA 5059	H136	MIL-DTL-46027	L	6.35 - 12.67	0.250 - 0.499	365	53.0	296	43.0	10
Alustar®		(table VI)		12.7 - 50.8	0.500 - 2.000	358	52.0	289	42.0	10
				50.83 - 76.2	2.001 - 3.000	344	50.0	289	42.0	10
AA 2519	T87	MIL-A-46192	L	12.7 - 38.1	0.500 - 1.500	455	66.0	407	59.0	10
		(table II)		38.1 - 50.8	1.501 - 2.000	455	66.0	407	59.0	9
				50.8 - 76.2	2.001 - 3.000	462	67.0	414	60.0	8
				76.2 - 101.6	3.001 - 4.000	469	68.0	421	61.0	7
AA 7017	T6	TL 2350-0004	LT	6 - 50	0.236 - 1.969	430	62.4	360	52.2	8
				> 50 - 76	>1.969 - 2.992	410	59.5	340	49.3	8
				> 76	>2.992	410	59.5	340	49.3	6
EN AW 7020	T6	TL 2350-0004	LT	≤ 25	≤0.984	350	50.8	280	40.6	10
				> 25 - 60	>0.984 - 2.362	340	49.3	275	40.0	8
AA 7039	T6	MIL-DTL-46063	L	≤ 38.1	≤1.5	414	60.0	352	51.0	9
		(table II)		> 38.1	>1.5	393	57.0	331	48.0	8

* Mechanical properties according to table VI of MIL-DTL-46027 for standard dimensions up to 60" x 140" (width x length)
For wider plates with dimensions 60" < width ≤ 100" mechanical properties are guaranteed according to MIL-DTL-46027 table II
Other dimensions on request

Corrosion tests were conducted by the material manufacturer according to ASTM G66 (ASSET Test), ASTM G67 (Weight loss Test) and ASTM G39 (Stress Corrosion Cracking). Figure 5-2 shows the results of the ASSET corrosion test results of welded and non-welded plates of AA5083 compared to AA5059 (ALUSTAR). Notable the improved corrosion behavior, no pitting corrosion is visible in the Alustar material.

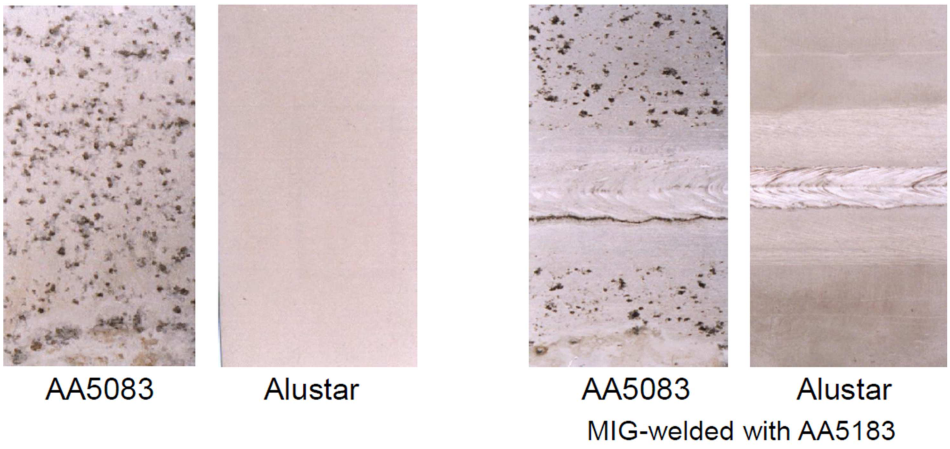


Figure 5-2 ASSET Corrosion Test Results before and after Welding [25]

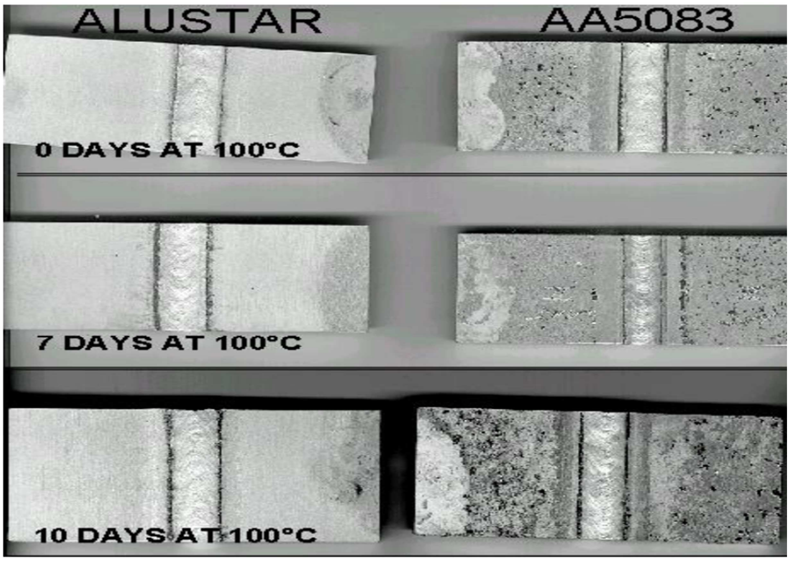


Figure 5-3 Surface of sensitized samples after the ASSET Test [25]

Figure 5-3 shows the surfaces of the sensitized welded samples after different times of testing.

In both examples can be seen, that corrosion resistance is better or equal to AA5083 before and after welding as well as in sensitized condition. Also Stress corrosion testing showed no SCC after 8000 hours off intermittently immersion in 3.5% NaCl and an applied stress (LT) of 195 MPa respectively 130 MPa in welded specimens. [25]

Up to now, there are was no fracture toughness testing done by Aleris for AA5059 in the O/H111 condition (e-mail by Thorsten Wehner, Manager Product Application, Aleris).

5.1.3 AA8090

Aluminum alloy 8090 is an aluminum- copper- magnesium- lithium alloy which was registered to the aluminum association in 1984. Containing 2.2% to 2.7% Lithium, it belongs to the 2nd generation AL-Li alloys and can be regarded a typical example of this group.

The outstanding attribute of this alloy is its low density of only 2.54 kg/dm^3 which is about 10% less than the one of average Al-alloys and one of the lowest values of commercial Al-alloys. This is due to the high content of lithium, which also accounts for the high modulus of elasticity. Another remarkable attribute of the material is its good damage tolerance. On the other hand, AA8090 exhibits drawbacks like a strong anisotropy in properties.

Several tempers have been developed to offer useful combinations of strength, damage tolerance and corrosion resistance as can be seen in Table 5-3.

Table 5-3 Temper designations for aluminum-lithium alloy 8090 [2]

Temper(a)	Characterization	Forms
T8, T8X	Near-peak-aged medium-strength sheet product	Sheet
T81	Underaged damage-tolerant sheet	Sheet
T8771, T651, T7E20	Near-peak-aged plate	Plate
T8151, T8E57	Underaged damage-tolerant plate	Plate
T6511, T8511/10	Medium-to-high-strength peak-aged extrusions	Extrusions
T8771, T852	Medium-strength peak-aged forgings	Forgings

(a) Temper designations are not registered; this listing is a recap of designations that producers and users have used.

Table 5-4 shows strengths at different temperatures of different tempers.

Primary strengthening precipitates in AA8090 are δ', T_1 and S'. Due to the low copper/ magnesium ration, the precipitation of S' is favored, so the achieved strengths are lower than the ones of other Al-Li alloys [2].

Alloy 8090 is available as sheet, plate, extrusions and forgings. While plates, extrusions and forgings usually have a recrystallized microstructure, high strength sheet is available with recrystallized or unrecrystallized microstructure. Figure 5-4 shows the recrystallized and unrecrystallized grain structure of alloy 8090 sheet.

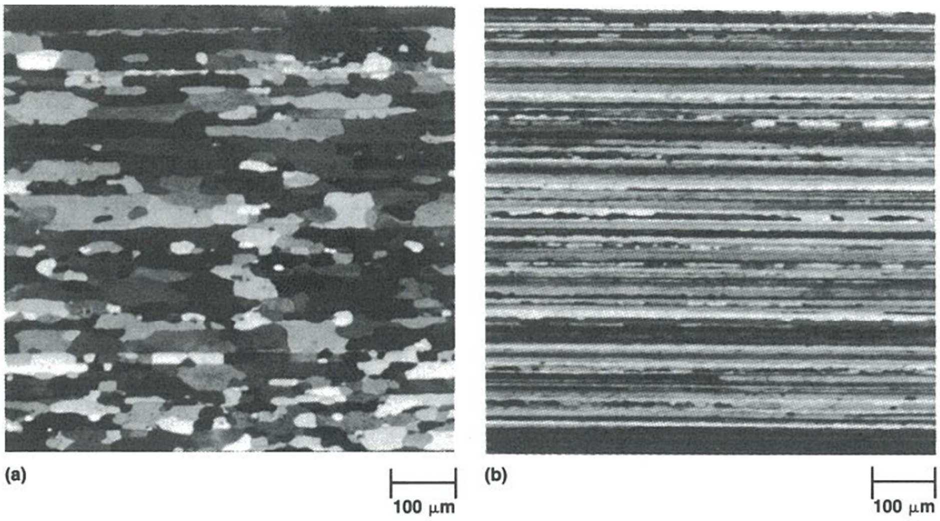


Figure 5-4 Recrystallized and unrecrystallized grain structure of AA8090 sheet

Strength and other mechanical properties of alloy 8090 in different conditions can be seen in the following Table 5-4. Tensile and toughness properties in Table 5-5.

