New product vision for Aerospace by applying of lightweight Al-Li based alloys and Al-Mg-Sc material technologies

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Abstract

In the neck-and-neck race from aluminium alloys and polymer based composite it seems there is a big chance for aluminium based technologies to take over the leading position in the future aerospace products again. This statement is an introduction of new design concepts with appropriate alloys and material technology, that supports the new approach of “care free” structure designed for minimum life cycle cost. The general challenge is therefore to provide integrated material-technologies solutions by considering all operational steps of whole value added chain by insuring that targeted structure properties are received.

1. Introduction

Concurrent consideration of material concepts, design principles and manufacturing technologies are imperative and require close interaction between the material supplier and aircraft manufacturer in order to generate economical, performance, structural and environmental benefits of current and future aircrafts. A competitive new aircraft program requires the implementation of new technologies in an integrated manner, which allows further optimization of the aircraft family. This approach is characterized by an evolutionary process that utilizes step-by-step use of mature technologies built on experience and acceptance gained in design, production and operation, but still offering potential for further optimization. However, one of the dominate design criteria is the structural damage capability of metallic fuselage structure in large areas.

Therefore aluminum alloys are considered due to continuously improved material performance, relatively moderate cost, possibility for usage of existing production techniques and tooling, common acceptance and extended experience in appropriate design, ageing characteristics, reparability, availability of standards and potential for further optimization in combination with new manufacturing technologies accompanying evolution of aircraft families. Whilst only two main types of aluminum alloys (Al-Cu-Mg alloys AA2X24 and Al-Zn-Mg-Cu alloys AA7X75 and AA7X5X) have been used in conventional airframe the last decades, various specifically tailored Al-Mg-Si, Al-Cu-X, Al-Li-X, Al-Mg-Sc and Al-Zn-Mg-Cu alloys have recently been applied or are expected to be used in future commercial aircraft, each of which is dedicated to a particular application in combination with new manufacturing technologies incorporating specific requirements of those components. Under pressure from competing CFRP (Carbon Fiber Reinforced Plastic) for structural application Al-Li based alloys and Al-Mg-Sc technologies are a new hope for the aluminium industry.

The most attractive reason for Lithium alloying is the beneficial impact on stiffness and weight reduction. Every addition of 1 wt.-% Li decreases the density by roughly 3% and increases the elastic Young’s modulus by 6%. By adding scandium the alloy systems Al-Mg, Al-Mg-Li and Al-Cu-Li increase in strength amounting to 20-50 MPa per 0.1 wt.-% Sc [1-4]. The low density, high modulus, improved material properties especially damage tolerance, weldability and good corrosion properties are the main objectives for introducing them in future aerospace products. There are only a limited number of processing differences compared to these used by conventional alloys that need to be considered during manufacturing to achieve the targeted properties of the parts. The new materials are designed for competitive lightweight products to issue a guarantee for improvement concerning performance, cost reduction, extended service life and reduced environmental impact. The needs expressed by Airbus (A380, later also for A350 and A400) have given a new impulse to develop new Al-Li-X and Al-Mg-Sc alloys, including the third-generation Al-Li low density alloys, with innovative joining concepts LBW (Laser Beam Welding)) and FSW (Friction Stir Welding) [5,6]. This paper is introducing two groups of novel high potential Al alloys such as Al-Li-X and Al-Mg-Sc and their significant improvements over the last years to enable improved performance of next generation airspace products.

2. Al-Li materials and products

2.1 Metallurgy of Al-Li alloys

The effect of lithium addition on the material properties of aluminium alloys depends on whether lithium is present in solution or as a secondary phase. Precipitation hardening in Al-Li alloys includes in most cases the formation of the δ' phase (Al_3Li) which is a metastable, ordered and coherent phase with a $L1_2$-type superlattice structure [7]. A large volume fraction of this phase has been noticed in Al-Li but also in Al-Cu-Li and Al-Mg-Li alloys, especially those belonging to the second generation.

In Al-Cu-Li alloys, further strengthening is obtained by the simultaneous formation of a second type of precipitates, depending on the amount of Cu and Li in the alloy. Table 1 shows the most important phases which can form in Al-Li alloys with Cu and Mg additions.

For a Cu amount of 3 to 4.5 wt% and Li of 1 to 2 wt%, the supersaturated solid solution α_{SS} partially precipitates as follows:

$$\alpha_{SS} \begin{array}{l} \nearrow \ \delta' \ (Al_3Li) \rightarrow \delta \ (AlLi) \\ \searrow \ \text{GP zones} \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta \ (Al_2Cu) \end{array}$$

for Cu contents of approximately 2 wt% and a Li contents more than 2 wt%, the reaction is the following:

$$\alpha_{SS} \begin{array}{l} \nearrow \ \delta' \ (Al_3Li) \rightarrow \delta \ (AlLi) \\ \searrow \ T_1 \ (Al_2CuLi) \end{array}$$

In Al-Mg-Li alloys magnesium contributes to the strength in two ways. It acts as a solid solution strengthener [7] and it decreases the solubility of lithium in aluminium. This results in an increase in the volume fraction of δ' phase. The aging sequence for Al-Mg-Li alloys is as follows:

$$\alpha_{SS} \longrightarrow \delta' \ (Al_3Li) \rightarrow Al_2MgLi$$

The subsequent formation of Al_2MgLi consumes nearby δ' particles and therefore, the reaction $\delta' \rightarrow \delta$ is suppressed. Under equilibrium conditions Al-Mg-Li alloys with the Mg/Li ratio in the range of 2.5 to 1.5 forms the phase Al_2MgLi [7].

The Guinier-Preston (GP) zones (in this example Al-Cu) are aggregations of Cu-atoms in the $\{100\}_\alpha$ planes of the Al-matrix and have a small disk shape [8]. The GP zones cause a lattice distortion due to the smaller size of Cu-atoms. They were revealed by X-ray investigations done by Guinier and Preston who tried to understand the hardening effect occurring in Al-Cu alloys.

