ICAS-88-6.7.2

ALLOY DESIGN, MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SUPERLIGHT HIGH STIFFNESS ALUMINIUM-LITHIUM MATERIALS

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Abstract

Recently, the interest of the aluminium industry and aircraft manufacturers in new generation aluminium alloys has dramatically increased, especially in the light of new emerging aircraft materials like non-metallic composites. Main attention has been focussed on a new generation of low density, high stiffness Li-containing Al alloys. Compared to conventional high strength Al alloys, they offer an about 10 % decrease in density along with an equivalent increase of the elastic modulus, thus allowing the structural weight of a component to be reduced by as much as 15 % or even more.

The alloys of the three main companies involved in Al-Li alloy development - Alcan International (UK), Alcoa (USA) and Cégédur Pechiney (F) are presented. The microstructures, the mechanical properties and the corrosion behaviour of these alloys are discussed and compared to conventional high-strength Al alloys of the 2XXX and 7XXX series. Furthermore, special emphasis is laid on superplasticity and problems of recycling. Finally, an outlook is given on the prospects of Al-Li alloys as construction material for future generation aircraft.

1. Introduction

Most developments in materials for aircraft and space applications are driven by the idea of saving structural weight. In that respect the reduction in density has been proven to be far more effective than any other measure, like, e.g., increased strength or stiffness or improved durability and damage tolerance performance [1]. This has also made Al alloys to be the most popular structural materials of today's aircraft generation. However, this leadership is challenged by new emerging non-metallic materials, like e.g. the carbon fibre reinforced composites, which reveal certain improved specific properties when compared to conventional high strength aluminium alloys. The aluminium industry has however taken this challenge by developing a new generation of superlight weight Al alloys with Lithium as a major alloying addition [2-6].

What makes these new Al-Li alloys so attractive?

Figure 1a shows the influence of various chemical elements on density when alloyed to aluminium [7]. It is obvious that Li reveals an outstanding behaviour. Since it is the lightest metallic element we know it decreases the density of Al alloys most effectively. With a density of 0.534 g/cm^3 Li weighs only one fifth of the "classical" light element aluminium. Zn or Cu, e.g., which are the prime alloying elements of the conventional 2XXX and 7XXX series high strength aluminium alloys, are roughly 14 and 18 times heavier than Li! More precisely, every weight percent Li added to Al alloys reduces the weight by about 3 % [8].

But Li not only reduces weight, it also increases stiffness. Figure 1b shows the influence of various alloying elements of binary Al alloys on the elastic modulus [7]. Again, Li takes an outstanding position in that it is the alloying element which most effectively increases stiffness. Every weight percent of Li added to Al raises the Young's modulus by about 4 %.

Compared to carbon fibre reinforced composites no new fabrication technology needs to be developed for Al-Li alloys. As metallic materials they can be rolled, extruded, forged, machined and handled very similar to conventional high strength Al alloys. Essentially no new investments are required by the aircraft manufacturers.

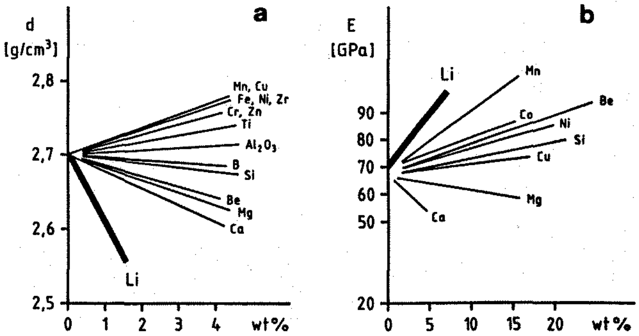

Fig. 1: Effect of alloying elements to aluminium on (a) density and (b) elastic modulus [6].

There are, however, also drawbacks associated to the addition of Li to Al. Al-Li alloys are more brittle and less tough when compared to conventional high strength Al alloys. Therefore, the metallurgical efforts to commercialize Al-Li alloys are concentrated on improving the fracture properties.

Then there is the price of the new Al-Li alloys. They are expected to be about two to four times more expensive than their conventional counterparts they intend to replace. Reasons for this high price include the expensiveness of Li and the investments which have to be made by the aluminium companies, since new melting and casting facilities have to be installed for Al-Li alloys. Furthermore, safety requirements are higher due to the high reactivity of Li.

In the following it is tried to review the present status of Al-Li alloy development, without claiming for completeness. Besides stressing more general the historical background of the new alloys, their microstructure, mechanical and corrosion properties as well as first applications, emphasis is laid on two special topics where Al-Li alloys might play a different role from that of conventional high strength Al alloys: superplasticity and recycling.

2. Historical Reflections

The first commercial Li-containing Al alloys were developed in Germany by the "Metallbank und Metallurgische Gesellschaft" in Frankfurt (today "Metallgesellschaft") already in 1924 [9]. These alloys, named "Scleron", contained only 0.1 % Li. They did not become a success, because at that time they had to compete against the "Duralumin", the forerunner of the still today very popular high strength Al alloy 2024. Moreover, it is believed that Li happened to be in the Scleron alloys just by chance, because of patent reasons.

The first Al alloy where Lithium was deliberately added to save weight was 2020. This alloy, developed in the 1950s by Alcoa, USA, contained about 1.3 wt.% Li [8,10]. For more than 15 years it was used on a US military airplane. Finally, it was withdrawn, because it did not fulfil the damage tolerant requirements established in the 1970s [10]. Again, the Al-Li alloy had to give way to advanced, high-toughness alloys like 7475 and 2024.

The present and third attempt to renew interest in Al-Li alloys can be seen as an answer to a threat, this time not coming from competition of other Al alloys, but from new non-metallic composites challenging metallic structures in general as materials for future aircraft generations.

This time the Al-Li initiative was taken by researchers at the Royal Aircraft Establishment (RAE) in the first half of the 1970s [11]. It led to the development of the first of the current generation of Al-Li alloys: Originally designated F92 [12], the alloy changed its name first to DTD XXXA/C and then to Lital A/C with the Aluminium Association registration number 8090, once the British Aluminium Co. - now Alcan International Ltd. - became involved in 1977 [13]. These activities in Europe revitalized commercial interest in Al-Li alloys all over the world [2-6,14], particularly at the Aluminum Company of America, Alcoa [15] and at *Cégédur* Pechiney in France [16].