Table 5-4 Tensile properties and fracture toughness of aluminum alloy 8090 [2]

Temper	Product form	Grain structure(a)	Direction	Minimum and typical(b) tensile properties: Ultimate tensile strength, MPa	ksi	0.2% yield strength, MPa	ksi	Elongation in 50 mm (2 in.), %	Minimum and typical(b) fracture toughness values: Fracture orientation(c) and toughness type (K_c or K_{Ic})(d)	Toughness value(b), MPa $\sqrt{m}$	ksi $\sqrt{in.}$
8090-T81 (underaged)	Damage-tolerant bare sheet <3.55 mm (0.140 in.) thick	R	Longitudinal	345–440	50–64	295–350	43–51	8–10 typ	L-T (K_c)	94–165	86–150
			Long transverse	385–450	56–65	290–325	42–47	10–12	T-L (K_c)	85 min	77 min
			45°	380–435	55–63	265–340	38.5–49	14 typ	S-L (K_c)	...	...
8090-T8X (peak aged)	Medium-strength sheet	UR	Longitudinal	470–490	68–71	380–425	55–62	4–5	L-T (K_c)	75 typ	68 typ
			Long transverse	450–485	65–70	350–440	51–64	4–7	T-L (K_c)	...	...
			45°	380–415	55–60	305–345	44–50	4–11	S-L (K_c)	...	...
8090-78X	Medium-strength sheet	R	Longitudinal	420–455	61–66	325–385	47–56	4–8	L-T (K_c)	...	...
			Long transverse	420–440	61–64	325–360	47–52	4–8	T-L (K_c)	...	...
			45°	420–425	61–62	325–340	47–49	4–10	S-L (K_c)	...	...
8090-T8771, 8090-T651 (peak aged)	Medium-strength plate	UR	Longitudinal	460–515	67–75	380–450	55–65	4–6 min	L-T (K_{Ic})	20–35	18–32
			Long transverse	435 min	63 min	365 min	53 min	4 min	T-L (K_{Ic})	13–30	12–27
			Short transverse	465 typ	67 typ	360 typ	52 typ	...	S-L (K_{Ic})	16 typ	14.5 typ
			45°	420 min	61 min	340 min	49 min	1–1.5 min			
8090-T8151 (underaged)	Damage-tolerant plate	UR	Longitudinal	435–450	63–65	345–370	50–54	5 min	L-T (K_{Ic})	35–49	32–45
			Long transverse	435 min	63 min	325 min	47 min	5 min	T-L (K_{Ic})	30–44	27–40
			45°	425 min	61.5 min	275 min	40 min	8 min	S-L (K_{Ic})	25 typ	23 typ
8090-T852	Die forgings with cold work, or hand forgings	UR	Longitudinal	425–495	62–72	340–415	49–60	6–8	L-T (K_{Ic})	30 typ	27 typ
			Long transverse	405–475	59–69	325–395	47–57	3–6	T-L (K_{Ic})	20 typ	18 typ
			45°	405–450	59–65	305–395	44–57	2–6	S-L (K_{Ic})	15 typ	14 typ
8090-T8511, 8090-T6511	Extrusions	UR	Longitudinal	460–510	67–74	395–450	57–65	3–6	...	...	...

(a) R, recrystallized; UR, unrecrystallized. (b) Unless otherwise specified as only a minimum (min) or a typical (typ) value, the two values given for a property represent its minimum and typical value. The minimum values are proposed by various customer and national specifications and do not reflect a uniform registration. (c) See Fig. 23 for a diagram of fracture orientations. (d) K_c, plane-stress fracture toughness; K_{Ic}, plane-strain fracture toughness

Table 5-5 Cryogenic tensile and toughness properties of 8090-T3 [2]

Test temperature, K	Direction	Tensile properties: Yield strength, MPa	ksi	Tensile strength, MPa	ksi	Elongation in 38 mm (1.5 in.), %	Reduction in area, %	Toughness, MPa $\sqrt{m}$	ksi $\sqrt{in.}$
295	Longitudinal	217	31.5	326	47	12	18	...	...
	Transverse	208	30	348	50.5	14	26	...	...
76	Longitudinal	248	36	458	66.5	22	27	97(a)	88(a)
	Transverse	241	35	450	65	20	37	60(b)	55(b)
20	Longitudinal	272	39.5	609	88.3	28	28	...	...
	Transverse	268	39	592	86	25	27	...	...
4	Longitudinal	280	41	605	88	26	28	74(a)	67(a)
	Transverse	270	39	597	86.5	24	29	50(b)	45(b)

(a) Toughness with an L-T crack orientation (crack plane and growth direction perpendicular to the rolling direction). (b) Toughness with a T-L crack orientation (crack plane and growth direction parallel to the rolling direction)

Corrosion properties like exfoliation ratings and SCC thresholds for alloy 8090 are mentioned in Table 5-6. Tensile behavior of weldments are shown in Table 5-7 and the fracture toughness of the alloy at cryogenic temperatures is displayed in Figure 5-5 Fracture toughness over temperature for alloy 8090.

Table 5-6 Exfoliation ratings and SCC thresholds for aluminum-lithium alloy 8090 [2]

Temper	Product	Microstructure	Exfoliation rating(a): EXCO test(b)	MASTMAASIS test(c)	Atmospheric exposure	SCC threshold
8090-T81 (underaged)	Sheet	Recrystallized	EA	EA	P, EA	60% of yield strength in the L-T direction
8090-T8 (peak aged)	Sheet	Recrystallized	ED	EA	P	
8090-T8510/11 (peak aged)	Extrusions	Unrecrystallized	...	...	...	75% of yield strength in the L-T direction
8090-T8771, 8090-T651 (peak aged)	Plate	Unrecrystallized	Surface P	...	Surface P	105–140 MPa (15–20 ksi) short-transverse threshold
8090-T851	Plate	Unrecrystallized	EC(d)	EB(d)	P, EA	
8090-T8 (peak aged)	Sheet	Unrecrystallized	EC	EB	...	75% of yield strength in the L-T direction
8090 (peak aged)	Forgings	Unrecrystallized	...	...	...	140 MPa (20 ksi) short-transverse threshold

(a) Exfoliation rating per ASTM G 34: P, pitting; EA, superficial—tiny blisters, thin slivers, flakes or powders with only slight separation of metal; EB, moderate, notable layering and penetration in metal; ED, very severe—penetration to a considerable depth and loss of metal. (b) Exfoliation corrosion test per ASTM G 34. (c) MASTMAASIS, modified ASTM acetic acid salt intermittent spray. (d) Rating at a plane location of T/2, where T is plate thickness

Table 5-7 Tensile behavior of 8090-T6 weldments [2]

Alloy	Filler	Heat treatment	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %
Unwelded 8090-T6	...	...	504	73	429	62.2	6
8090-T6	Al	As-welded	165	24	137	19.9	5
8090-T6	Al-5Si	As-welded	205	30	165	24	3
8090-T6	Al-5Mg	As-welded	228	33	176	25.5	4
8090-T6	Al-5Mg	As-welded + T6 temper	302	43.8	245	35.5	4
7017-T6	Al-5Mg	30 days natural aging	340	49	220	32	8
8090-T6	Al-5Mg (+Zr)	As-welded	235	34	183	26.5	4
8090-T6	8090	As-welded	310	45	285	41	2
8090-T6	8090	As-welded + T6 temper	367	53.2	315	45.5	4
2219-T851	2319	As-welded	300	43.5	185	27	5

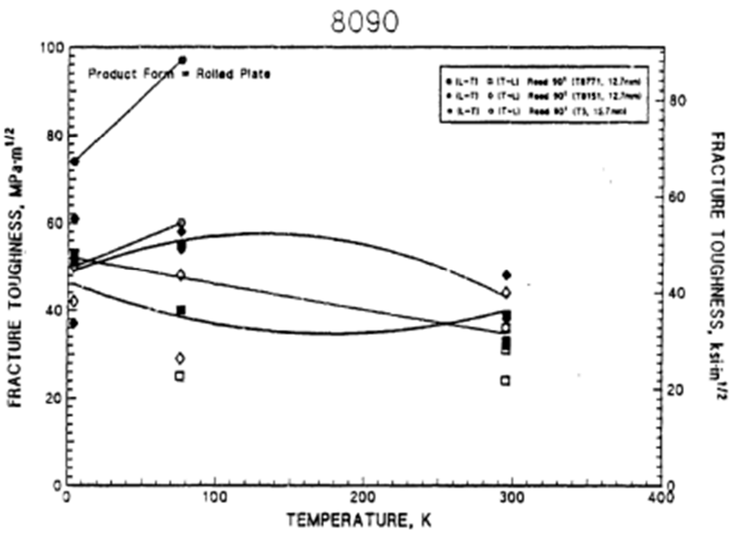


Figure 5-5 Fracture toughness over temperature for alloy 8090 [28]

Excessive data is available concerning AA8090, and some of them seem very promising, like the low density and the good properties at cryogenic temperatures. But like other 2nd generation alloys, its availability is doubtful although the material it is listed at some shops (www.smithshp.com). According to Aluminum producers, the production of 2nd generation alloys was discontinued with development of new products. This is why this alloy is not included in the final tradeoff.

5.1.4 AA2219

Aluminum Alloy 2219 has a famous history in cryogenic applications, as it was used as material for the Space Shuttle Tank before it was replaced by AA2195. The material seems very suitable for the use in cryogenic applications and is widely applied in this field.

Strength and elongation to break both increase, as temperature is lowered. For AA2219 T81, yield strength raises from 345 MPa at room temperature to 420 MPa at -195°C. Elongation to break rises from 12% at room temperature to 16% at -195°C, which is quite a high level considering the alloys in this paper, nevertheless low compared to some stainless steels, which makes it the chief deterrent for use in the public sector. [2]

Comparing Figure 5-6 and Figure 5-7 illustrates, that differences in properties in different directions are quite small, so the material shows good isotropic behavior. Also strength increases as temperature falls. The same behavior can be seen for fracture toughness as shown in Figure 5-8.

Alloy 2219 is easily welded with all arc welding methods.

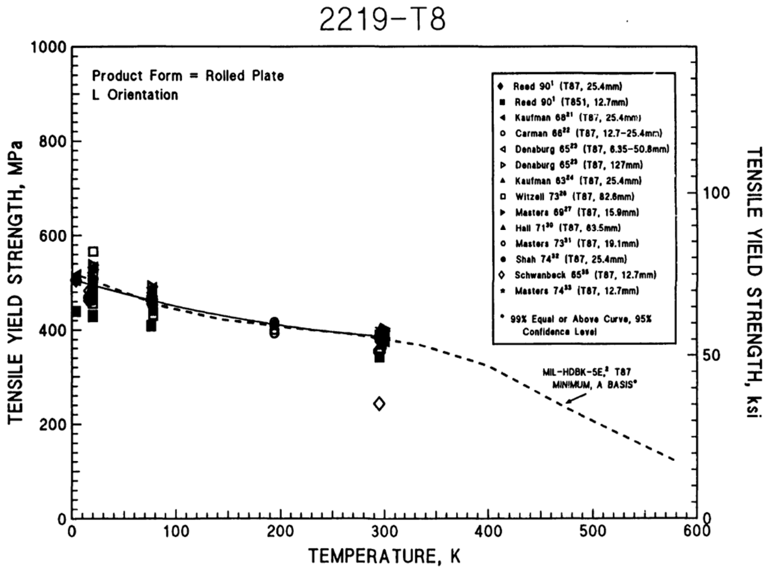


Figure 5-6 Yield Strength of Alloy 2219 T8- L Orientation [29]