During ageing the GP(I) zones (single layer) become two-layered GP(II) zones. The GP(II) zones, also called Θ'', are coherent and metastable and lead to the further hardening of the material. Then the Θ' phase, which is semi-coherent and still metastable, forms continuously. Finally the incoherent and stable Θ phase appears, but the complete precipitation sequence only occurs if the ageing temperature does not exceed the GP solvus. Moreover, phases can coexist at a given stage of the ageing process. The precipitate status of the GP zones is discussed in literature [8], their role in the precipitation and the hardening is acknowledged. T_1 precipitates (Al_2CuLi) have a hexagonal crystal structure and are needle or plate shaped. It is an equilibrium phase lying on {111} planes, responsible for the main hardening effect in Al-Cu-Li alloys. The heterogeneous nucleation of the T_1 phase is enhanced by the presence of dislocations acting as initiation sites.

Table 1: Most important precipitates which can form in Al-alloys containing Li, Cu and Mg and their characteristics [7, 9]

Phase	Short designation	Structure	Shape	Remarks
Al_3Li	δ'	cubic	spherical	coherent, hardener
AlLi	δ	cubic	rod, plate	incoherent
$\approx Al_5Cu_2$	θ''/GP(II)	tetragonal	plate	coherent, metastable
Al_2Cu	θ'	tetragonal	plate	semi-coherent, metastable, hardener
Al_2Cu	θ	tetragonal	plate	incoherent, stable
Al_6Cu_4Li	T	hexagonal	plate	
Al_2CuLi	T_1	hexagonal	-	coherent, hardener
Al_6CuLi_3	T_2	icosahedral	rod	slight hardener
Al_2MgLi	S′	hexagonal	rod, needle	semi-coherent hardener
Al_2CuMg	S	hexagonal	rod	semi-coherent hardener
$Al_3(Zr,Li)$	α'	cubic	spherical	coherent

The strengthening mechanisms of the different phases are still under discussion in literature. It appears that different types, size and repartition of precipitates can lead to a similar level of strength, but a given precipitate distribution can be adequate to reach high levels of strength however, can be detrimental to other properties such as toughness or fatigue resistance at the same time. However, choosing the alloy composition is not sufficient enough to determine the presence of the phases and their distribution in the final product. Factors like the availability of nucleation sites for heterogeneous nucleation and the stability or the competitive growth of phases are also of importance. Therefore the influence of the process parameters on the microstructure and the precipitation mechanism is the subject of many studies. Hence, material properties such as strength and ductility can be influenced to some extent, by optimizing the material process chain to obtain a certain size and distribution of the hardening phases. Three generations of Al-Li alloys can be distinguished at different levels of successful applications.

2.2 The first generation of Al-Li alloys

Al-Li alloys have been the subject of increased research and development in recent years, activities having emerged as a family of attractive lightweight alternatives to traditional Al-Cu-Mg and Al-Zn-Mg-Cu high strength aluminum alloys and composite materials. Al-Li-X (Table 2) alloys offer opportunities for significant improvements in the aero-structural performance through an attractive property combination of low density, high elastic modulus, high static tensile and yield strengths and good resistance to fatigue crack propagation. Moreover, Al-Li-X alloys are characterized by valuable operational and technological properties. They have good corrosion resistance, excellent cryogenic properties, and attractive high damage tolerance behaviour. The beginning of the research addressing aluminum alloys containing Li began in the 1920’s in Germany. 0.1 wt.-% Li was introduced in an alloy called “Scleron” (Al-Zn-Cu-Li) [10]. A first development of Al-Cu-Li-Mn-Cd alloys (2020) driven by low density was realized by Alcoa in the 1950’s. The alloy was used in form of plate for the wing skins of the US Navy’s supersonic ‘Vigilante’ airplane A-5A and RA-5C due to its high strength, low density, high elastic modulus and very good corrosion properties (Fig. 1). This aircraft was retired after 20 years of service life with no reported cracks or corrosion issues. However, problems with low ductility and fracture toughness led to termination of its application and production in the late 1960’s. The Russian analogue alloy VAD23 was being used in small quantities in form of extrusions and sheets. The 2020 and VAD23 (in 1964 used for TU144 supersonic airplane) alloys didn’t find a wide application due to the fact, that the high density didn’t provide enough considerable weight saving of the structure. The Russian low density Al-Mg-Li alloys 1420, 1421 (with Scandium) were used in differential as well as integral fuselage structures of YAK38 in 1969 (Figure 2) and MIG29 in 1984 (Figure 3).

Table 2: Chemical composition of different Al-Li alloys [5, 9, 11, 12]

Alloy	Li	Cu	Mg	Ag	Zr	Sc	Mn	Zn	Country-Company	Year
1st GENERATION										
2020	1,2	4,5					0,5		USA-Alcoa	1958
1420	2,1		5,2		0,12				Russia-KUMZ/VIAM	1965
1421	2,1		5,2		0,9	0,17			Russia-KUMZ/VIAM	1965
2nd GENERATION ≥ 2%										
2090	2,1	2,7			0,11				USA-Alcoa	1984
2091	2,0	1,3			0,11				France-Pechiney	1985
8090	2,4	1,2	0,8		0,11				USA-Alcoa	1984
1430 2091	1,7	1,6	2,7		0,11				Russia-KUMZ/VIAM	1980-85
1440 8090	2,4	1,5	0,8		0,11				Russia-KUMZ/VIAM	1980-85
1441	1,9	1,9	0,9		0,11				Russia-KUMZ/VIAM	1980-85
1450 2090	2,1	2,9			0,11				Russia-KUMZ/VIAM	1980-85
1451	1,6	2,9			0,11				Russia-KUMZ/VIAM	1985
1460 2090	2,25	2,9			0,10	0,09			Russia-KUMZ/VIAM	1980-85
3rd GENERATION ≤ 2%										
2094 Weldelite 049	1,1	4,8	0,7	0,4	0,11			0,25	USA Reynolds/McCook	1989
2195 Weldelite 049	1	4,0	0,4	0,4	0,11				USA-LM/Reynolds	1992
2397	1,4	2,8	≥0.25		0,11		0,3		USA-Alcoa	1993
2297	1,4	2,8	≥0.25		0,11		0,3	≥0.50	USA-LM/Reynolds	1997
2098	1,1	3,5		0,33	0,14				USA Reynolds/McCook	199X
2196	1,75	2,9	0,5	0,4	0,11		≥0.35	≥0.35	USA-LM/Reynolds	2000
2099	1,8	2,7	0,3		0,09		0,3	0,7	USA-Alcoa	2003
2050	1,0	3,6	0,4	0,4	0,11		0,35	≥0.25	France-Pechiney	2004
2198	1,0	3,2	0,5	0,4	0,11		≥0.50	≥0.35	USA Reynolds/McCook	2005
2199	1,6	2,6	0,2		0,09		0,3		USA-Alcoa	2005
2060	0,75	3,95	0,85	0,25	0,11		0,3	0,4	USA-Alcoa	2011
2055	1,15	3,7	0,4	0,4	0,11		0,3	0,5	USA-Alcoa	2012
1424	1,65		5		Zr	Sc		Zn	Russia-KUMZ/VIAM	1998
1461	1,75	3,0				0,07		Zn	Russia-KUMZ/VIAM	1999
1464	1,65	3,25			0,06	0,09			Russia-KUMZ/VIAM	2006
1469	1,5	3,4				Sc			Russia-KUMZ/VIAM	2007