Table 1: The new Al-Li alloys proposed by Alcan (UK), Alcoa (USA) and Pechiney (France).

Producer	*Tradename*	*Alloy No.*	*Chemical Composition Range* Li	Cu	Mg	Zr	*Density* g/cm^3
Alcan	Lital A	8090	2.2-2.7	1.0-1.6	0.6-1.3	0.04-0.16	2.54
	Lital B	8091	2.4-2.8	1.6-2.2	0.5-1.2	0.08-0.16	2.55
	Lital C	8090	2.2-2.7	1.0-1.6	0.6-1.3	0.04-0.16	2.54
Alcoa	Alithalite Goal A	X 8090 A	2.1-2.7	1.1-1.6	0.8-1.4	0.08-0.15	2.55
	Alithalite Goal B	2090	1.9-2.6	2.4-3.0	-	0.08-0.15	2.57
	Alithalite Goal C	X 8192	2.3-2.9	0.4-0.7	0.9-1.4	0.08-0.15	2.52
	Alithalite Goal D	X 8092	2.1-2.7	0.5-0.8	0.9-1.4	0.08-0.15	2.52
Pechiney	CP 271	8090	2.2-2.7	1.0-1.6	0.6-1.3	0.04-0.16	2.54
	CP 274	2091	1.7-2.3	1.8-2.5	1.1-1.9	0.04-0.16	2.58
	CP 276	X 2XXX	1.9-2.6	2.5-3.3	0.2-0.8	0.04-0.16	2.58
	CP 277	X XXXX	-	-	-	-	-

3. The New Al-Li Alloys

Although there are great efforts put into the development of the new Al-Li alloys, particularly in the United States and Europe, it is fair to say that essentially three companies are setting the pace. These are - in alphabetical order - Alcan (United Kingdom), Alcoa (USA) and Pechiney (France). All alloys which have so far been internationally registered, were developed by them.

The alloys proposed by the three aluminium producers are listed in Table 1, along with the Aluminum Association designation code, the chemical composition range and the density, where known already. All alloys are either of the Al-Cu-Li-Mg-Zr type (2X9X) or Al-Li-Cu-Mg-Zr type (8X9X), the only exception being Alcoa’s Al-Cu-Li-Zr alloy 2090 which does not contain Mg. For all alloys the Lithium contents vary between 1.7 and 2.9 wt.%. Densities as published by the producers range from about 2.52 to 2.58 g/cm^3. Compared to densities of conventional high strength aluminium alloys like 2024 (2.77 g/cm^3) or 7475 (2.80 g/cm^3) this represents a decrease in density of about 7 to 10 %.

Of all the alloys listed in Table 1, only four have been registered to date by the Aluminum Association: 2090, 2091, 8090 and 8091. Alloys with an X have experimental character with registration requested: e.g. X 8092 or X 8192. One alloy, X 8090 A is requested for registration by Alcoa as a national variant to the common European

Table 2: Various alloy categories for the new Al-Li alloys according to the conventional high strength Al alloys to be replaced.

Alloy Category (Replaced Alloy)	Al-Li Alloy	Tradename	Producer	Additional Comments
Damage Tolerant	8090	Lital C	Alcan	
(2024-T3)	X 8090 A	Alithalite Goal A	Alcoa	
	2091	CP 274	Pechiney	
Medium Strength	8090	Lital A	Alcan	
(2014-T6)	X 8092	Alithalite Goal D	Alcoa	Stress Corrosion Resistant
(2214-T6)	X 8192	Alithalite Goal C	Alcoa	Low Density
(7075-T73)	8090	CP 271	Pechiney	Low Density
	2091	CP 274	Pechiney	High Toughness
High Strength	8091	Lital B	Alcan	
(7075-T6)	2090	Alithalite Goal B	Alcoa	
(7010/7050)	X 2XXX	CP 276	Pechiney	
Very Low Density	X 8192	Alithalite Goal C	Alcoa	Medium Strength
	X XXXX	CP 277	Pechiney	
Stress Corrosion Resistant (7075-T73)	X 8092	Alithalite Goal D	Alcoa	Medium Strength

alloy 8090.

It is obvious from Table 1 that only Alcan has registered so far all of its alloys while both Alcoa and Pechiney have still some alloys at an early development stage. Of the four alloys internationally registered, the two 809X series alloys show some advantage in density over the two 209X variants (Table 1).

To compare the different alloys of the three companies it is necessary to categorize them. This has been done in Table 2 where the new Al-Li alloys are put into various alloy categories as proposed by the aluminium producers [13,15,16] along with the conventional high strength alloys to be replaced. It should be mentioned that the categorizing in Table 2 can only serve as a rough classification, for various reasons. Firstly, the table does not distinguish between product forms like sheet, plate, extrusions or forgings, the latter two might even be further subdivided into thin and thick products. Secondly, the category can very well change with product form. So, as medium strength replacements Pechiney proposes 2091-T8 for sheet, however, 8090-T8 for extrusions. Thirdly, the same alloys might be found in several categories, because the table does not distinguish between different tempers. So 8090 in a strongly underaged condition (Lital C) is proposed by Alcan to be a substitute for the damage tolerant 2024-T3, while in a further aged condition (Lital A) it would be able to replace medium strength alloys like 2014-T6. Pechiney recommends 2091-T8X for damage tolerant sheet while a 2091-T8 temper would replace medium strength sheet. Finally, the classification of the various new Al-Li alloys is not definite since some alloys listed in Table 2 still undergo extensive development, e.g. X 8092 or X 8192. For the Pechiney alloy CP 277, the chemical composition has not yet even been published. Therefore, for a more detailed study the reader is referred to the publications of the producers [13,15,16].

Some additional comments can however be made. Most advanced and at the edge of widespread commerical application are the damage tolerant Al-Li alloys followed by the medium strength variants. These two categories would also allow the three producers to go for one common alloy: 8090. This RAE patented alloy [12] is jointly registered by Alcan and Pechiney and slightly modified by Alcoa (Table 1).