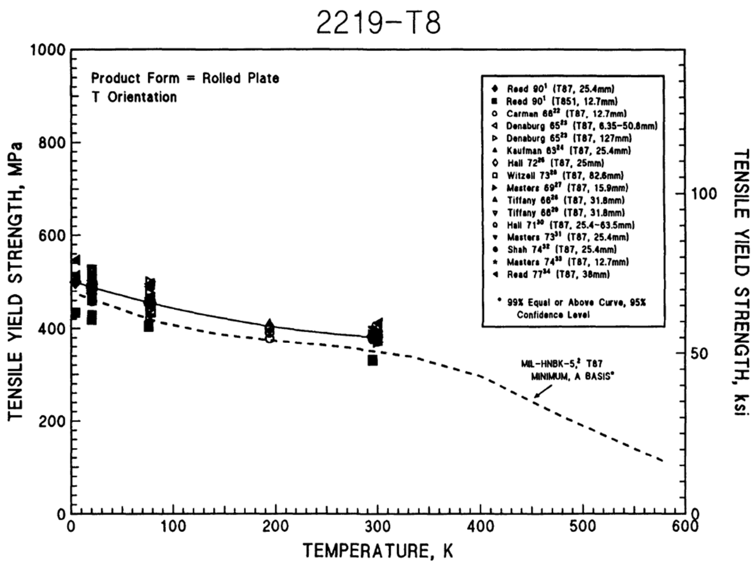


Figure 5-7 Yield Strengt of Alloy 2219 T8- T Orientation [29]

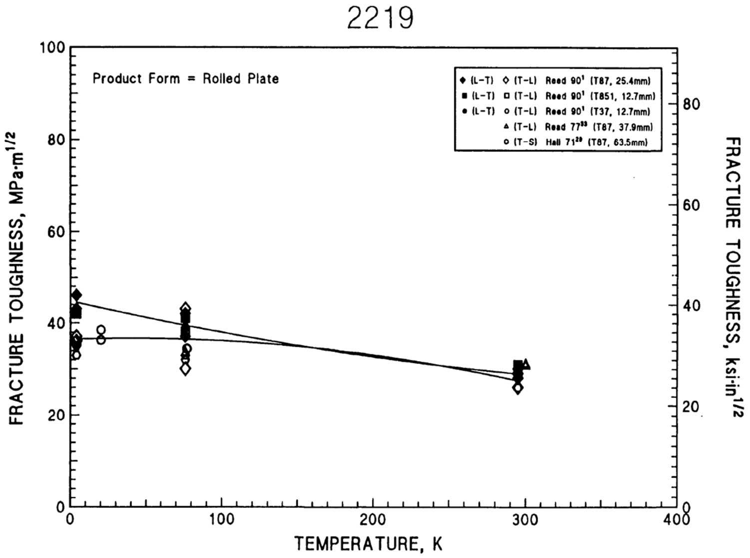


Figure 5-8 Fracture Toughness vs. Temperature of Alloy 2219 [29]

Alloy 2219 is well established in aerospace and cryogenic applications. Data on the alloy is easily available. The material itself is also available, consequently it is included in the final tradeoff.

5.1.5 AA2195

Aluminum alloy 2195, developed by ALCAN in 1992, belongs to the Weldalite 049 family [11].

This alloy owes its high profile probably to the fact, that it was used in the Space Shuttle as material for the “super lightweight tank” (SLWT), a designation the external tank of the Space Shuttle got after the preceding material, 2219, was replaced by the higher strength and less dense 2195.

Downside of the Material is for example its anisotropic behavior. Strength values decrease about 18% in angle of 55° to longitudinal axis (rolling direction), see Figure 5-9 Strength and Elongation depending from rolling direction for alloy 2195 Figure 5-9.

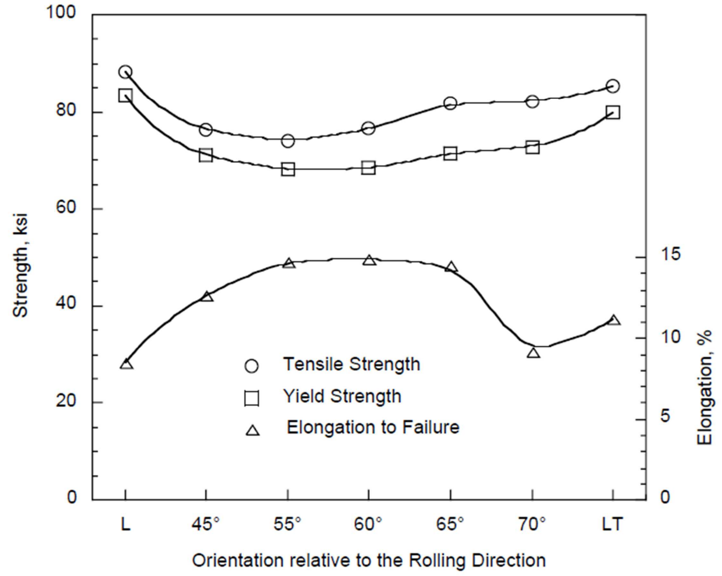


Figure 5-9 Strength and Elongation depending from rolling direction for alloy 2195 [30]

Although the material is quite famous, data concerning mechanical properties and behavior is hard to find. Figure 5-10 shows test results of tensile strength of base material and FSW welded parts, conducted by different labs, in comparison.

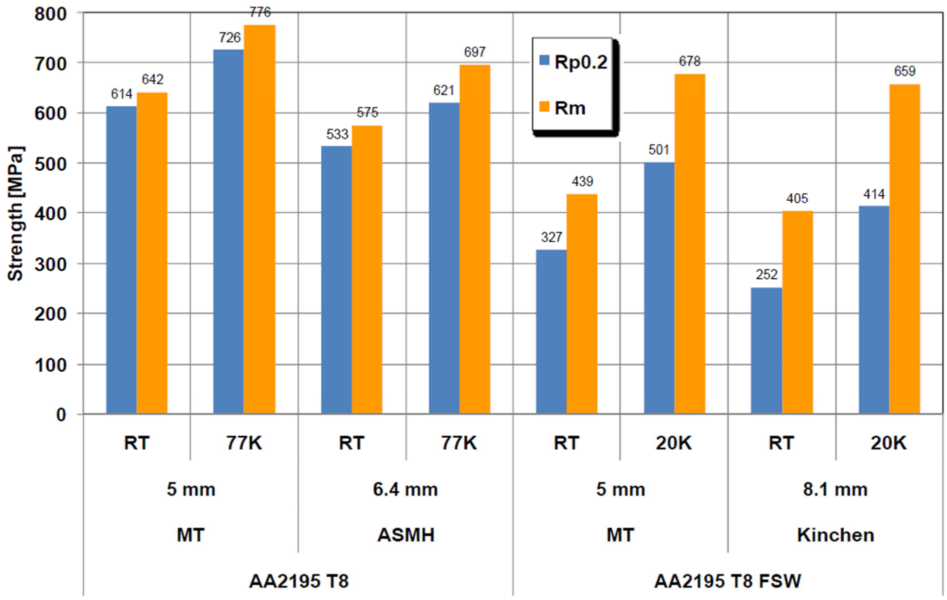


Figure 5-10 Strength of 2195 base material and FSW weldments

Table 5-8 Plain-strain fracture toughness of Weldalite 049 extruded bar [2]

Temperature °C	Temperature °F	Temper designation	Orientation(a)	K_{Ic} MPa√m	K_{Ic} ksi√in.	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi
21	70	T3	L-T	36.9	33.6	530	77	405	59
21	70	T3	T-L	30.9	28.1	485	70	350	51
21	70	T3	T-L	29.8	27.1	485	70	350	51
21	70	T6E4	L-T	30	27.3	650	94	605	88
21	70	T6E4	L-T	29	26.4	650	94	605	88
−195	−320	T3	T-L	31.8	28.9	615	89	455	66
−195	−320	T3	T-L	30.9	28.1	615	89	455	66

(a) L-T, crack plane perpendicular to extrusion direction; T-L, crack plane parallel to extrusion direction

Table 5-9 Mean longitudinal tensile properties of Weldalite 049 in various tempers and product forms [2]

Description and/or temper	Yield strength MPa	Yield strength ksi	Ultimate tensile strength MPa	Ultimate tensile strength ksi	Elongation in 50 mm (2 in.), %
Extruded products(a)					
T3	407	59.0	529	76.7	16.6
T4	438	63.5	591	85.7	15.7
Reversion	331	48.0	484	70.2	24.2
T6	680	98.7	720	104.4	3.7
T8	692	100.4	713	103.5	5.3
2219-T81					
Minimum	303	44.0	420	61.0	6.0
Typical	352	51.0	455	66.0	10.0
Rolled products(b)					
T8, 5 mm (0.2 in.) thick(c)	643	93.3	664	96.3	5.7
T6, 5 mm (0.2 in.) thick(c)	625	90.7	660	95.8	5.2
T6A, 5 (0.2 in.) mm thick	642	93.1	665	96.5	5.2
T6B, 5 (0.2 in.) mm thick	662	96.0	686	99.5	3.7
T6A, 6.35 mm (0.25 in.) thick	671	97.3	700	101.6	5.3
T6B, 6.35 mm (0.25 in.) thick	668	96.7	692	100.3	5.6
T6A, 9.5 mm (0.38 in.) thick	650	94.3	672	97.4	5.1
Forging(d)					
T4, naturally aged for 1000 h	392	56.9	559	81.1	18.5
Slightly underaged (170 °C, or 340 °F, for 20 h)	658	95.5	702	101.8	5.0

(a) Most are 100 × 9.5 mm (4 × 0.375 in.) extruded plate. (b) Rolled from 180 kg (400 lb) pilot commercial ingots. (c) For tankage. (d) Commercial hook forging

In Table 5-8, fracture toughness and strength values of alloy 2195 are listed. Table 5-9 lists tensile properties of the alloy in different conditions.

Although the material is listed at some shops like Smiths High Performance in the UK (www.smithshp.com), the actual availability of the material is doubtful, as by producers of AL-Li alloys was stated, production of former generation alloys was discontinued with development of new products. Consequently, this alloy is not included in the final tradeoff.

5.2 New Materials

5.2.1 AA5024

Aluminum Alloy 5024 is- as the number indicates- a material of the Al-Mg series which was modified by the addition of scandium. It was developed by Corus/Aleris as an alternative to the Al-Li alloys which are used in aerospace applications. Main advantage of the alloy is the easy weldability compared to Al-Li alloys. The material was developed by the smelter in cooperation with Airbus to achieve a material suitable for fuselage skins with welded-on stringers. In this project, the stringers were welded on by laser beam welding, but welding by conventional methods seems to be possible as well. Nevertheless, quite an amount of testing would be necessary in this field, as well as for the welding process itself as for the thermal treatment of the welded part.

A major drawback of the material is the high price of scandium, which makes the alloy quite expensive. According to the producer, the future of the alloy depends on the chart development of the scandium price. If the price for the alloying element does not decrease in the near future, the development and production of the alloy is likely to be discontinued. Right now, this alloy is not used in any commercial aerospace application.

The properties of AA5024 are achieved by exposing the alloy to a temperature of about 300° Celsius before the material is delivered to the customer. During this treatment, the aluminum-scandium compound Al_3Sc precipitates from the matrix.

Usually, aluminum alloy 5024 is produced in sheet form. There also were trials to produce the material as plate, but properties were worse than that of sheet material due to less cold work during production. So it does not seem to make much sense to produce the alloy in plate form, especially, as plates of aluminum alloys often are machined by stock removal, which is quite adversely in combination with a high material price.