The use of Scandium as an alloying element in aluminium alloys was started at first by scientist of the former Soviet Union [13]. Since 1970 the 1420 alloy has been used as the main structural material in the riveted structure of vertical take-off YAK-36 aero plane, ensuring the weight saving by 10-12%. The window frames and some primary components in passenger aircrafts IL76, IL-96, TU-204 as well as stringers and skin of helicopters were made of this alloy. One of the main advantages of 1420 alloy is its good weldability. The introduction of the minor Sc-addition into 1420 alloy results in the formation of secondary $Al_3(Sc,Zr)$ phase. These precipitates produce directly strengthening effects by precipitate hardening and grain structure control during manufacturing, so that the 1421 alloy is characterized by improved strength properties and better weldability, but lower ductility. In 1980 the 1420 alloy was recommended for use in the new modification of the supersonic "MIG" fighter for the production of the welded pressurized fuel tank and the cockpit. The combined consideration of Al-Mg-Li alloy together with fusion-welded integral design enables a total structural weight gain of 24% relative to conventional riveted design comprising Al-Cu-Mg alloys for MIG29 application.

Figure 1: 2020 plate in Navy's RA-5C Vigilante aircraft

Figure 2: 1420 for YaK38 jet

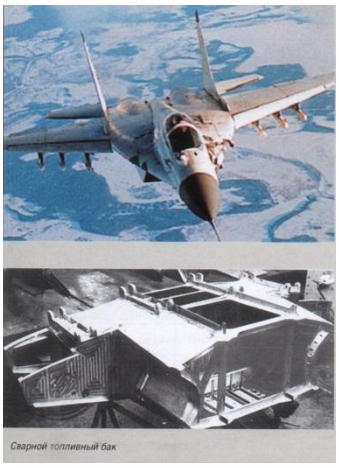


Figure 3: 1420 in MIG-29/Welded Integral Fuel Tank

2.3 The second generation of Al-Li alloys

Based on the Arab oil embargo in the early 1970's, fuel costs were projected to reach very high levels. This possibility stimulated high-risk developments efforts of novel aluminium based materials. Therefore since the mid-1970's, companies like ALCOA and KUMZ have intensively developed Al-Li alloys, but a lot of these new alloys never found practical application. Some reasons for this were that the first generation of these alloys presented to the aerospace industry had unsuitable properties such as high brittleness, low ductility, unstable crack propagation and thermal instability. Contrary to 2020 and VAD23 the new alloys contain Zr instead of Mn and Cd. The introduction of Zr supports the formation of the secondary precipitation of the $\beta(Al_3Zr)$ phase. This phase is saving the non-recrystallized structure of the deformed semi-finished products after heat treatments and ensures the increase of strength and corrosion resistance. Also the content of Fe and Si was limited with the aim of improving the structural properties.

Alloys such as AA2090 and AA8090, developed in the 1980's, were characterized by attractive high modulus and low density but anisotropic mechanical properties. Bombardier's experience with structure parts manufactured by stretch forming from Al-Li 2090 sheets have shown high planar anisotropy, poor ST properties and lack of thermal stability. Damage tolerance was also affected due to unusual crack path behaviour. Also the weight-saving potential of these materials did not justify their two-to-four-times higher costs in comparison to the standard aeronautical materials 2024 and 7075. However, these alloys did not receive widespread use due to property anisotropy, low toughness, and poor corrosion resistance. Only the Westland-Augusta EH101 helicopter uses 8090 forgings and sheets and 2090 and 2091 sheet in the internal structure and fuselage.

Research and development efforts in Russia with the focus on Al-Li alloys for aerospace applications led to the development of a new Al-Li alloy series with attractive characteristics including moderate to high strength, good weldability, good elevated temperature and cryogenic mechanical properties, high corrosion resistance and superplastic formability. This new alloy series includes Al-Cu-Li alloys (1450, 1460) and Al-Cu-Mg-Li alloys (1440, 1441). The high-strength weldable 1460 alloy was developed for cryogenic applications. Due to the Sc addition the weldability of 1460 was improved in comparison to 1450. Various extruded and forged semi-products, plates, and hot-rolled sheets of these alloys are produced on an industrial basis.

Alloy 1441 is a Russian Al-Cu-Li-Mg based medium strength alloy [14]. It provides high workability under both cold and hot deformation compared to Al-Li alloys of other systems. Compared to these Al-Cu-Mg alloys, 1441 has similar strength but exhibits 7% lower density and 12% higher elastic modulus next to high damage tolerance, corrosion properties as well as high workability. This alloy is also available as 0.5 mm thin foils, which makes it an interesting material candidate for GLARE material. The level of anisotropy is modest and comparatively lower than commonly associated with Al-Li alloys.

The Boeing and NASA’s Delta Rocket DC-XA program used Russia’s extensive experience base with highly weldable Al-Li-Cu alloys for a cryogenic tank (LO2) made from 1460 alloy. A further successful application of the Russian medium strength Al-Cu-Li-Mg alloy 1441 was in Hydroplane BE-200 and BE-103 as skin material und 1430, 1440, 1450 alloy in the Antonov 224.

In general, although density reduction was clearly attractive, the 2nd generation of Al-Li semi-finished products containing high Li concentration exhibited several characteristics that were considered undesirable by airframe designers. Therefore, the Al-Li alloys of first and second generations have not found any major nor long-run application in airframe structures.