Sticking to an as less as possible number of different alloys has been a major demand of the aircraft industry. For the three high strength Al-Li alloys proposed no such commonness has come in sight. Furthermore, these alloys still undergo extensive development as well as the category of very low density alloys. Due to their high strengths and/or high lithium contents, they often do not yet meet the ductility or toughness goals to match the properties of the corresponding conventional Al alloys they intend to replace.

4. Microstructure

The most characteristic microstructural feature of Al-Li alloys is the Al_3Li or δ' phase [8,14]. This metastable phase forms very fine precipitates (20 to 200 nm) which are spherical, coherent with the matrix and - contrary to other metastable phases in high strength Al alloys - they are ordered (Fig. 2a). Therefore, some relationship exists to the γ' phase in Ni base superalloys. The coherent and ordered nature of δ' leads to microscopically localized slip, early crack nucleation and is therefore considered to be one reason for the lower ductility and toughness of Al-Li alloys compared to conventional high strength Al alloys.

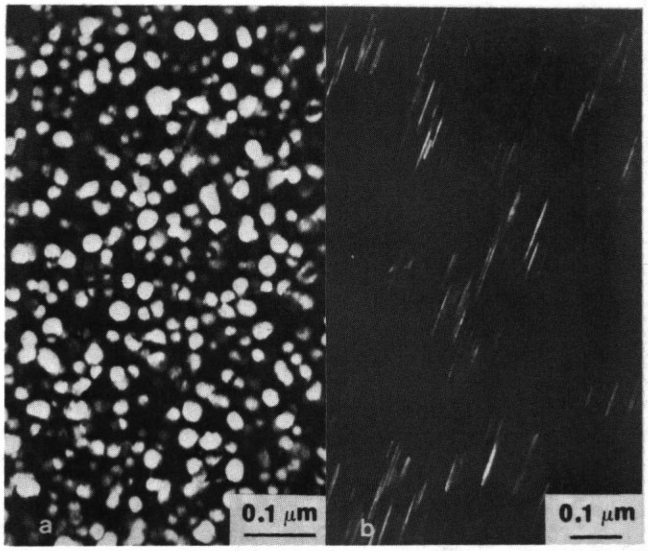

Fig. 2: Transmission electron microscopy dark field micrographs of 2091 showing δ' particles (a) and S' precipitates (b) after 1000 h at 150 °C [40].

The alloy design of the new Al-Li alloys, i.e., going from binary Al-Li alloys to ternary (Al-Li-Cu) or quaternary (Al-Li-Cu-Mg) alloys, is aimed at coprecipitation of additional, non-coherent and non-ordered phases - like S' (Fig. 2b) or T_1 - which besides leading to a more homogenized slip and thus increased ductility further adds to the strength of the alloys. Furthermore, small amounts of Zr are added to all Al-Li alloys to effectively stabilize the grain size [8,14].

5. Mechanical Properties

Besides density reduction, Li increases the elastic modulus. The increase achieved with the four so far registered Al-Li alloys - 2090, 2091, 8090 and 8091 - ranges between 6 and 12 % depending on the conventional high strength Al alloys to be compared with [6,15-17]. The specific modulus increase - i.e., the Young's modulus corrected for density - can easily reach values beyond 20 % (Table 3).

Table 3: Density, elastic modulus and specific elastic modulus of 8090 compared to the conventional high strength Al alloys 2014, 2024 and 7075. Relative changes of 8090 to 2014, 2024 and 7075 are given in brackets [6].

	8090	2014	2024	7075
ρ, g/cm^3	2.54	2.80 (−9.3%)	2.77 (−8.3%)	2.80 (−9.3%)
E, GPa	79.5	72.4 (+9.8%)	72.4 (+9.8%)	71.0 (+12.0%)
E/ρ		(+21.1%)	(+19.8%)	(+23.4%)

Since their hardening mechanisms are fairly understood [8,14], it has not been a problem for Al-Li alloys to match the yield and tensile strength levels of their Li-free counterparts. This was, however, not the case for the ductility. With increased aging, a grain boundary failure mode is observed which goes along with reduced ductility [18-26]. This effect is especially pronounced for plate material in the short transverse direction [19-21,23]. Various reasons for the low energy grain boundary fracture have been discussed. These include the extensive coplanar slip due to the ordered and coherent nature of the age-hardening phase δ', grain boundary particles along with a precipitate-free zone, segregation of impurity elements like Na, K or low-melting compounds of those two elements at grain boundaries, or segregation of Li itself at grain boundaries [18-26]. Although these embrittling mechanisms are not finally understood, there is consensus that impurity levels should be kept low for Al-Li alloys. Attempts in this direction were shown to be very promising in improving short transverse ductility [13].

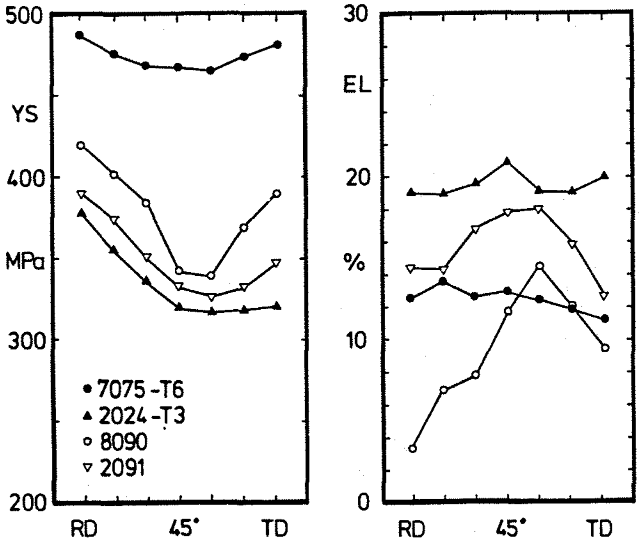

Fig. 3: Yield strength (YS) and elongation to fracture (EL) measured on sheet material of 7075, 2024, 8090 (unrecrystallized) and 2091 (recrystallized). "Round-the-clock" tensile tests were performed in rolling direction (RD), in transverse direction (TD) and 15°, 30°, 45°, 60°, 75° off RD [25,29].