Theoretically, it is also possible to form the material by extrusion, but the strength of the extruded material is worse than that of rolled sheet.

So far, the material has not been tested at cryogenic temperatures by the producer.

The prize of the material is round about $50 per kilo, according to informal information of the producer. (Telephone conversation with Dr. Matthias Miermeister, Aleris, July 29th, 2013)

This material is an interesting representative of the Al-Sc group and is included in the final tradeoff.

5.2.2 C557

Alloy C557 was developed by ALCOA as a material resistant to H2O2, more corrosion resistant than 7X0X and 7X11 (two experimental Al-Sc alloys which do not contain secondary strengthening precipitates from Mg, Zn, and Cu)

Although some properties of the material seem promising, it has shown adversely cracking behavior at low temperatures as found in tests conducted by NASA. Also no supplier for this material could be found, it is currently not offered by the producer. Hence I could not take part in the final tradeoff.

5.2.3 AA2198

2198 is a modification of 2098, which was designed for some high load fuselage parts of the F-16 fighter by McCook Metals. The variation 2198, differing in a lower content of Copper and some other minor adaption in chemical composition to optimize toughness, was developed by ALCAN in 2005. [16]

Figure 5-11 shows tensile tests of alloy 2198, samples taken in L, T and D direction and of two different tempers T3 and T8

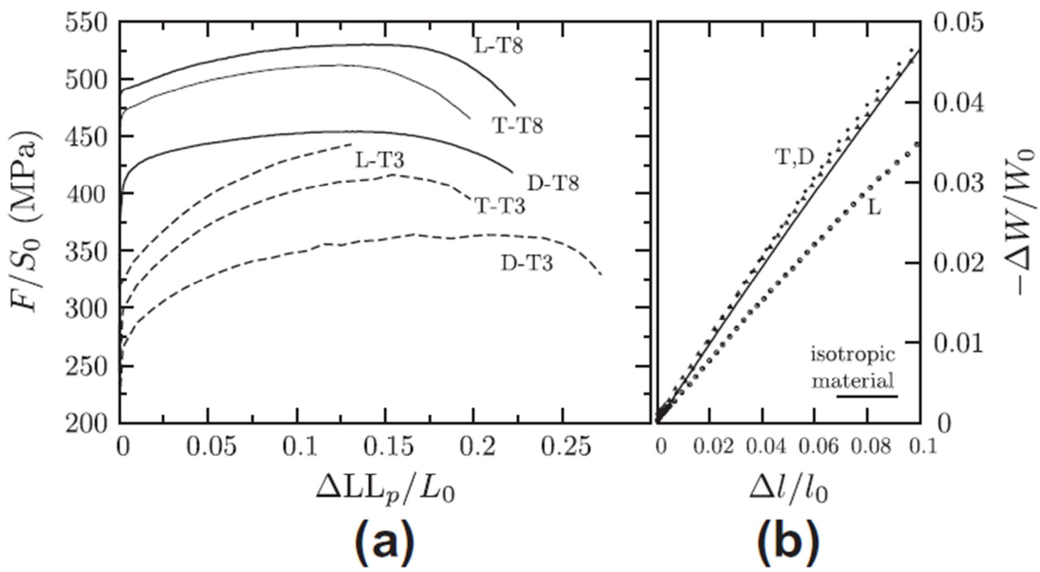


Figure 5-11 Tensile tests of alloy 2198 in different directions

Figure 5-11 (a) shows the nominal stress as a function of displacement. It is typical for Al-Cu-Li alloys, that D- direction shows a much lower yield limit than other directions. It is notable, that T3 material in L- direction fails while the load is still increasing, so it does not show necking. Figure 5-11 (b) shows the specimen- width reduction as a function of axial strain. Dotted lines are test specimen, solid line is the isotropic case for reference. Notable is the large deviation of the L- direction, while T and D are close to isotropy. [16]

There was no supplier found for this material. It is not included in the tradeoff.

5.2.4 2099 and 2199

Aluminum alloys 2099 and 2199 were registered by ALCOA in the 2000s and developed in the years before, so they can be considered as fairly new materials. The composition of AA2099 and AA2199 is basically equal and differs only by the tolerance windows of the composition elements. Table 5-10 shows the composition limits of AA2099 and AA2199 as registered at the Aluminum Association.

Table 5-10 Aluminum Association Registered Composition for 2099 and 2199 [31]

Alloy (wt%)	2099	2199
Cu	2.4 - 3.0	2.3 - 2.9
Li	1.6 - 2.0	1.4 - 1.8
Zn	0.40 - 1.0	0.2 - 0.9
Mg	0.1 - 0.5	0.05 - 0.40
Mn	0.1 - 0.5	0.1 - 0.5
Zr	0.05 - 0.12	0.05 - 0.12
Fe	0.07 max.	0.07 max.
Si	0.05 max.	0.05 max.
Al	Remainder	Remainder

The purpose of the Copper is to form strengthening precipitates of T_1 (Al_2CuLi) and θ' (Al_2Cu) Type. Also some T_2 (Al_6CuLi_3) is formed, which increases toughness. While T1 nucleates at dislocations and subgrain boundaries, T_1 and T_2 phase can form at grain boundaries. However, to much precipitation at grain boundaries can be adversely to toughness.

Lithium is of course added to reduce the density of the alloy, but it also increases strength. Additional to its contribution to T_1, T_2 and θ', lithium also is present in δ' (Al_3Li), which enhances strength of the alloy.

Zinc is added to enhance the corrosion resistance of the alloy. As it has not been observed in precipitates, it is most likely present in solid solution. Magnesium enhances strength, as it substitutes for Li in the T_1 phase to form Al_2(Cu, Li-Mg) precipitates. There is no precipitate exclusively formed by Mg.

Manganese forms incoherent $Al_{20}Cu_2Mn_3$ dispersoids. This phase improves damage tolerance with regards to fatigue and fracture toughness by homogenizing slip. It also influences grain size and texture evolution during thermo mechanical processing.

Zirconium forms coherent β' (Al_3Zr) dispersoids, which is the main phase used to control recrystallization as well as the δ' phase (Al_3Li) precipitates on the surface of β' dispersoids.

The T_1 phase is the most effective strengthener in the aluminum- lithium alloy. Its effect can be increased to a great extent by stretching of the material prior to aging. It was found, that stretching prior to aging improves the strength- toughness relationship in Al-Li alloys. This is due to the fact, that stretching reduces the size of strengthening precipitates and increases their volume fraction. Stretching also reduces the precipitation of T_1 and T_2 at grain boundaries. This can be seen by comparing the strength and toughness of products in the T6 temper (where no stretching is performed) and T8 temper (where stretching is performed prior to aging).

Alloy 2099 and Alloy 2199 products are processed to have an unrecrystallized microstructure, as this is the preferred microstructure for precipitation hardened aluminum alloys for an improved fracture toughness. 2099 and 2199 exhibit the “brass” structure of unrecrystallized conditions, which lead to a disadvantageous strong anisotropy in properties, only to a low extent. [31]

Table 5-11 shows some properties of 2199 plate in two different tempers compared to 2024 plate.

Table 5-11 Properties for Al-Li 2199-T8E79 and 2199-T8E80 plate compared to 2024-T351

Alloy	2024-T351	2199-T8E79	2199-T8E80
Thickness, mm (in.)	25.4-38.1 (1 - 1.5)	12.7-38.1 (0.5-1.5)	12.7-38.1 (0.5-1.5)
Basis	A⁻	S (est.)*	S (est.)*
F_{tu}, MPa (ksi)			
L	428 (62)	400 (58)	428 (62)
LT	428 (62)	400 (58)	428 (62)
F_{ty}, MPa (ksi)			
L	324 (47)	345 (50)	380 (55)
LT	290 (42)	345 (50)	380 (55)
F_{cy}, MPa (ksi)			
L	269 (39)	345 (50)	380 (55)
LT	304 (44)	345 (50)	380 (55)
F_{su}, MPa (ksi)			
L-S	255 (37)	235 (34)	248 (36)
T-S	255 (37)	235 (34)	248 (36)
F_{bru} [a], MPa (ksi) e/D = 1.5			
L	649 (94)	593 (86)	649 (94)
LT	649 (94)	607 (88)	656 (95)
F_{bru} [a], MPa (ksi) e/D = 2.0			
L	794 (115)	780 (113)	842 (122)
LT	794 (115)	794 (115)	849 (123)
e, percent (S-basis)			
L	7	8	8
LT	-	9	8
Klc (K_Q), MPa√m (ksi√in)			
L-T	30 (27)	42 (38)	42 (38)
T-L	-	36 (33)	36 (33)
Kc^, MPa√m (ksi√in)			
L-T	-	143 (130)	143 (130)
T-L	-	121 (110)	121 (110)
Spectrum FCG, % increase flights	Baseline	45%	35%
Stress Corrosion, MPa (ksi) LT, 30 days	> 170 (25)	> 310 (45)	> 310 (45)
Exfoliation Corrosion	ED	EA#	EA#
Density, g/cm³ (lb/in³)	2.77 (0.100)	2.64 (0.095)	2.64 (0.095)
E, GPa (msi)	73.8 (10.7)	77.3 (11.2)	77.3 (11.2)

⁻Static values from MMPDS 1 April 2005, * Estimates, [a] Bearing values are "dry pin" values. ^M(T), W=406mm, B=6.35mm, # ASTM G85 Annex 2.

Table 5-12 Properties of Al-Li 2099 T83 extrusions compared to 2024 T3511 [31]

Alloy	2024-T3511	2099-T83
Specification	AMS 4152/4164/4165	AMS 4287
Thickness, mm (in.)	19.05-38.07 (0.75 -1.5)	12.70-25.37 (0.50 - 0.999)
Basis	A	A
F_{tu}, MPa (ksi)		
L	449 (65)	545 (79)
LT	386 (56)	503 (73)
F_{ty}, MPa (ksi)		
L	317 (46)	490 (71)
LT	255 (37)	448 (65)
F_{cy}, MPa (ksi)		
L	283 (41)	476 (69)
LT	276 (40)	476 (69)
F_{su}, MPa (ksi)		
L-S	228 (33)	276 (40)
T-S	228 (33)	262 (38)
F_{bru} [a], MPa (ksi) e/D = 1.5		
L	580 (84)	710 (103)
LT	580 (84)	703 (102)
F_{bru} [a], MPa (ksi) e/D = 2.0		
L	725 (105)	917 (133)
LT	725 (105)	910 (132)
e, percent (S-basis)		
L	10	6
LT	-	6
Stress Corrosion, MPa (ksi)		
LT, 40 days	> 250 (36)	330 (48)
Exfoliation Corrosion	EC	EA
Density, g/cm^3 (lb/in^3)	2.78 (0.100)	2.63 (0.095)
E, 10^3 MPa (msi)	74.5 (10.8)	78.6 (11.4)
E_c, 10^3 MPa (msi)	75.9 (11.0)	82.1 (11.9)
[a] Bearing values are "dry pin" values.		