2.4 The third generation of Al-Li alloys

At the end of eighties the next generation of Al-Li alloys was produced by reducing the amount of Li to find a compromise between weight reductions and maintaining the appropriate mechanical and physical properties. Special studies of Al-Cu-Li alloys with Mg and Ag addition were performed.

The “Weldalite”-type alloys such as AA2195 were developed for welded cryogenic fuel tank application on space launch systems on the external tank of the NSTS Space Shuttle, the so called SLWT (super light-weight tank) in the 1990’s (Fig. 4) [15]. This alloy offered a specific strength/toughness and density combination to meet the demanding design goals. Alloy AA2195 shows optimized cryogenic fracture toughness and excellent stress corrosion cracking (SCC) resistance and exhibits significant performance improvements compared to alloy AA2219 with 40% higher strength and 5% weight savings. The substitution of alloy AA2219 by AA2195 plates for the Space Shuttle External Tank resulted in a weight reduction of nearly 3.600 kg and helped to increase the Shuttle payload. The metallurgical design of the AA2195 alloy facilitates high specific strength levels due to low density from Li addition and high strength from the T_1 strengthening phase. Small amounts of Mg and Ag are added in order to lower the solubility of Li in solid solution and to promote precipitation of the T_1 phase.

Figure 4: Space Shuttle Large External Tank

AA2196 alloy is an Al-Cu-Li-Mg-Ag based variant within the Weldalite® family of alloys that was developed as a lightweight replacement of AA7075-T6 and AA7050-T76 aircraft applications. The Li content was increased in AA2196 compared to AA2195 in order to maximize weight savings while maintaining durability and damage tolerance requirements. Li:Cu atomic ratio was properly adjusted to avoid δ’ phase precipitation and promote formation of T_1 hardening phases. As a result, AA2196 exhibits a prosperous combination of tensile and fracture toughness properties as well as corrosion resistance. AA2196-T8511 extrusions are particularly recommended for compression-dominated structures. If buckling is the dominant design criterion, the higher Young's modulus enables extra weight reduction saving in addition to the density.

AA2297 is an Al-Cu-Li-Mn-Zr based alloy that was developed to provide improved fatigue and damage tolerance with equivalent strength and corrosion versus incumbent alloys AA2124-T851 and AA7050-T73 plate applications (<150 mm). Cu:Li ratio are controlled to promote T_1 as main hardening phase and to avoid δ’ precipitates in T8 temper. Mn is added in minor amounts in order to reduce yield strength anisotropy. Spectrum fatigue is typically 3-5 times higher than other aerospace aluminum alloys. Specific mechanical properties are enhanced by a density of 2.65 g/cm^3, which offers a 5% weight reduction when compared to conventional alloys. AA2297-T87 plates are already applied to fatigue critical components in F16 fighter aircrafts. Moderate tensile strength level in combination with good damage tolerance and excellent corrosion characteristics makes 2297-T8 very attractive for frames, spars and bulkheads.

AA2098 is an Al-Cu-Li-Mg-Ag alloy that is designed to provide a balanced combination of high strength, low density, high fatigue resistance, high fracture toughness and good corrosion resistance for aerospace applications. It is used in form of thin plate and sheet for military fuselage for F16 fighter aircraft as is 2098-T8 (Figure 5).

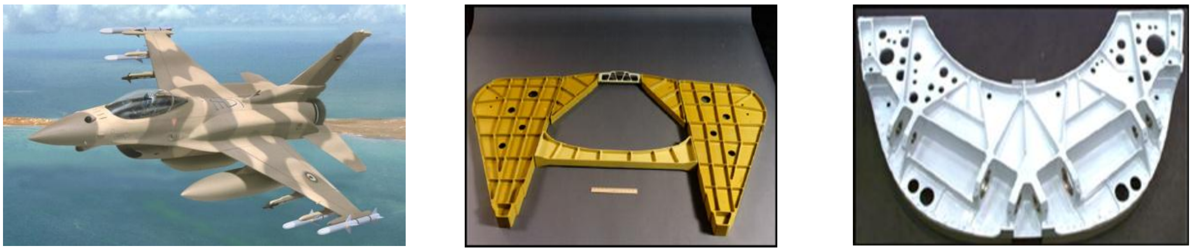


Figure 5: AA2098 application for upper blanking of F16

The business case for using Al-Li alloys in previous commercial applications was limited. However, in the last few years new interest in Al-Li alloys exists driven by significantly higher performance requirements demanded by the new commercial aircraft. The reason for this situation is the rapidly increasing use of composites in airframe, in commercial aircrafts such as A380, A350XWB and Boing 787 as well as business aircrafts such Raytheon and Dassaut. The increased usage of composite is driven by the performance improvement of composite materials compared to conventional aluminum alloys. Increased performance of composite structure offers benefits in both reduced weight and maintenance costs (longer inspection intervals, better corrosion resistance), but typically increase the purchase cost.

Based on the experiences of 2090 and other 2nd generation Al-Li alloys Alcoa has developed a number of Al-Li alloys with benefits, such as 2199 sheet and plate for fuselage and lower wing applications respectively and 2099 extrusions for internal structure. Successful reduction of anisotropy for the mechanical properties by composition optimization and control of crystallographic texture, grain size and shape, cold deformation, amount and type of precipitates solved the crack deviation problem of the 2nd Al-Li generation alloys. The alloy 2199 exhibits outstanding fracture toughness also after thermal exposure at 85°C/1000 h demonstrating improved thermal stability of Al-Li products [12].

Two extruded Al-Li alloys of the latest generation were qualified by Airbus: the Constallium alloy 2196 (former Alcan) and the Alcoa alloy 2099. The Airbus applies the high strength Al-Cu-Li alloy (2099, 2196) as extrusion in the main deck floor (cross beam, seat rail) and cockpit floor structure of A380. They offer high static strength and lower density compared to the current 7xxx series alloy. The 2099 alloy is also qualified as thin gage extrusion usable for stringer application.