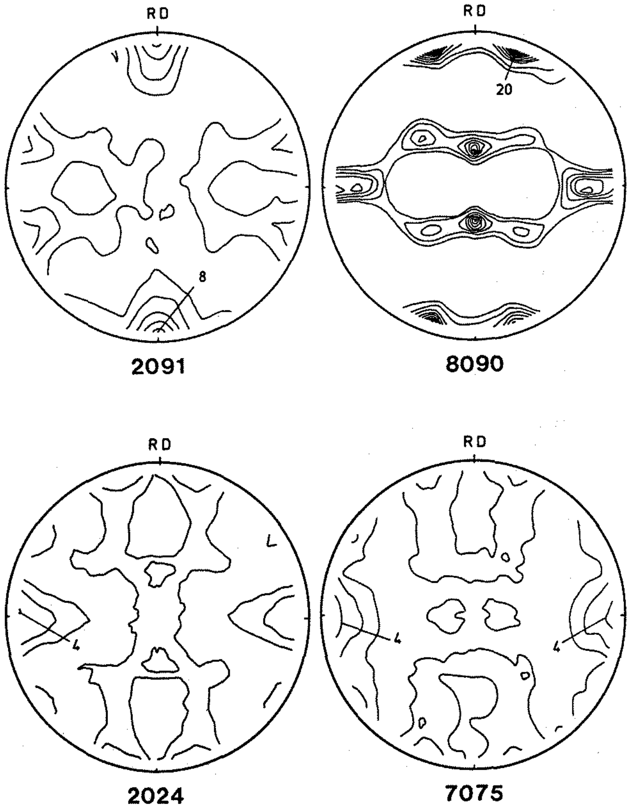

Fig. 4: {111} pole figures determined on sheet material of 2091 (recrystallized), 8090 (unrecrystallized), 2024 and 7075 [25,29].

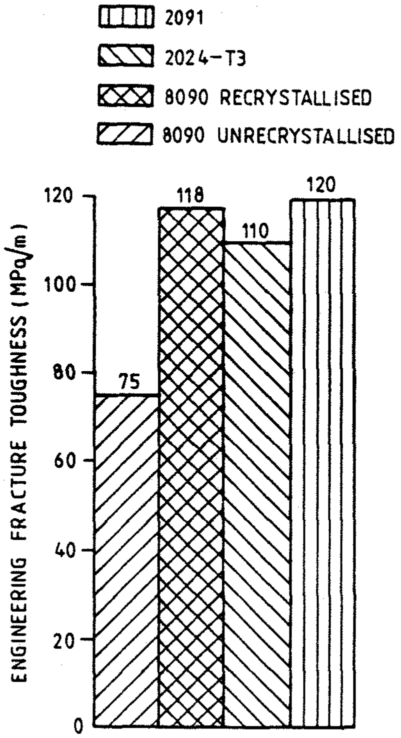

Fig. 5: Comparison of the fracture toughness of damage tolerant sheet alloys [13].

Furthermore, early Al-Li production material revealed anisotropic tensile properties, not known to that extent from conventional high strength Al alloys. So, sheet showed an anisotropy with tensile direction [27-29] as shown in Fig. 3, and plate revealed a gradient in through-thickness direction [20,30-32]. Meanwhile, it is accepted that these anomalies are a result of the crystallographic texture which is more pronounced in Al-Li alloys [27-33]. This is evident from Fig. 4 where {111} pole figures of the four alloys in Fig. 3 are shown. The two Li-containing alloys reveal a stronger texture than the two Li-free alloys. This is consistent with the stronger anisotropy of 8090 and 2091 (Fig. 3). Comparing the unrecrystallized 8090 with the recrystallized 2091 sheet, it seems that recrystallization tends to reduce the preferred crystallographic orientation (Fig. 4) and thus the anisotropy of tensile properties (Fig. 3). These and other measures, like changes of the thermomechanical processing route, the aging practice and the alloying ingredients have enabled the aluminium producers to now offer semifinished Al-Li products with far more isotropic properties.

The ingot quality of today's Al-Li alloys is much improved. Since Na has been recognised as one of the reasons for low ductility and toughness, the Na level is kept below 10 ppm [34]. In this respect it is worth mentioning the development of a new electrolysis process by Sumitomo Light Metal, enabling to produce an Al-20Li master alloy with extremely low impurity levels [35].

Fracture toughness, which is a major requirement for damage tolerant sheet material, was further improved by producing sheet with a recrystallized microstructure. From Fig. 5 it is evident that recrystallized Al-Li sheet can easily match the fracture toughness properties of 2024-T3, the conventional damage tolerant alloy [13]. As a side effect recrystallized structures have improved isotropy at an only slight expense of strength. For plate material, introduction of large strains has been shown to substantially improve fracture toughness, especially in short transverse direction [13].

Since Al-Li alloys are primarily developed for aerospace applications, their fatigue performance is of major interest. It was shown that in high-cycle fatigue Al-Li alloys could match the properties of the conventional alloys to be replaced [20,27,36,37]. An example is given in Fig. 6, where S-N curves are shown for 2024-T851 and 8090-T651 [37]. For both longitudinal and transverse direction the Al-Li alloy showed higher fatigue strength values.

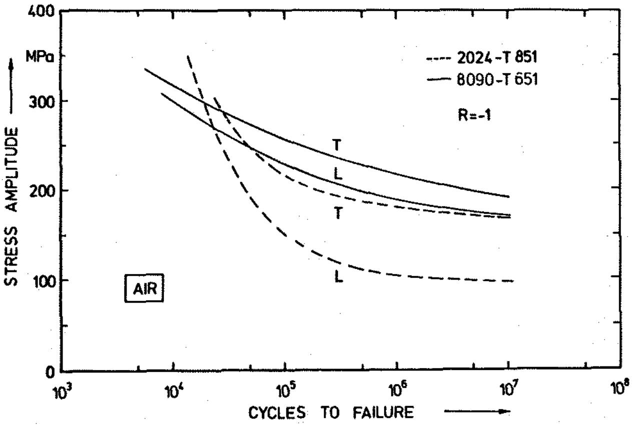

Fig. 6: High cycle fatigue properties of 8090-T651 and 2024-T851 plate material tested in longitudinal (L) and transverse (T) direction at R = -1 (push-pull) in laboratory air [37].