Table 5-13 Properties of Al-Li 2199 T8 compared to 2024 T351 [31]

Alloy	Alc. 2024-T3	Bare 2199-T8Prime
Specification	AMS-QQ-A -250/15	Estimated
Thickness, mm (in.)	3.3-6.3 (0.123-0.248)	3.0-6.0 (0.118-0.236)
Basis	S	S (est.)
F_{tu}, MPa (ksi)		
L	435 (63)	410 (59)
LT	427 (62)	430 (62)
F_{ty}, MPa (ksi)		
L	311 (45)	345 (50)
LT	311 (45)	340 (49)
F_{cy}, MPa (ksi)		
L	311 (45)	340 (49)
LT	311 (45)	370 (54)
e, percent (S-basis)		
L	15	10
LT	15	8
Kapp, MPa√m (ksi√in)		
T-L [typical]	[88] ([80])	[99] ([90])
FCG, R=0.1, T-L, @ ΔK mm/cycle (in/cycle) [typical]		
10 MPa√m (9.1 ksi√in)	[1.6E-04] ([6.3E-06])	[6.8E-05] ([2.7E-06])
20 MPa√m (18.2 ksi√in)	[1.1E-03] ([4.3E-05])	[2.8E-04] ([1.1E-05])
30 MPa√m (27.3 ksi√in)	[4.7E-03] ([1.9E-04])	[6.5E-04] ([2.6E-05])
Exfoliation Corrosion	n/a	EA
Density, g/cm^3 (lb/in^3)	2.77 (0.100)	2.64 (0.095)
E, GPa (msi)	72.5 (10.5)	78 (11.3)

According to a telephone conversation on August 1st 2013 with Dr. Achim Hofmann, Business Development & Application Engineering Manager at ALCOA, aluminum alloy 2099 is currently the only Al-Li alloy produced and commercially available by ALCOA. Drawbacks of 2nd generation alloys, especially it's affection to form cracks and micro cracks, have led to their discontinuation. AA8090 is founded in some cases especially for single applications and special customers. There is one other Al-Li alloy, 2055, in production, but this alloy is currently under development and not commercially available.

As stated by Dr. Hofmann, there are different methods conceivable to produce tubes of 2099 at ALCOA. One is to extrude the tube, which is possible from wall thicknesses of about 5mm and above. It might be an option to draw the tubes, but this process turned out to be very problematic in the past. Another option is to impact extrude the tubes, where wall thicknesses of about 1 to 2 millimeters should be possible. This way, a tube with a pressed seam will form. This pressed seam is superior to a weld seam in properties, nevertheless it is inferior to base material.

Production of bent tubes, as it is done now, by deep drawing two half shells and weld them together also seems very problematic, as stated by Mr. Gerriet Feyen, Application Engineer at ALCOA, in a telephone conversation. The Sheets of AA2099 receive a quit complex thermo mechanical processing at the factory, before they are delivered to the customer, and formability of the sheets is very limited in this condition.

Welding of the material also is quite complicated. As with welding, the thermal processing of the material is destroyed, it would have to be done again afterwards. As the thermal mechanical processing also, as the name indicates, involves a special sequence of mechanical treatments like working of the material, and thermal treatments, the welded parts should be worked after welding, which seems quite impracticable. So, the reachable mechanical properties of an arc welded seam would be far below the properties of base material. In any case, excessive testing is likely to be necessary to get the process running.

The prize of the alloy depends on many factors and cannot be stated generally, but as a rule of thumb it is about up to 60$ per kilo according to informal information given by ALCOA.

As this material is practically the only one available of the Al-Li group, it is sent to the final tradeoff.

6 FEM Analysis

To check, if aluminum alloys are suitable for the actual feed line design at all, and to get an approximate value for the mechanical stress in the feed line, an FEM analysis was conducted by Magna Steyr with an existing model of the reference feed line. As no specific material was chosen at this point, the material constants which were used for the analysis were mean values for aluminum alloys. As these values do not differ greatly, this approximation seems acceptable for getting a guidance value for aluminum. Material constants used in the FEM analysis were:

- Density
- Modulus of elasticity
- Poisson’s ratio
- Coefficient of thermal expansion

Values checked in the FEM analysis were the first Eigenfrequency, which is given by ESA to be around 100Hz at minimum. Further checked were the stresses in the line due to the pressure of the fuel, due to the thermal expansion, due to the weight of the line and the fuel, due to an enforced displacement of the line ends and due to a combination of these loads.

To calculate stresses in the feed line, von-Mises method for comparison stress was used.

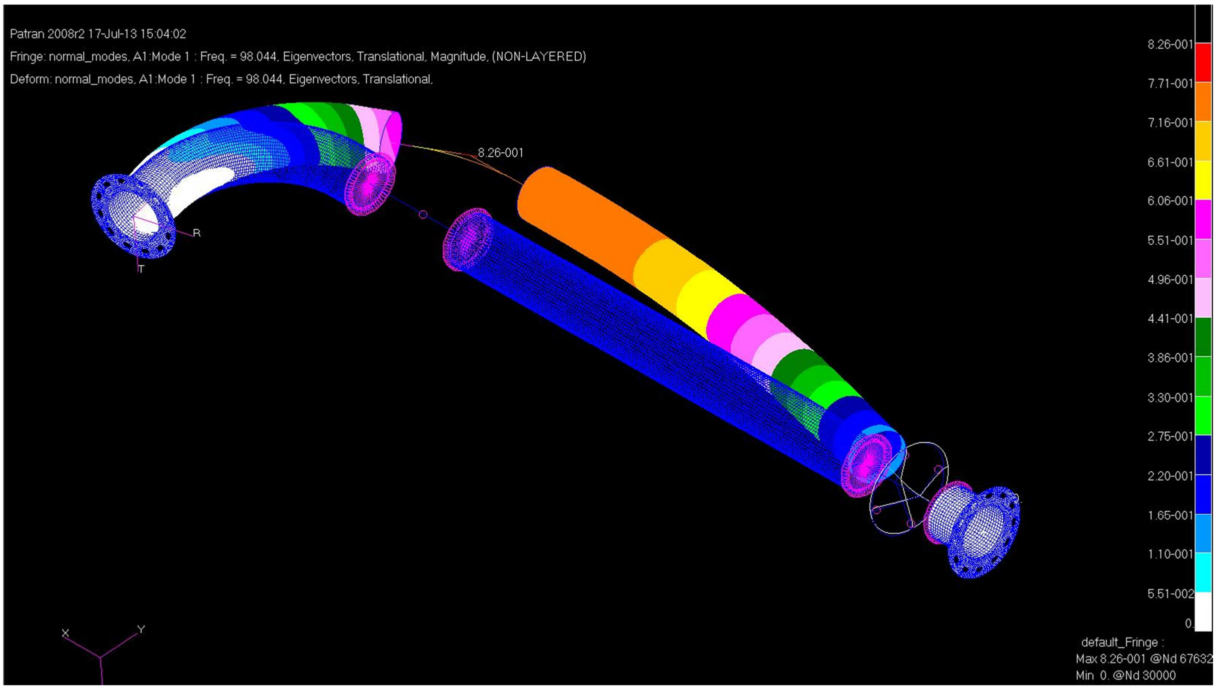


Figure 6-1 FEM Analysis of Aluminum Feed Line Eigenfrequency

The first calculated eigenfrequency of the feed line made of an aluminum alloy is at 98Hz. Although the desired value is 100Hz, this is sufficient

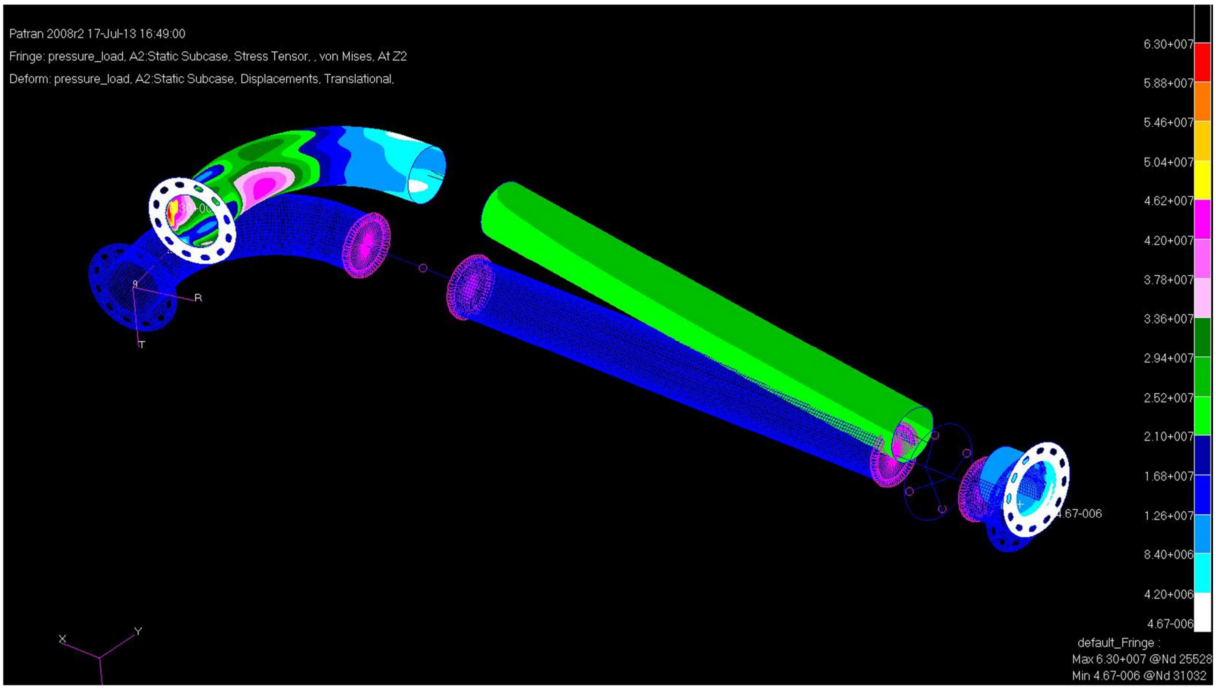


Figure 6-2 FEM analysis of Aluminum Feed Line Pressure Load

The calculated stress level is quite low. For pressure load, it is not more than 63MPa as can be seen in Figure 6-2