The most promising monolithic materials for future fuselage skin applications are the 2199 from Alcoa and the 2198 from Alcan. Derivates from these Al-Li alloys are currently evaluated (by Airbus, Boeing, Bombardier for instance) for use in lightweight, damage-tolerant airframe structures of commercial airplanes, again due to strong demand for further weight reductions and availability of alloys with improved material performance. The alloy 2198 was developed on base of 2098 alloy used in F16 fuselage parts and optimized with regard to fracture toughness by reduction of copper content. The improving material properties especially in terms of damage tolerance could allow considerable weight saving in future aircraft generations.

In the 1990’s based on the requirements for light-weight weldable alloys the Al-Li alloys 1424 (Al-Mg-Li) with medium-strength and damage-tolerance properties and 1464 (Al-Cu-Li) with high-strength were developed by EADS in a joint research program between the All-Russian Institute of Aviation Materials (VIAM) and the Institute of Light Alloys (VILS). For later application the weldability and thermal stability under service conditions played a key role for the 1464 alloy. The basis for this was the Russian weldable alloy for application in the cryogenic temperature 1460. The precipitation behavior of this alloy system is very complex. Depending on the aging conditions basically δ’ (Al_3Li), Θ’ (Al_2Cu) and T_1 (Al_2LiCu) phases are responsible for the material properties. Two effects are responsible for the thermal instability. The increase in size of the already existing δ’phases (Al_3Li) is a dominant reason. The ongoing formation of δ’ phases at Θ’ phase, β’phase (Al_3Zr, Al_3Sc or Al_3(Sc, Zr) has a minor influence as well. To achieve the microstructure stability at elevated temperature the formation of stable δ (AlLi) phase and the minimized activation energy of δ’ (Al_3Li) phases need to be controlled by an advanced thermo-mechanical treatment. The thermo-mechanical processing and heat treatment dispose of successful achievement in terms of the mechanical properties, fracture toughness and crack propagation rate, corrosion resistance and weldability [5].

Al-Mg-Li alloy 1424 was developed on the basis of Russian 1420 and 1421 alloys for application of fuselage structures of Airbus commercial airplanes [16]. The Li and Mg content was decreased in 1424 alloy compared to 1421 alloy together with optimized heat treatment and production technology in order to provide appropriate damage-tolerant behavior and thermal stability [17]. The main advantages of 1424 alloy are high crack growth resistance, fracture toughness and thermal stability together with high corrosion resistance, lower density and a higher modulus of elasticity. The main strengthening phase is the coherent, metastable δ’ (Al_3Li)-phase. Next to precipitation strengthening there are two additional hardening mechanisms: solid solution strengthening by magnesium dissolved in solid solution, and retention of a finely polygonized, sub-grained structure (0.5-2. 0 μm) as result of Zr and Sc recrystallization inhibitors.

The potential advantages of Al-Li alloys led aluminum producers and aircraft manufacturers to invest enormous resources in developing Al-Li alloys for aerospace applications. As a result, several Al-Li alloys have become commercially available, each one having inherent advantages and restrictions. Therefore the current and planned facilities of casting houses in France and Germany are opening a new page in the aerospace industry for application of existing low density alloys in aerospace. Thus it offers the chance of developing further advanced lower density alloys not only under the consideration of the structure requirements and manufacturing steps related to the targeted properties of the parts but also due to the recycling issues within the overall supply chain.

3. Al-Mg-Sc materials and products

3.1 Metallurgy of Al-Sc alloys

It is known that trace additions of Scandium (Sc) in an extent of 0.1-0.5 wt.-% depending on type and amount of major and other trace alloying elements and thermo-mechanical treatment is an effective grain refiner and recrystallization inhibitor. It can favour a significant hardening effect and improves corrosion behaviour and weldability. Grain refinement is also an important topic for wrought and cast aluminum alloys as well as for welding.

The strong grain refining efficiency attributed to Sc-addition is essentially governed by two factors. First, formation of great number of primary Al_3Sc particles in the melt facilitates high density of nucleation sites that are activated at low undercooling ΔT. Secondly, the high nucleation efficiency of these particles is attributed to the unique similarity of crystal lattice of Al_3Sc phase and α_{Al} in terms of size and structure [18]. Grain refinement has been demonstrated for various aluminium alloy systems, including binary Al-Sc ternary Al-Sc-Zr and higher order systems of Al-Li-Sc, Al-Li-Mg-Sc, Al-Cu-Sc, Al-Zn-Mg-Sc and Al-Mg-Sc [19, 20].

Fine-grained materials are attractive since they exhibit rather improved mechanical properties such as high yield strength and hardness levels related to the Hall-Petch relationship together with high ductility and superplasticity at relatively low temperatures and high strain rates. The main objectives for grain refinement during casting and welding are related to improved feeding of the melt into cavities of solidifying metal, reducing problems of shrinkage porosity and hot cracking and providing development of a homogeneously fine microstructure [21]. Formation of small, equiaxed grains instead of a coarse, columnar solidification structure also improves semi-product fabricability and mechanical properties of cast and especially thick-section wrought products. The Sc-addition can offer benefits in case of fusion welding where its ability for grain refinement reduces sharply the alloys hot cracking tendency while considerably increasing mechanical properties of the welded joint [22].

The beneficial effects from the Sc-addition are basically linked to the formation of a coherent, primary and secondary Al_3Sc phase. It exhibits spherical morphology, thereby featuring a cubic crystal structure Ll_2 type with a lattice parameter of 0.4105 nm (pure aluminium 0.4049 nm). Due to the slight difference in lattice mismatch the Al_3Sc particles are effective nuclei for solidification. Although primary particles are reported to exhibit the same basic cubic morphology, they appear in a wide range of particle sizes from ~1 µm up to 20 µm [23].

The maximum solubility of Sc is approx. 0.38 wt.-% but it is possible to obtain higher supersaturated solution of Sc in Al-alloys by fast cooling during solidification. In case of non-equilibrium solidification with a cooling rate of ~100°C/s and higher, increases the supersaturation to ~ 0.6 - 5 wt.%. Some studies report that the maximum solid solubility of Sc in aluminum can be increased to 1.2 and 3 wt.-% at solidification rates of 10^3 and 10^5°C/s, respectively. The slight difference in lattice parameter facilitates the precipitation of coherent and extremely fine distributed secondary phases from the oversaturated solid solution. The Al_3Sc crystalline structure, particle morphology, number density and dispersity is responsible for a much more pronounced influence on structure and properties of aluminium alloys in comparison with other transition metals such as Cr, Mn or Zr. Therefore, the grain refining effect of Scandium is further enhanced by Ti due to the formation of $Al_3(Sc,Ti)$ particles that apparently are even more effective nuclei for aluminium solidification. The formation of secondary Al_3Sc particles within decomposition of a supersaturated solid solution takes place during heat treatment in the range of 250°C-500°C. The Al_3Sc phase exhibits no metastable modifications and retains fully coherence with aluminium matrix in a wide particle size range [24].