In fatigue crack growth Al-Li alloys proved to be mostly superior to their conventional high strength counterparts [13,20,27,34,37-41]. Tests performed at a R-ratio (minimum load/maximum load) of 0.1 on compact tension specimens of 8090-T651, 2024-T351 and 2024-T851 [37] revealed that the Al-Li alloy showed the highest resistance to crack propagation over the entire range investigated (Fig. 7). As the R-ratio is increased to 0.7 the superiority of the Al-Li alloy partly disappears (Fig. 7). These are evidences that the high fatigue crack propagation resistance of Al-Li alloys is primarily a result of crack closure effects. Substantially, this means

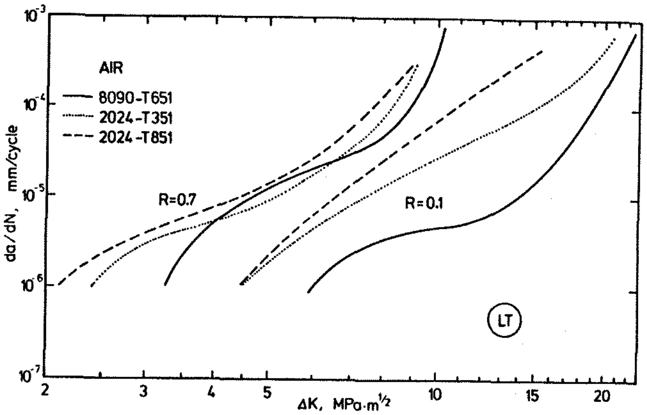

Fig. 7: Fatigue crack growth curves of 8090-T651, 2024-T351 and 2024-T851 plate material tested in LT orientation at R = 0.1 and 0.7 in laboratory air [39].

that during the unloading part of the cycle the crack does not fully close, thus decreasing the effective stress intensity amplitude at the crack tip. Various reasons are claimed to be responsible for closure: surface roughness, fretting debris or oxide deposits on the fracture surface. Finally, a strong tendency for cracks to branch or deflect was observed which also will lead to reduced stress intensities at the crack tip(s) thus further decreasing the crack growth rate [39].

6. Corrosion

To evaluate the new Al-Li alloys it is not sufficient to know their mechanical properties, but it is also essential to understand their corrosion behaviour, since these alloys will be exposed to a wide range of atmospheres during their lifetime, which might very well reach 30 years or more.

Usually, the corrosion behaviour is sufficiently characterized, when the resistance to five different types of corrosion - pitting corrosion, intergranular corrosion, exfoliation corrosion, stress corrosion cracking (SCC) and corrosion fatigue - is known.

For all these corrosion types various accelerated tests have been developed, which - within a time period between a few hours and a couple of weeks - should give a quick answer on the question whether a material is susceptible to an individual type of corrosion. Moreover, various individual types of tests are in practice to evaluate one single type of corrosion. For example, SCC can be determined on double cantilever beam specimens, C-rings, bent-beam specimens or simply tension specimens. Furthermore, tests can be performed under constant load, constant strain, or constant strain rate. Moreover, the length of exposure can differ as well as the corrosive environment. Here normally alternate immersion in 3.5 % NaCl solution is used, but continuous immersion and other electrolytes are also employed. To evaluate the exfoliation corrosion behaviour the EXCO test (ASTM G34-79) is used as well as an intermittent acidified salt spray test, the MASTMAASIS test.

To even more complicate the situation, some of these tests are only designed for high strength Al alloys of the 2XXX and/or 7XXX series, leaving the question, whether they are also appropriate for the Li-containing Al alloys.

All this might give an idea of the complexity of the evaluation of the corrosion behaviour of Al-Li alloys. Not surprisingly, results are sometimes contradictious. For instance, there is still controversy about which short-term exfoliation test to use for Al-Li alloys. Final answers, however, can only be given once sufficient data on long-term marine atmospheric tests have been generated. But this implies a certain problem: Since Al-Li alloys are relatively new, only few alloys with anticipated heat treatment have already experienced extended outdoor exposure. More results are needed to argue on a safe basis.

Despite of these shortcomings, some more general comments on the corrosion behaviour of Al-Li alloys can, however, be made already:

- Like the conventional high strength Al alloys, Al-Li alloys show a certain degree of susceptibility to localized corrosion. Therefore, they will need to be cladded to provide galvanic protection like the 2XXX and 7XXX series alloys. Attempts to clad Al-Li alloys, e.g. with 7072, 1145 or 1230 have proved to be successful [34,42].

- The resistance to SCC of Al-Li plate material is high in in-plane orientation. In short transverse direction Al-Li alloys can be susceptible to SCC, however, they still might be superior to conventional high strength Al alloys as shown, e.g., in Fig. 8 [43,44].

- The corrosion properties strongly vary with aging time. Underaging as well as overaging can be efficient in increasing the resistance to exfoliation and intergranular attack but may also increase the susceptibility to SCC [25,45]. Table 4 gives an example of how the threshold stress for SCC of 2091 sheet material substantially increases with increasing aging, all tempers still being underaged [25]. 8090, which is aged to peak strength, shows no SCC-susceptibility, as can be seen from the nearly equivalent values of the SCC threshold stress and 0.2 % yield stress (Table 4).