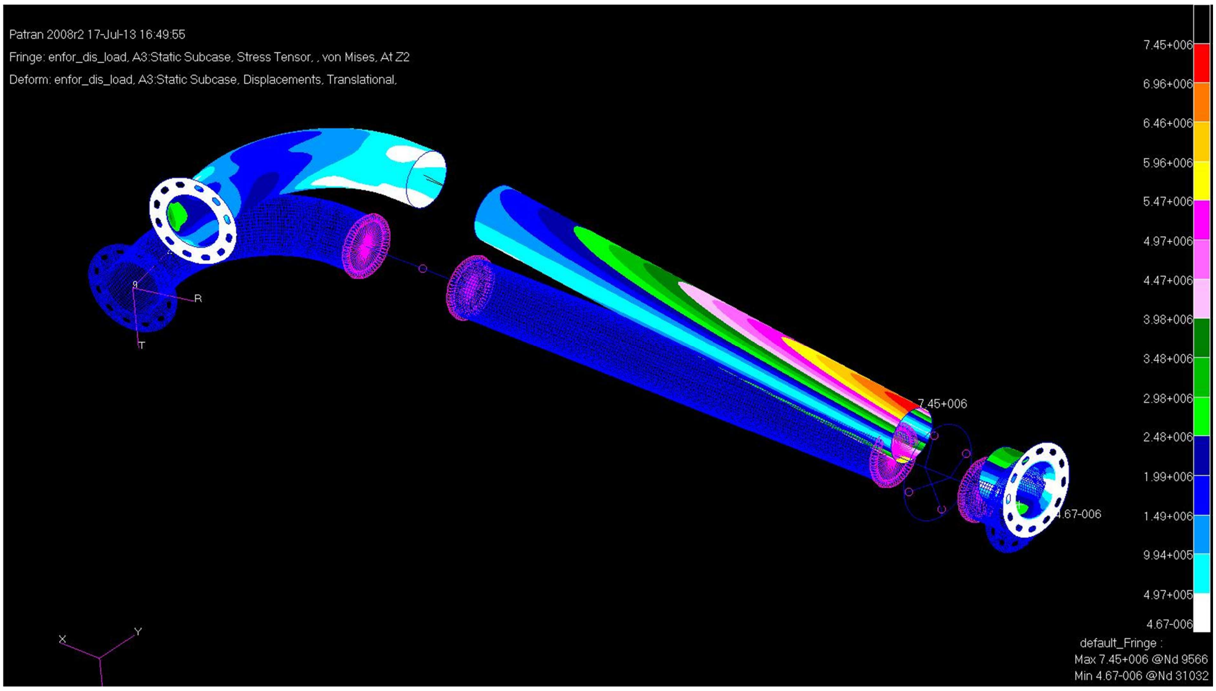


Figure 6-3 FEM Analysis of Aluminum Feed Line Enforced Displacement

Calculated stress level due to enforced displacement is as low as 7.45MPa as shown in Figure 6-3

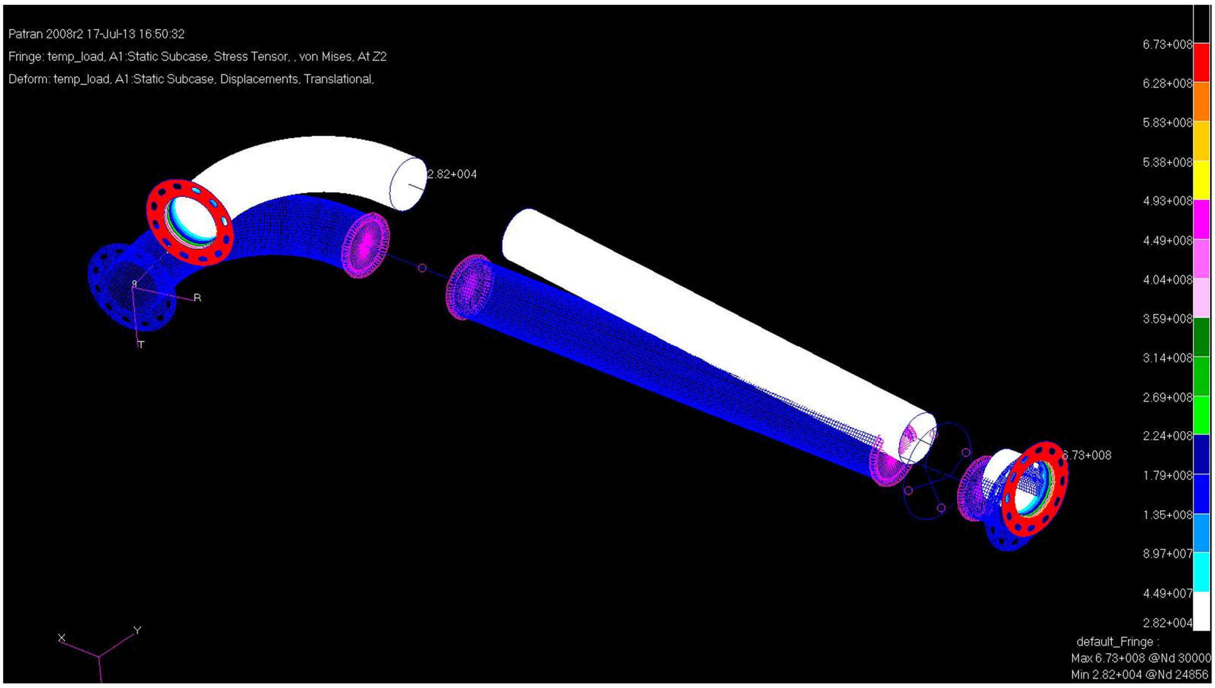


Figure 6-4 FEM Analysis of Aluminum Feed Line Thermal Expansion

The calculation of stresses due to the thermal expansion of the feed line shows very high values as is shown in Figure 6-4. Taking a closer look, one can see that this calculation is inaccurate due to an insufficient modeling of the feed line. The flanges are modeled as rigid, while in reality they would also be exposed to the temperature difference and therefore would experience the same expansion as the feed line itself. The real stresses in the feed line are by far smaller.

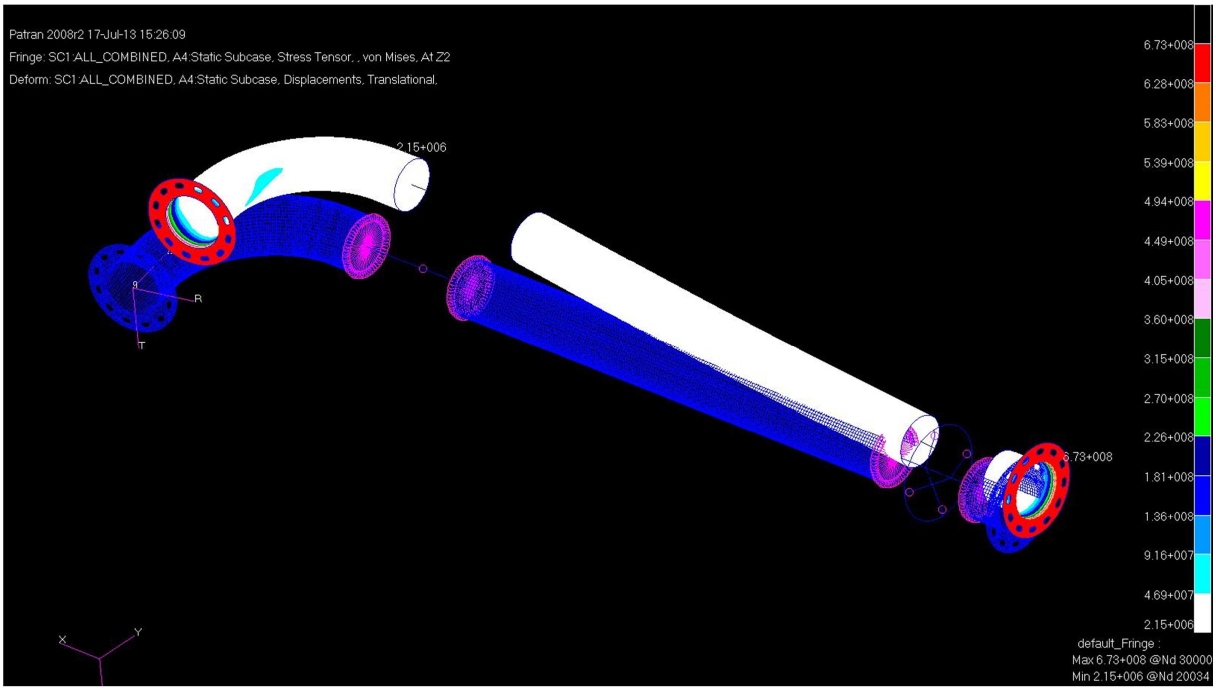


Figure 6-5 FEM Analysis of Aluminum Feed Line Combined Load

Looking at the combined load of the feed line in Figure 6-5, one can see that the stress level in the feed line is below 100MPa and therefore not in the range where the super high strength aerospace aluminum alloys are needed. It looks like regular aluminum alloys would also be sufficient. So in the following comparison, regular aluminum alloys also are considered.

7 Weight comparison

To investigate the possible weight savings by replacing the material for the feed line by aluminum, an FEM analysis was performed. To do so, an already existing FEM model of a reference feed line, consisting of a straight tube, a bent tube, two compensators and two flanges, was used to check if the established design is suitable for the substitution of aluminum. For a first test, one of the weaker candidate materials, AA5059, was used. As it turned out, strength is not the critical factor in material decision; the weak material AA5059 easily fulfilled the requirement of strength. Also the more critical factor of the eigenfrequency was fulfilled.

Concerning this, it is likely, that all the considered aluminum alloys will fulfill the requirements on mechanical properties and the decision will be influenced to a greater extent by other properties like corrosion behavior, easiness of processing, availability and price.

In a previous project, the weight of the existing reference feed line (stainless steel) was determined by weighting every single part of it. The findings are listed in Table 7-1. The weights of the aluminum line parts are calculated in relation of the material densities, assuming identical part design.

In Table 7-1 the weights of five different line concepts are compared. In the first row, the reference line is mentioned with weight of its parts as it is produced currently. In the following rows, there are the weights of the line made of two different aluminum alloys in two different concepts. In the first row of every alloy section, the tube parts and the flanges are made out of the aluminum alloy but the compensators are made of steel as they are now. In the second row of the alloy section, the compensator housings also are made of the aluminum alloy. As the compensator bellow probably cannot be produced of aluminum, it is calculated as steel in all cases.

The aluminum alloys chosen for the weight comparison are AA5059, which is an alloy of a very low density, and AA2219, which has quite high density. This should show the influence of material density to the line weight.