The secondary Al_3Sc particles tend to coagulate, whereby the coagulation rate rises as the Sc content increases. With a longer temperature influence of 300°C and higher, the strengthening effect of scandium becomes lost in the case of the alloys containing more Sc due to coagulation [25]. A common approach to improve the thermal stability of Sc-containing precipitates is the simultaneous addition of Sc and Zr, which results in substitution of Al_3Sc by $Al_3(Sc_{1-x}, Zr_{x})$. In this case adding Zr in range of 0.10-0.15 wt.% has a positive effect on the properties of Al-Mg-Sc alloys. Zr is a commonly used dispersoid forming element that is added to aluminium alloys in order to control the recrystallization resistance of wrought aluminium alloys. Zr is the most important element associated with addition of Sc.(120)(31) It dissolves by up to 50% in the Al_3Sc phase by formation of a ternary $Al_3(Sc,Zr)$ phase with the same $L1_2$ lattice type like binary Al_3Sc.

During annealing in a temperature range between 200°C and 500°C, secondary Al_3Sc or in case of simultaneous addition of Sc and Zr the $Al_3(Sc_{1-x}, Zr_x)$ particles precipitate from the supersaturated solid solution within a solid-state decomposition process that is characterized by a nucleation stage, a growth stage and finally a coarsening stage(120). In contrast to reversible precipitation a reaction of conventional hardening phases associated with heat-treatable aluminium alloys, decomposition of Sc and Zr is irreversible, because the temperature level necessary for dissolution of Al_3Sc or $Al_3(Sc_{1-x}, Zr_x)$ is too high and limited by possibility for liquation. The influence of secondary Al_3Sc or $Al_3(Sc_{1-x}, Zr_x)$ can be divided into two major classes of particles. These particles are similar in crystal structure but different in size, amount and spacing, which is related to different temperature regimes for decomposition of the supersaturated solid solution:

- Precipitation of secondary Al_3Sc or $Al_3(Sc_{1-x}, Zr_x)$ particles during high temperature processes in the range of 400°C to 500°C. As a consequence, a dense distribution of dispersoids with a typical size in the range of 20-50 nm is established. These dispersoids will not have a significant particle strengthening effect on the alloy, but favour good recrystallization resistance and possibility for superplastic forming.

- Formation of small Al_3Sc or $Al_3(Sc_{1-x}, Zr_x)$ precipitates during annealing in the temperature range between 300°C and 350°C results in significant precipitation hardening of an alloy supersaturated in Sc and Zr. This strengthening effect is connected with retention of small particle size in range of 2-6 nm, high density and homogeneous distribution of Al_3Sc or $Al_3(Sc_{1-x}, Zr_x)$ precipitates.

The high anti-recrystallization effectiveness caused by either exclusive addition of Sc or simultaneous addition of Sc and Zr is related to a high number density of homogeneously distributed, coherent and small Al_3Sc or $Al_3(Sc_{1-x}, Zr_x)$ dispersoid particles. Special ternary $Al_3(Sc_{1-x}, Zr_x)$ dispersoids feature a high V_f/r ratio together with enhanced thermal stability even at high annealing temperatures compared to alloys employing only Al_3Zr [24]. Figure 6 demonstrates the superior effectiveness of Sc in comparison to commonly used dispersoid forming elements Cr, Mn and Zr on stabilization of grain structure.(125) The graph shows the interrelation between temperature with 50% degree recrystallization of cold-rolled sheets of binary alloys of Al-Mn, Al-Cr, Al-Zr and Al-Sc as a function of alloying content (AE in wt.-%). Figure 7 illustrates that addition of 0.15 wt.-% Zr to cold-rolled sheets of Al-0.4 wt.-% Sc improves the anti-recrystallization effect represented by increase of recrystallization temperature from ~560°C to 620°C.(121) The conclusions are generally in line with the results reported elsewhere. It is shown that the addition of 0.2 wt.-% Zr to Al-0.2 wt.-% Sc increases temperature of recrystallization start to temperatures higher than 600°C.

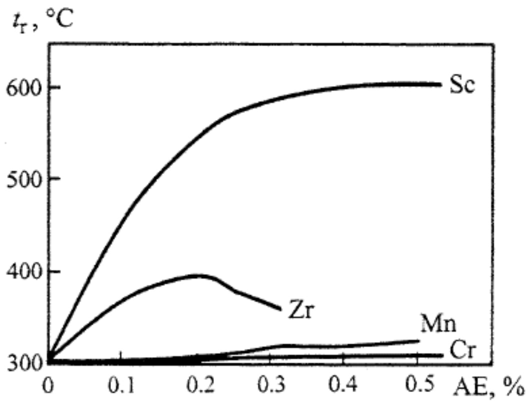


Figure 6: Recrystallization temperature (50% recrystallization) of cold-rolled sheets of binary Al-Sc, Al-Zr, Al-Mn and Al-Cr [26]

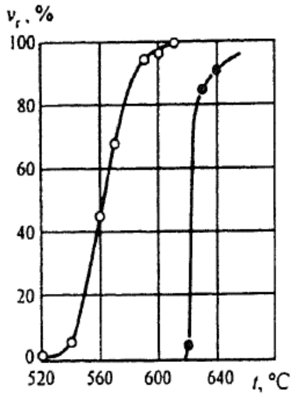


Figure 7: Volume fraction V_f of recrystallized structure in cold-rolled sheets of Al–0.4%Sc (○); Al–0.4%Sc-0.15%Zr (●) as a function of annealing temperature [27]

The benefits of Sc-addition can be either intensified or compromised by interactions with other alloying elements. These elements can be classified in those that

- form strong compounds with Sc and exclude Sc from desired effects (Si, Cu, Fe, Co, Ni),
- do not form any compounds with Sc (Zn, Mg, Li),
- form multi-component aluminide particles with Sc (Zr, Ti, Hf, V, Nb, Ta, Mn, Cr, Mo, W, Re, i.e. mainly transition metals).