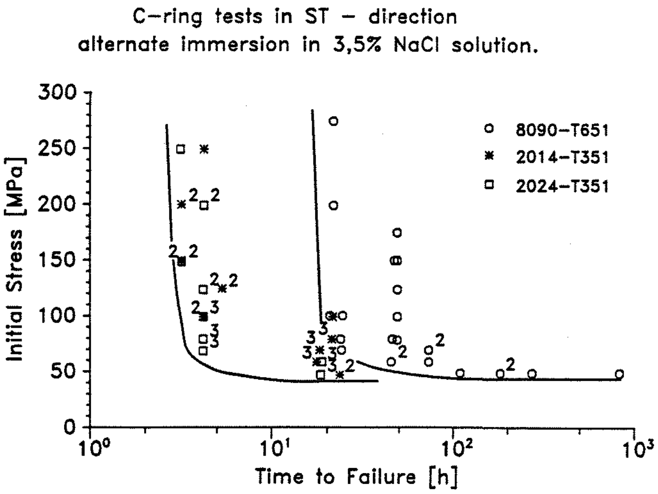

Fig. 8: Stress corrosion tests performed on C-ring specimens in ST direction of 8090-T651, 2014-T351 and 2024-T851 alternately immersed in 3.5 % NaCl solution [43,44].

- The mechanisms responsible for SCC are probably anodic dissolution and hydrogen embrittlement [25,34,43].

- Alloying can influence the corrosion behaviour. While Cu increases the corrosion susceptibility, Zn tends to increase the SCC resistance [34,45,46].

To summarize: It is evident that still further work has to be performed to fully understand the overall corrosion behaviour of Al-Li alloys. Nevertheless, the apparent problems, which are partly similar in conventional high strength Al alloys, can be overcome, e.g., by applying clad material, special thermomechanical treatments, microstructural changes or alloying modifications. Care has to be taken to properly balance the corrosion and the mechanical properties of final components [25].

Table 4: Results on SCC performed on 2091, 8090 and 2024 [25].

Material		Threshold Stress MPa	0.2% Yield Stress MPa
2091-CP274	12h/135°C	150	355
	12h/150°C	200	365
	100h/150°C	300	390
2024-T3 unclad		350	365
8090-T6		390	396

bent-beam stress-corrosion test specimens (ASTM G39-79)
- stressed in the longitudinal direction
- alternate immersion in 3.5% NaCl solution
- maximum period: 30 days
- failure criterion: macroscopic fracture

7. Superplasticity

Superplasticity is the ability of an alloy to plastically deform to high elongations - 1000 % or even more - as known, e.g., from plastics or glasses. Therefore, superplastic forming (SPF) is considered to be a new promising and cost efficient near net shape technology, especially when combined with diffusion bonding.

To make an alloy behave superplastic, several requirements have to be fulfilled: So the deformation has to take place at high temperatures, normally about half of the absolute melting point, and at a forming rate usually lower than employed in conventional forming procedures. As far as the material is concerned, it has to have a very fine grain size ($\lesssim 10$ μm) which should be stable during the forming procedure. This latter requirement limits the number of alloys with superplastic potential. For aerospace materials, titanium alloys are probably the ones which can be superplastically deformed most easily since often semi-products reveal already a sufficiently fine grain structure [17,47,48]. For high strength Al alloys specific thermomechanical treatments are proposed to establish a fine-grained microstructure. For 7075, e.g., this is done by high deformation of a severely overaged condition, where fine dispersed particles act as recrystallization nuclei during further heating [49]. For 7475, thus processed, grain sizes as small as 15 μm and below were produced and total elongations as high as 1200 % were achieved [50].

How do Al-Li alloys behave superplastically?

Due to small amounts of Zr, the grain structure of Al-Li alloys is normally substantially finer than in conventional high strength Al alloys [8]. Therefore, Al-Li alloys have an excellent potential for superplasticity. Like titanium alloys, standard Al-Li sheet material may already reveal reasonable superplastic strain capability [17]. Moreover, at least two of the major companies involved in Al-Li alloy development - Alcoa and Alcan - are working on sheet material specifically optimised for superplasticity [17,51,52]. Although both companies do not specify their thermomechanical processing routes, it is essential for SPF sheet to be in high deformed and unrecrystallized condition with a fine subgrain size. During the superplastic forming process the Al-Li alloys undergo dynamic recrystallization. Therefore, the SPF-design idea resembles more that of the "Supral" series of alloys - high Zr content Al alloys specifically designed for superplasticity [53]. Elongations of more than 600 % are reported for 2090, 8090 and 8091 [51,52]. Table 5 summarizes a case study performed on a variety of Al-Li based alloys [17]. It is worth mentioning that deformation degrees of 1000 and 1200 % were achieved for 8090 and 8091, respectively.

Table 5: Elongations achieved in superplastically deformed Al-Li based alloys [17].

Al–Li Alloy	Elongation %
Al–2Li	320
Al–3.3Li–0.15Zr	340
Al–3Li–0.5Zr	1035
Al–2.8Mg–2.7Li–0.15Zr	680
Al–2.5Li–1.2Cu–0.5Mg–0.1Zr	875
Al–4Cu–3Li–0.5Zr	825
Al–2.9Cu–1.9Li–1Mg–0.15Zr	798
Al–2.8Cu–1.9Li–0.9Mg–0.2Zr	654
Al–4Cu–2Li–0.2Zr	700
Al–2.4Li–1.2Cu–0.6Mg–0.1Zr (8090)	1000
Al–2.5Li–1.8Cu–0.7Mg–0.12Zr (8091)	1200

Generally it is observed that recrystallization during the forming process leads to a strength loss. Anisotropy of tensile properties - a phenomenon often more pronounced in Al-Li sheet than in conventional Al sheet - is, however, much reduced after superplastic deformation.

As known already from Li-free SPF Al alloys, cavitation is a problem for Al-Li alloys, as well. Therefore, it is suggested that back pressure should be employed during the superplastic forming process of Al-Li sheet material.

Various components have been successfully made by superplastic forming and diffusion bonding, demonstrating the excellent SPF capability of this new class of lightweight alloys. Figure 9 shows a case study from BAe of an undercarriage door made of 8090. This part consists of an outer skin, a core and an inner skin - all superplastically formed and joined by rivetting. The weight saving is 20 %; approximately half the saving comes from the Al-Li alloy and half from utilising the SPF process. The number of details could be reduced from 96 to 11, and the number of fasteners from 1466 to 540.