Table 7-1 Comparison of Weights of Feed Lines of Different Material

Comparison of Line Weight with different Materials, assuming identical design					
Weight in Grammes					
	Stainless Steel 304L	AA5059, steel compansators	AA5059, aluminum compensators (excl. bellow)	AA2219, steel compensators	AA2219, aluminum compensators (excl. Bellow)
Density [g/ccm]	8	2.64	2.64	2.82	2.82
Bent Tube and Flange (calculated)	4240.00	1393.90	1393.90	1494.60	1494.60
Compensator 1 (weighted)	3204.00	3204.00	1057.32	3204.00	1129.41
Straight Tube (calculated)	1556.00	513.48	513.48	548.49	548.49
Compensator 2 (weighted)	4398.00	4398.00	1451.34	4398.00	1550.30
Flange (weighted)	701.50	231.50	231.50	247.28	247.28
Temperature Sensor	591.00	591.00	591.00	591.00	591.00
Bolts, Washer, Nuts	624.00	624.00	624.00	624.00	624.00
Thermal Insulation	3107.00	3107.00	3107.00	3107.00	3107.00
Sealing Ring	58.00	58.00	58.00	58.00	58.00
Total Weight	18479.50	14120.88	9027.54	14272.37	9350.07

As can be seen in Table 7-1, the material density is not the crucial point in weight saving as it was assumed by the project team in the beginning. The weight difference between the line made out of one of the lowest densities, AA5059, and one of the heaviest aluminum alloy, AA2219, is only a few hundred grams. A much greater effect would have the substitution of the compensator housings by an aluminum alloy. This way, the weight of the line could be cut in half. Based on this, there is an attempt at Magna Steyr is to develop compensators made of aluminum and produce them in hose.

8 Availability and Cost calculation

8.1 Availability of materials

The acquisition of the considered materials seems not to be as simple as one might guess. Quite many materials which are assumed to be standard, as they are already used in aerospace applications of different manufacturers, are not stock produced. As the amount of material needed in this project is far less than that of a smelter charge, we have to go back to alloys which are produced at least fairly regular.

To check the availability of the investigated materials, major international producers of aluminum alloys, as well as some smaller regional aluminum smelters were contacted. Companies, which engaged in communication concerning this project include ALCOA International respectively ALCOA UK and Germany, Aleris Germany, AMAG (Ranshofen, Austria), LKR (Ranshofen) and SAG (Lend, Austria). Other contacted companies did not respond the request or the communication did not lead to an valuable output.

ALCOA is one of the world leading producers of aluminum and aluminum products. Next to the production of standard alloys and products, ALCOA took and takes major role in developing new alloys like the aluminum lithium alloys for aerospace applications, which stand out by high strength at a low density. Actual available Al-Li alloys include AA2099 and AA2060, while production of previous generation alloys like e.g. AA8090 was discontinued due to the drawbacks of these materials. AA2099 is available in various shapes like sheets, plates and extrusions from production plants in Germany and the UK. This material is the actual available Al-Li alloy by ALCOA. AA2060 seems not commonly available now. The alloy was mentioned by Mr. Gerriet Feyen as possibly allocable from production plants in the United States in our first telephone conversation, but not regarded any further in the following correspondence with the company, where solely AA2099 was discussed as a possible material.

The price for the alloy was given only as a noncommittal guiding value and was stated to vary between $30 and $60 per kilo depending on various factors like shape, temper grade, purchase order quantity and so on.

Aleris, another major producer of aluminum and aluminum products developed the Aluminum- Magnesium- Scandium alloy 5024 as an alternative for the expensive Aluminum-Lithium alloys for aerospace use.

The production and availability of the material in the future depends on the development of the scandium prize at the commodity exchange. Manufacturing of the alloy will only be continued if the market prize of scandium decreases in the future, as otherwise the material cannot be produced to a marketable price.

Alloy 5024 is produced in Koblenz, Germany and is available only as sheet material. As guiding value for the prize was stated $35 per kilo.

Alloy 5059 and alloy 2219 are also available at Aleris. As this alloys do not contain rare and expensive alloying elements, the price of the alloy can be estimated to be around $6 to $10 per kilo, which is an average value for commercial aluminum alloys, even if there was no value given by the producer.

Aluminum alloy 5059 is available as plate material, starting from a thickness of 12.7mm, AA2199 is available in various shapes starting from thicknesses of 2.5mm.

SAG, an Austrian aluminum smelter managed to produce alloy 2196 in trial processes and claims to be able to produce the material in an experimental crucible in smaller amounts of a few hundred kilos. Processing to a semi-finished product would have to be arranged separately. The price of this alloy was estimated in a first approximation to be around $25 per kilo.

Another Austrian aluminum smelter, AMAG, produces an improved version of alloy 6061. This material is available only in sheet form. As the regular version of AA6061 is a very common aluminum material, and is used widely in all kinds of applications in industry and is produced by a variety of manufacturers, acquisition of alloy 6061 is probably least problematically of all the regarded alloys. As aluminum alloy 6061 does not contain special alloying elements, the price of the material should be around the average aluminum price.

The information in this section was derived from personal meetings, telephone conversations and e-mail contacts with representatives of the mentioned companies.

8.2 Cost calculation

The production costs of a feed line consist of the costs of the material and the costs of manufacturing. The approximate costs of the material are mentioned above, but the exact costs of manufacturing are hardly to estimate. As a first approximation, in the utility analysis the assumed number of needed production steps is taken as a basis for a comparison of manufacturing costs. As an example, the costs for a material which is expected to need several steps of heat treatment is assumed to be higher than that of a material which does not.

9 Material Tradeoff- Utility Analysis

To compare the different materials and to find the best suitable one, a utility analysis is performed. In this analysis, the different single attributes of the project are given points according to their importance. Then the materials are weighted according to what extent they fulfill this single attributes. Multiplying the importance of an attribute with the grade of fulfillment gives the points of a material concerning this single feature. Finally, these points are summed up for each material option, and the material which reaches the highest total amount of points, represents the most suitable one.

A crucial point in such an analysis is the weighting of the attributes by their importance and the grading of the different alternatives concerning the fulfillment of the attributes. As this often needs the evaluation of not quantifiable issues, these ratings are always subjective. To achieve an outcome which resembles reality as close as possible, it is recommended to have the rating performed by different persons. The numbers finally taken for the utility analysis are the mean values of the different ratings.

There are three ways to do the weighting of the importance of the items in a utility analysis. The first is to perform a ranking from the most important to the least important. If there are e.g. 5 items to rank, the one which is least important gets one point, the one which is most important is ranked fife points. This system is quite simple to perform, but on the other hand, it is the least significant one. It just ranks the different attributes, but it does not compare them to each other.

The second way is to assign every item a value out of a specific range. For example one point for not important to five points for crucial. This way, the single items are set in relation to each other to some extent.

The third way is to distribute a fixed total amount of points to the different items. Typically, a hundred points are chosen for this system, so the points given to an item resemble the percentage to which it is weighted. Usually, this system is assumed to be the superior one, as it compares the importance of every single item in relation to each other. [32]

To quantify the grade, to which a material option fulfills the different demands is also not as simple. Here also three different approaches are distinguished.

First one is to just to differ between true and false, the option fulfills the demand or it does not. This is not very meaningful and only applicable to exclude knock out criterions. For this project this is not helpful, as impossible options were already excluded and this is just a selection of the most suitable one.

Second one is to perform a ranking. The different options are ranked according to the grade they fulfill the demand. This way is more useful than the first one, but still not really good as it does not take into account to what extent an option is better than another one.

The third way to grade the different options is to denote every option a value out of a preliminary defined range, for example one point to fife points. This way, differences in fulfillment grade are respected more than in the other methods.

If the attributes can be quantified, the points for fulfillment grade can easily be assigned. If they are not, the grade of fulfillment has to be formulated verbally and a value has to be stated. [32] This is the method that was used in this project.

The material properties which finally were used as comparison values in this utility analysis are basically the ones mentioned above from the document provided by Magna Steyr concerning the tradeoff of the material groups CFRP, polyimides and aluminum alloys. Some adjustments were made to incorporate the specific characteristics of a comparison in one material group.

In Table 9-1 the material properties used as comparison values for the utility analysis are listed. Additionally the importance value given to the property, as well as a short description is mentioned.

The importance values donated to the specific properties were chosen in cooperation with employees of Magna Steyr involved in this project.

Table 9-1 Rating of Importance of Properties

Requirement	**Weighting points out of 4**	
Maturity of Technology	3	How far developed is the material? A lower dregree of maturity means more effort to put the material into service. However, it is still possible to evaluate and test a material which is new, but seems promising
Specific Tensile Strength	1	As long as it reaches sufficient values, higher strength does not add value to the material. Geometric limits are not driven by strength of the material but by limits of practicability
Specific Elastic Stiffness	2	Effects the eigenfrequency. First eigenfrequency should be at min. around 100Hz
Behavior at Low Temperature	3	Property changing when temperature falls. E.g. strength, toughness
Allowable Strain ε	3	High allowable strain enable deformation without exceeding maximum stresses
CTE/Allowable Strain	1	CTE/ε is proportional to interface force due to temperature change
Machinability	4	Can the material be machined? Cut, milled, turned,…
Formability	4	Can the material be bent, rolled,… ?
Weldability	4	Is it possible to weld the material? How difficult is it to weld?
Material Availability	4	Is the material (easy) available? In what forms is it available?
Specific Material Price	3	Prize per kilo of material
Manufacturing Costs	4	How many (how expensive) manufacturing steps are needed?
Damage Tolerance	3	Elongation to break, K1C
Corrosion Behavior	2	Corrosion behavior, lines are protected during storage

In Table 9-2 the rating values of the fulfillment grades of the single material properties are described.

Table 9-2 Fulfillment Ratings

Requirement		Weighting
Maturity of Technology		Material experimental: 1 point to material well established: 5 points
Specific Tensile Strength		below 100: 1 point, 100 to 125: 2 points, 125 to 150: 3 points, 150 to 175: 4 points, above 175: 5 points. Strength values at room temperature, depends on temper, if possible, temper T6 is chosen for comparability, if otherwise it is mentioned
Specific Elastic Stiffness		$\sqrt{(E/\rho)} \sim \omega$, values between around 5 and 5.5, for comparison with other materials (not aluminum) probably greater differences, up to 5.1, 1 point, 5.1-5.2, 2 points, 5.2-5.3, 3 points, 5.3-5.4, 4 points, above 5.4, 5 points
Behavior at Low Temperature		values are donated according to over all performace of the material. Personal rating
Allowable Strain ε		yield strength / modulus, σ/E Range from 0.23% to 0.6%, 0.2-0.3, 1p;0.3-0.4, 2p; 0.4-0.5, 3p; 0.5-0.6, 4p, above, 5p--- all very close, meaningful to distinguish?
CTE/Allowable Strain		Interface force is proportional CTE/ε, CTE usually 20°C to 100°C ; above 7000, 1p; 7000-6000, 2p; 6000-5000, 3p; 5000-4000, 4p; below 4000, 5p
Machinability		no fixed numbers but personal rating
Formability		personal rating according to descriptions
Weldability		personal rating according to descriptions
Material Availability		no fixed numbers possible, personal rating
Specific Material Price		Prize per kilo, up to $10,- 5 points, $10 to$20, 4 points, $20 to $30, 3 points, $30 to $40, 2 points, above $40, 1 point
Manufacturing Costs		as the price of single manufacturing steps is hard to identify, the number of needed production steps is counted, personal rating
Damage Tolerance		derived from K1C values and elongation to break, personal rating
Corrosion		no fixed numbers, personal rating