However, Cu can react with Sc and forms a W-phase ($Al_{5.4-8}Cu_{6.6-4}Sc$). Al, Si and Sc can form a ternary Al-Si-Sc phase, which is frequently referred to as V-phase. It is reported that appearance of this phase completely neutralizes the beneficial effects related to Sc-addition, even at low Si-contents of about 0.4 wt.-%.

3.2 Al-Mg-Sc new material concepts

The fuselage share of the structural weight of a commercial aircraft is extremely high. A reduction in weight together with improving resistance to corrosion decisively influence the direct operating costs of fixed-route services for airlines and hence the cost effectiveness. An additional advantage is yielded by reducing the manufacturing costs of a welded structure. In the 1990’s these requirements led EADS to develop a welded, integral fuselage construction. However, the prerequisite for this is the availability of the appropriate weldable materials (LBW-laser beam welding, FSW-friction stir welding), such as the Al-Mg-Sc with a small addition of Scandium in the range of 0.10-0.30 wt.% , with the necessary technological properties and efficient welding methods [28-35]. The extremely favourable properties of the Al-Mg-Sc alloys were exploited in the former Soviet Union for use in welded structures (welded housing, tanks) in spaceflight. This led to a reduction in weight together with an increase in efficiency.

Various types of commercial Sc-containing alloys and filler alloys in the Al-Mg systems have been developed in Russia, whereas only two western commercial counterpart namely AA5025, exists up to date (Table 3). The 5025 alloy is intended for use as welding wire. Within the framework of a BMBF (German Federal Ministry of Education and Research) project, a weldable, corrosion-resistant Al-Mg-Sc alloy (AA5024) was developed for use in transportation technology, with a focus on aeronautical applications.

The Al-Mg-Sc alloys (Ko8242/AA5024) based on the 5xxx alloys with a small addition of Scandium, offers in comparison to conventional alloys reduced density compared to AA2024, AA2524 AA6013 (Table 4 & Table 5), good fatigue and damage tolerance properties and excellent corrosion resistance.

Table 3: Chemical composition of different Al-Mg-Sc alloys and filler metals [11, 12, 36]

Type	Mg	Cu	Mn	Zr	Ti	Sc	Cr	Fe	Si
AA5024	3.9-5.1	0.2	0.2	0.05-0.2	0.2	0.10-0.40	0.1	0.4	0.25
AA5025	4.5-6.0	<0.1	<0.2	0.1-0.25	0.05-0.20	0.05-0.55	<0.2	<0.25	<0.25
01515	1.0-1.5	-	0.1-0.2	0.1-0.15	-	0.2-0.3	-	<0.2	<0.15
01523	1.9-2.5	-	0.1-0.2	0.1-0.15	-	0.2-0.3	-	<0.2	<0.15
01525	2.8-3.8					0.1-0.15			
01535	4.0-4.5	-	0.1-0.2	0.1-0.15	-	0.2-0.3	-	<0.2	<0.15
01530	3.9-4.7					0.3-0.5			
01545	5.0-5.5	-	0.1-0.2	0.1-0.15	-	0.2-0.3	-	<0.2	<0.15
01545K	4.0-4.9	<0.01	0.2-0.3	0.06-0.12	0.05-0.10	0.2-0.3	-	<0.1	<0.07
01570	5.4-6.4					0.15-0.35			
01571	6.0-6.5	-	0.1-0.25	0.1-0.15	0.05-0.10	0.25-0.35	0.1-0.15	<0.2	<0.15
01597	5.5-6.5	-	0.35-0.6	0.1-0.15	0.10-0.15	0.35-0.50	0.1-0.15	<0.15	<0.10

Table 4: Chemical composition of aluminium alloys for fuselage application

Alloy		Mg	Mn	Sc	Zr	Si	Cu	Zn
AlCuMg	2024	1.2-1.8	0.3-0.9	-	0.2	<0.5	3.8-4.9	<0.25
AlMgSiCu	6013	0.8-1.2	0.2-0.8	-	-	0.6-1.0	0.6-1.1	-
	6056	0.6-1.2	0.4-1.0	-	0.2	0.7-1.3	0.5-1.1	0.1-0.7
AlCuLi	1464	0.1-0.6	0.05-0.5	Sc	0.05-0.12	0.02-0.15	3.0-3.5	0.01-1.0
AlMgSc	5xxx+Sc	3.0-6.0	Mn	Sc	Zr	0.11	0.029	-
AlMgLi	1424	5.35	-	0.08	0.09	<0.05	-	0.65

Table 5: Physical properties of the new alloys in comparison to 2024

Alloy		Density [g/cm³]	Young's Modulus [MPa]	$\Delta\rho$ [%]	ΔYoung's Modulus [%]
AlCuMg	2024	2.78	69.000	-	-
AlMgSiCu	6013, 6065	2.71	70.000	-2.5	+1.5
AlCuLi	1464	2.64	76.900	-5	+11.1
AlMgSc	5xxx+Sc	2.65	73.000	-4.7	+5.8
AlMgLi	1424	2.52	77.000	-9.4	+11.6

The very good damage tolerance properties of the Al-Mg-Sc alloys could permit a beneficial application in the skin of fuselage sections driven by damage tolerance requirements. This material shows also an excellent weldability for Laser Beam Welding as well as Fricture Stir Welding (Figure 8). Laser beam welding is predestined for joining fuselage structure thanks to low heat exposure of components, a narrow welding seam, a high process speed of 1000 cm/min in comparison to 10 cm/min for riveting and a high degree of automatic potential. The realisation of this concept presupposes the availability of weldable aluminium alloys that meet the requirements for outer skin structures. The butt-joining of skin sheets can be realized by means of FSW. In this process the joint is achieved by kneading the edge areas of the parts being joined. In this way materials can be joined that are otherwise metallurgical incompatible for welding purposes.

The new developed Al-Mg-Sc materials received the required material properties, but unfortunately the stretch forming method, which is commonly used by Airbus to form fuselage shells having double curvature, were not applicable for this material. In order to solve this problem, the creep-forming process has been developed and applied for welded stringer-skin structure.