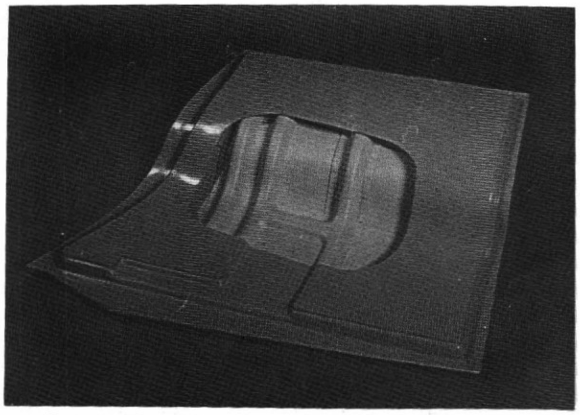

Fig. 9: BAe case study of a superplastically formed 8090 undercarriage door (courtesy: Alcan International).

8. Recycling

Although wrought Al-Li alloys contain less than 3 wt.% Li (Table 1), the price for the Li is usually higher than for the remaining more than 97 % of alloying elements. Therefore, it has been recognised by both the aluminium industry and the aircraft manufacturers that for economical reasons recycling of Al-Li scrap is a key issue [16,54-56]. However, for recycling, Al-Li scrap has to be separated from scrap of conventional Al alloys for both economical and safety reasons. There is the fear that Li could "contaminate" conventional Al alloys, thus leading to degradation of mechanical properties. Furthermore, Li would harm the line of conventional melting furnaces. Preliminary investigations on Li additions up to 8000 ppm to Al-Si alloys did not show an influence on tensile strength. More work has, however, to be carried out to see how other properties like ductility, toughness or stress corrosion cracking are affected [54].

Generally, the Al-Li scrap is divided into two categories, the solid scrap and the thin scrap, like, e.g., in the form of machining swarf. Whereas solid scrap can easily be handled by simply bringing it back to the production plant for direct recycling, it is difficult to handle the swarf, which - unfortunately - makes up the major portion of the scrap. Because of quality considerations the swarf is unsuitable for being recycled within the Al-Li loop, since it would be contaminated by Li-free Al alloys or - even worse - by other aircraft materials such as stainless steel or titanium alloys [16,54]. Furthermore, care has to be taken by secondary aluminium smelters who handle large portions of recycled material. The Al-Li producers are aware of their responsibility and have initiated appropriate R&D programs [16,54,56].

Since no recycling process has yet reached maturity of large scale commercial application, it was proposed for the short time - while market volumes are small - that the Li should be removed from the scrap while only the Al is recycled, before in the medium time processes would allow to fully recycle the expensive Li [54].

9. Commercial Applications

Although new materials in aerospace are usually first tested on military aircraft, their use in civil aircraft is considered to be more important, since this can demonstrate two things at a time: Firstly, the confidence in the new material attesting it a sufficient degree of maturity and, secondly, the economical superiority over the present solution. In the case of Al-Li alloys this means that their use in military airplanes demonstrates that Al-Li alloys can fly, while use in civil aircraft shows that they can fly economically.

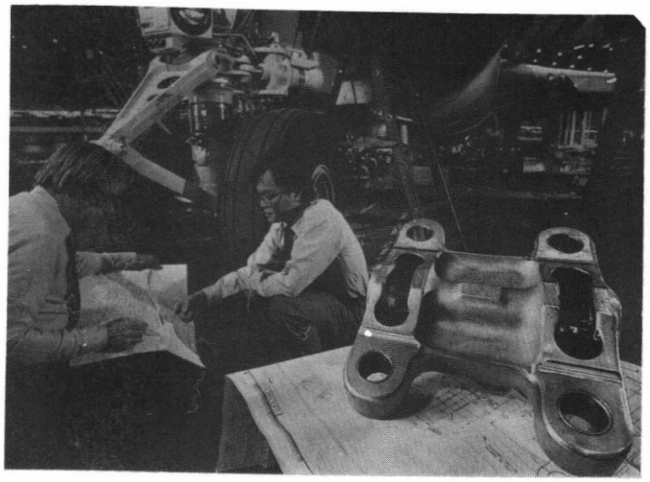

Fig. 10: 2090 forging which serves as tow fitting on a Boeing 747 landing gear (courtesy: Aluminum Company of America).

The Boeing Commercial Airplane Company announced the first use of an Al-Li alloy on a commercial airplane [56]. The Alcoa alloy 2090 was chosen as material for tow fittings on four B-747 front landing gear struts (Fig. 10). These fittings are the attachment point for the tractors that are used to tow 747s at airports. They experience high loads during towing and are extensively exposed to the elements during all take-offs and landings. The fittings are 7 % lighter than the standard alloy fittings they replace.

The next major step was made by the McDonnell Douglas Aircraft Company. It decided to use 2090 extrusions for floor beams on its first five MD-11 transports to be delivered in 1990. Here, Al-Li parts are expected to reduce the aircraft weight by about 145 kg. About 55 % of the weight savings are attributed to the reduced density of the alloy while the rest is a result of the improved mechanical properties [57].

Airbus Industrie has announced that the new A330 and A340 may see the introduction of Al-Li alloys. This will probably not be the case initially, but Al-Li alloys may well be introduced at a certain point in the production run [58]. In a first step stringers and parts of the secondary structure will be made out of Al-Li alloys. Then it is tried to use Al-Li sheet material for the fuselage skin [59].

10. Outlook

As it looks today, damage tolerant and medium strength Al-Li alloys are at the edge of becoming commercial construction material. Further research and development work still has to be performed on the very high strength and/or low density alloys (Table 2), especially to meet the ductility and toughness goals. Grain boundary embrittlement needs to be fully understood as well as the various forms of anisotropy so that measures can be taken to eliminate these undesired properties.

More insight is necessary to better understand the corrosion properties, general corrosion as well as stress corrosion cracking. A consensus has to be found on what are the appropriate short-term corrosion tests. For this reason more data need to be generated on long-term outdoor field tests.

Quite surprisingly, there is a problem of capacity. The question is raised whether the aluminium companies can produce enough Al-Li to meet the quantity and schedule requirements of aerospace programs [56]. This is, however, considered to be a short-term problem which should be overcome once demand is manifested by extended orders for series aircraft. A prerequisite for extended use of Al-Li alloys is, however, a solution to the scrap problem.