Table 9-3 Fulfillment Rating of Specific Alloys Part 1

		AA6061			AA2219	
Maturity of Technology		5	Alloy is well established and in use for a long time		4	Alloy used in several space applications, not as common as standard materials
Specific Tensile Strength		2	290 MPa, (AMAG) /2.7 g/cm³=107.4 MPa/g/cm³		2	290 MPa, (ASM)/ 2.84 g/cm³=102.1 MPa/g/cm³
Specific Elastic Stiffness		1	E=68.9 GPa, ρ=2.7 g/cm³ -> √(E/ρ)= 5.05		2	E= 73.8 Gpa, ρ=2.84 g/cm³ ->√(E/ρ)=5.1
Behavior at Low Temperature		5	Strength, Fatigue strength, elongation to break increase as temperature falls		5	
Allowable Strain ε		3	290MPa/68900MPA=0.004		2	290MPa/73800MPa=0.0039
CTE/Allowable Strain		3	23.6µm/m*K / 0.004 = 5900		3	22.5µm/m*K / 0.0039 = 5769
Machinability		5	Machined, welded, formed easily with standard processes		5	Machinable with standard equipment
Formability		4	Forming is done in several kinds, maybe tempering needed		4	Forming possible, tempering might be necessary
Weldability		4	Material is weldable with several methods, tempering needed		4	Best weldability of 2xxx materials, anyway not as easy as other groups
Material Availability		5	Material is produced by many manufacturers and available from Stock by many retailers		3	Material is available at specific manufacturers, not as common as conventional alloys
Specific Material Price		5	No special alloying elements, no patent protection		4	Material has no expensive alloying elements. Estimation as no prize was given.
Manufacturing Costs		4	cutting and machining is no problem, welding is not problematic, some heat treatment might be necessary		2	Machining and welding easily, some heat treatment might be necessary between production steps. Coating of Product might be necessary
Damage Tolerance		4	Elongation to break 12% (T6) to 25% (T4), rising at low temperatures. K1C (TL, ambient) 29 MPa √m		3	Elongation to break quite low (4%-12%), K1C value only for T82, 36 MPA √m
Corrosion		4	under ordinary environments no protection needed, for severe environments cladding is applied		2	Corrosion properties are inferior to other Aluminum alloys. Coating of Products is recommended

Table 9-4 fulfillment Rating of Specific Alloys Part 2

		AA5059 O/ H111 Temper			AA5024	
Maturity of Technology		4	Alloy is relatively new and in use mainly in different fields (armor, shipbuilding, road transportation of liquid gases).		2	Material is not in use jet
Specific Tensile Strength		1	160 MPa, O temper (manufacturer) /2.64 g/cm^3= 60.6 $MPa/g/cm^3$		2	310 Mpa /2.65 g/cm^3= 117 $MPa/g/cm^3$
Specific Elastic Stiffness		2	E=70.4 Gpa, ρ=2.64 g/cm^3 ->$\sqrt{(E/\rho)}$=5.16		3	E=72GPa, ρ=2.65g/cm^3->$\sqrt{(E/\rho)}$= 5.21
Behavior at Low Temperature		5			5	no cryogenic data, probably no problem
Allowable Strain ε		1	160MPa/70400MPa=0.0023		3	310MPa/72000MPa=0.0043
CTE/Allowable Strain		1	23µm/m*K / 0.0023=10000		3	23µm/m*K / 0.0043=5348
Machinability		5	Machinable with standard equipment,		5	no special methods needed
Formability		5	Forming possible, no tempering		2	usually formed by creep forming processes
Weldability		5	easily welded, no tempering needed		2	welding challenging, laser beam methods applied
Material Availability		3	Material available, but only from one manufacturer and in limited shapes		2	Material available only from one manufacturer, only in sheet form, availability in the future is questionable (acc. to producer)
Specific Material Prize		4	No expensive alloying elements, alloy is patented, estimation as no prize was given.		1	Expensive alloying elements, Prize 40-50 per kilo
Manufacturing Costs		5	machining and welding easily, no heat treatment necessary		2	expensive welding methods, special heat treatment necessary after welding
Damage Tolerance		4	Elongation to break quite high (25%), no K1C data available for O temper		5	Excellent, according to producer
Corrosion		5	Corrosion resistance excellent, material in use in shipbuilding (saltwater)		4	Good, according to producer

Table 9-5 Fulfillment Rating of Specific Alloys Part 3

		2196 T851			2099 T8E67	
Maturity of Technology		4	Material was produced for many years		4	Material in testing phase of some aircraft manufacturers
Specific Tensile Strength		5	470MPa / 2.63 g/cm³ = 178.7 MPa/g/cm³		4	430MPa /2.63 g/cm³= 163.5 MPa/g/cm³
Specific Elastic Stiffness		5	E=77.6GPa, ρ=2.63g/cm³ -> √(E/ρ)=5.43		5	E=78GPa, ρ=2.63g/cm³ ->√(E/ρ)=5.45
Behavior at Low Temperature		5			5	
Allowable Strain ε		5	470MPA/77600MPa=0.006		4	430MPa/78000MPa=0.0055
CTE/Allowable Strain		5	23µm/m*K / 0.006=3833		4	23µm/m*K / 0.0055=4181
Machinability		5	no special methods needed		5	no special methods needed
Formability		3	forming possible, probably special tempe needed		4	forming comparable to conventional alloys, tempering needed
Weldability		3	welding possible, special processes and tempering necessary		3	welding possible with some efforts concerning methods and tempering
Material Availability		3	Material not produced by big suppliers, small Austrian company could cast alloy especially, semi-finished products would have to be made separately		3	Material available from one manufacturer as Sheet and Extrusion
Specific Material Prize		3	about $25 per kilo (according to producer)		1	Expensive Lithium content, about 30$ to 60$ per kilo.
Manufacturing Costs		3	Careful welding needed, tempering between manufacturing steps		3	Special welding methods needed, tempering between manufacturing steps needed
Damage Tolerance		5	low data, according to producer "excellent damage tolerance properties"		5	K1C very high (55MPa*√m), elongation to break medium
Corrosion		4	EA (mild exfoliation)		4	stress corrosion good, mild exfoliation

Table 9-6 Utility Analysis Part 1

Material designation		6061		2219		5059	
	Weighting factor of requirement	fulfillment rating	requirement points of material	fulfillment rating	requirement points of material	fulfillment rating	requirement points of material
Maturity of technology	3	5	15	4	12	4	12
yield tensile strength σ	1	2	2	2	2	1	1
specific elastic stiffness E/ρ	2	1	2	2	4	2	4
behaviour at high and low temperature	3	5	15	5	15	5	15
Allowable Strain ε	3	3	9	2	6	1	3
CTE to allowable strain ratio CTE/ε	1	3	3	3	3	1	1
Machinability	4	5	20	5	20	5	20
Formability	4	4	16	4	16	5	20
Weldability	4	4	16	4	16	5	20
Material availability	4	5	20	3	12	3	12
specific material prize	3	5	15	4	12	4	12
manifacturing costs	4	4	16	2	8	5	20
damage tolerance	3	4	12	3	9	4	12
corrosion behavior	2	4	8	2	4	5	10
Total points of material			**169**		**139**		**162**

Table 9-7 Utility Analysis Part 2

Material designation		5024		2196		2099	
	Weighting factor of requirement	fulfillment rating	requirement points of material	fulfillment rating	requirement points of material	fulfillment rating	requirement points of material
Maturity of technology	0	2	6	4	12	4	12
yield tensile strength σ	0	2	2	5	5	4	4
specific elastic stiffness E/ρ	0	3	6	5	10	5	10
behaviour at high and low temperature	0	5	15	5	15	5	15
Allowable Strain ε	0	3	9	5	15	4	12
CTE to allowable strain ratio CTE/ε	0	3	3	5	5	4	4
Machinability	0	5	20	5	20	5	20
Formability	0	2	8	3	12	4	16
Weldability	0	2	8	3	12	3	12
Material availability	0	2	8	3	12	3	12
specific material prize	0	1	3	3	9	1	3
manifacturing costs	0	2	8	3	12	3	12
damage tolerance	0	5	15	5	15	5	15
corrosion behavior	0	4	8	4	8	4	8
Total points of material			**119**		**162**		**155**

As can be seen in the Tables of the utility matrix, aluminum alloy 6061 gained most of the points and therefore is the best suitable material for the feed lines according to this comparison. It has to be kept in mind that this outcome bases on personal ratings to a great extent. By minor changes of some rating points the result could be different. To keep this rating process as impartial as possible, the ratings were done in accordance with the project team at Magna Steyr and several different persons were involved.

10 Discussion

As can be seen by the results of the utility analysis, the material option with the best technical properties is not always the best suitable one for a specific project. Aluminum alloy 6061 won the competition between the different materials mainly due to its economic advantages compared to the other ones. The good price and easy availability turned the balance, even mechanical properties of other materials were superior.

It is highly recommended, that the decision for a concrete material, temper grade, rolling condition, as well as joining methods, weld parameters and so on, is made in close cooperation with material manufacturers and their R&D, as they have best knowledge and most experience in this field of research. As it is a requirement of ESA in this project, to have all project partners and component suppliers located in Europe, for example the Austrian companies AMAG and LKR would be best suited to cooperate in this field. They already have made good achievements especially with the alloy 6061 like the development of a special thermo mechanical processing for improved material properties.

11 Summary

The material for space launcher feed lines, currently stainless austenitic steel, should be replaced by an aluminum alloy due to weight and cost savings. Special emphasis should be placed to aluminum- lithium and aluminum- scandium alloys. To this, a literature review was carried out on aluminum alloys in general and on Al-Li and Al-Sc alloys in particular to assess the general suitability of the material for this purpose. In the next step, deeper information was searched about some specific alloys and a FEM analysis was conducted to find out about the practicability of the actual line design for the new material. In this step it turned out, that the super characteristics of the Al-Li and Al-Sc alloys would not benefit the project very much and regular aluminum alloys would be sufficient. As a consequence, conventional aluminum alloys were considered in the following assessment process. Also the influence of the material density to the final product was verified, as this point was strongly emphasized by the commissioning company. Finally, the various characteristics of the different material options were compared in a utility analysis to find the best suitable one. At the end, aluminum alloy 6061 was chosen for further development.

12 Outlook

The material selected in this thesis, aluminum alloy 6061, was chosen by Magna Steyr as the aluminum representative for the comparison with the other material groups. As it also seemed best suitable in this tradeoff, it will be the material further researches are performed with. Right now, there are attempts to join the material to austenitic stainless steel parts used in the compensators by welding methods. So the aim is to also manufacture the compensator housings of the aluminum alloy, which would bring remarkable weight savings of the feed lines. As it is probably not possible, to weld an aluminum material to austenitic steel directly, there are attempts to use an intermediate layer of a third material, maybe copper or nickel, between the two metals. At the moment, there are negotiations between Magna Steyr and Graz University of Technology to cooperate in this field of research.

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