The very high thermal stability of the microstructure due to the influence of Sc-addition, demonstrated in Figure 9, enables the application of creep forming temperature to up to 325°C without spring-back effect [37-39]. The principle advantages of the creep-forming process of welded structures with Al-Mg-Sc alloys are:

- Possibility of forming the alloy without spring-back at the end of the manufacturing process
- Hardening of the weldment joints nearly to the level of parent material after forming at elevated temperature
- Welding in flat configuration
- Simplified the laser beam welding of the stringer to the sheet under plane conditions, with or without filler wire
- Essential reduction of the manufacturing steps up to 9 steps in comparison by conventional riveting technology of AA2024 -22 steps.

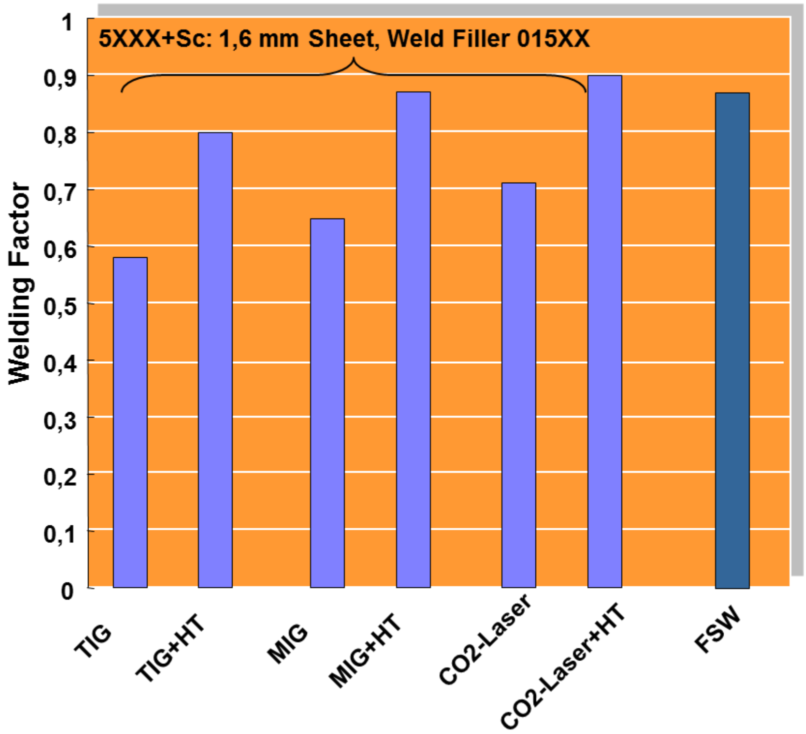


Figure 8: Weldability of Al-Mg-Sc alloy for the welding techniques: TIG (tungsten inert gas), MIG (metal inert gas), CO_2 laser and FSW; HT - heat treatment

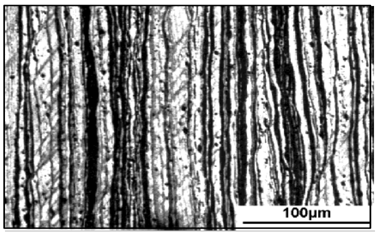
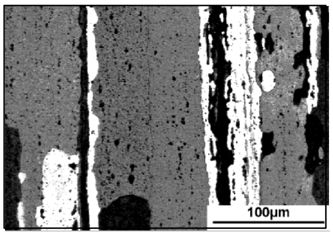
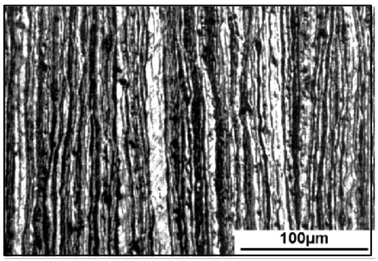
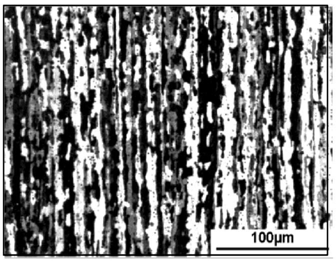
Alloy	400°C/2 h	550°C/2 h
AlMg3Sc0.15		
AlMg4,5Sc0.3		

Figure 9: Microstructure evolution of the Al-Mg-Sc material for two different alloys at higher temperatures

Using this creep forming technology at elevated temperature, there is no distortion or spring-back of the material, thus enabling a high-precision and cost-effective production process. Nevertheless, the material is under further development in order to improve the static properties. The new alloy Ko8242 and next “generation” of Al-Mg-Sc alloys with improved static properties are strong competitors to Al-Li alloys for a fuselage skin application.

4. Conclusions

To maintain the metallic fuselage as a competitive technology in comparison to the composite fuselage new design concepts with appropriate alloys and material technology are needed to support the new approach of “care free” structure designed for minimum life cycle cost. While aluminium alloys are under increased pressure from composites, the use of innovative light-weight aluminium alloys provide benefits over composites such as lower risk and better value as equipment tools. Assembly techniques and training are the same as conventional Al alloys so time and money is not spent on refitting the workplace. The repair and maintenance of metallic structure is also familiar to airlines and repair shops around the world. Also recycling at the end of the aircraft’s life is significantly easier than for composites. Today a combination of low weight, good damage tolerance, reliability, low manufacturing cost and recyclability are needed to satisfy the required operating cost and safety of the aircraft. A reduction in weight together with improving resistance to corrosion decisively influence the direct operating costs of fixed-route services for airlines and hence the cost effectiveness. Weight savings on the aircraft structure have a direct effect on fuel savings, as well as reducing other operation costs. The use of new Al-Li alloys can provide significant weight savings to airframe structures. Careful consideration while designing components to minimize the raw material sizes and the associated buy/fly ratios can reduce these additional material costs. Also Al-Mg-Sc alloys technology offers opportunity for cost and weight savings because it does not require cladding to provide high corrosion resistance. Therefore the fully cost/weight benefit of Al-Mg-Sc alloys and technologies is possible by application of the new creep forming manufacturing process chain for integral structure. The weight reduction potential of Al-Mg-Sc as well as the cost/weight is highly interesting for application in aerospace. The major manufacturing steps as well as the structural performance of Al-Mg-Sc alloys have been already demonstrated for some relevant aerospace application components.

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