The future is already directed towards second and third generation Al-Li alloys, which includes material processed via the powder metallurgy route. Furthermore, Al-Li alloys can also be quite attractive candidates for metal matrix composites or for hybrid composite laminates like ARALL.

11. Acknowledgement

The authors are indebted to R. Braun and K. Welpmann for valuable discussions and to Ch. Kotauschek for the careful preparation of the manuscript.

12. References

1. J.C. Ekvall, J.E. Rhodes and G.G. Wald, "Methodology for Evaluating Weight Savings from Basic Material Properties", in: "Design of Fatigue and Fracture Resistant Structures", ASTM STP 761, pp. 328-341, Philadelphia, 1982.

2. T.H. Sanders, Jr. and E.A. Starke, Jr. (Eds.), "Aluminum-Lithium Alloys", TMS-AIME, Warrendale, PA, 1981.

3. T.H. Sanders, Jr. and E.A. Starke, Jr. (Eds.), "Aluminum-Lithium Alloys II", TMS-AIME, Warrendale, PA, 1984.

4. C. Baker, P.J. Gregson, S.J. Harris and C.J. Peel (Eds.), "Aluminium-Lithium Alloys III", The Institute of Metals, London, 1986.

5. G. Champier, B. Dubost, D. Miannay and L. Sabetay (Eds.), "4th International Aluminium-Lithium Conference", Les Editions de Physique, Les Ulis, Cedex, France, 1987.

6. M. Peters and K. Welpmann, "Aluminium-Lithium - eine neue Generation metallischer Leichtbauwerkstoffe", Metall 39 (1985), pp. 1141-1144.

7. G. Le Roy, "Les Alliages Aluminium-Lithium: La Riposte de l'Aluminium", Matériaux et Techniques, May/June 1986, pp. 187-196.

8. K. Welpmann, M. Peters and T.H.Sanders, Jr., a) "Aluminium-Lithium Alloys (I): Metallurgical Fundamentals", Aluminium 60 (1984), pp. E641-E646. b)"Aluminium-Lithium Alloys (II): Mechanical Properties", Aluminium 60 (1984), pp. E709-712.

9. O. Reuleaux, "Scleron-Legierungen", Zeitschrift für Metallkunde 16 (1924), pp. 436-437.

10. E.S. Balmuth and R. Schmidt, "A Perspective on the Development of Aluminum-Lithium Alloys", in [2], pp. 69-88.

11. B. Evans, "Engineering Aspects of Aluminium-Lithium Alloys", in: "Advanced Materials Research and Developments for Transport/Light Metals", Eds. R.J.H. Wanhill, W.J.G. Bunk and J.G. Wurm, pp. 71-84, Les Editions de Physique, Les Ulis, Cedex, France, 1985.

12. C.J. Peel and B. Evans, U.K. Patent GB 2115836B, 1983.

13. R. Grimes, T. Davis, H.J. Saxty and J.E. Fearon, "Progress to Aluminium-Lithium Semi-Fabricated Products", in [5], pp. 11-24.

14. E.A. Starke, Jr., T.H. Sanders, Jr. and I.G. Palmer, "New Approaches to Alloy Development in the Al-Li System", Journal of Metals 33, August 1981, pp. 24-33.

15. P.E. Bretz, "Alithalite Alloy Development Production", in [5], pp. 25-31.

16. G. Le Roy, R. Mace, D. Marchive, P. Meyer, R. Nossent and F. Schlecht, "Status Report on the Development of Aluminium-Lithium at Pechiney", in [5], pp. 33-39.

17. R. Grimes, "The Manufacture of Superplastic Alloys", in "Superplasticity", pp. 8.1-8.16, AGARD-LS-154, 1987.

18. A.K. Vasudévan, A.C. Miller and M.M. Kersker, "Contribution of Na-Segregation to Fracture Behaviour of Al-11.4 at.% Li Alloys", in [3], pp. 181-199.

19. W.S. Miller, M.P. Thomas, D.J. Lloyd and C. Creber, "Deformation and Fracture in Al-Li Base Alloys", in [4], pp. 584-594.

20. M. Peters, V. Bachmann, K. Welpmann, H. Bellingradt, J. Eschweiler and R. Braun, "Mechanical Properties of Al-Li DTD XXXA Plate Material", DFVLR-FB 86-40, pp. 1-75, DFVLR, Köln, 1986.

21. K. Welpmann, M. Peters and H.J. Dudek, "Ductility and Fracture Behaviour of Al-Li Alloys Compared to Conventional High Strength Al Alloys", Proc. 8th International Light Metal Congress, Leoben, Austria, 1987.

22. S. Suresh, A.K. Vasudévan, M. Tosten and P.R. Howell, "Microscopic and Macroscopic Aspects of Fracture in Lithium-Containing Aluminum Alloys", Acta Metallurgica 35 (1987), pp. 25-46.

23. M. Peters, J. Eschweiler and K. Welpmann, "Fracture Behaviour of 8090 Plate Material", Proc. 7th European Conf. on Fracture (ECF7), Budapest, 19-24 Sept. 1988.

24. D. Webster, "The Effect of Low Melting Point Impurities on the Properties of Al-Li Alloys", in [5], pp. 685-691.

25. K. Welpmann, H. Buhl, R. Braun and M. Peters, "Mechanical Properties and Corrosion Behaviour of 2091 Sheet Material", in [5], pp. 677-683.

26. L. Hautefeuille, R. Rahonadj, Y. Barbaux and M. Clavel, "Toughness and Heat Treatment Relationship in a 2091 Aluminium Alloy", in [5], pp. 669-675.

27. M. Peters, K. Welpmann, W. Zink and T.H. Sanders, Jr., "Fatigue Behaviour of an Al-Li-Cu-Mg Alloy", in [4], pp. 239-246.

28. I.G. Palmer, W.S. Miller, D.J. Lloyd and M.J. Bull, "Effect of Grain Structure and Texture on Mechanical Properties of Al-Li Base Alloys", in [4], pp. 565-575.

29. M. Peters, K. Welpmann and T.H. Sanders, Jr., "Aging Characteristics and Mechanical Properties of the Al-Li Alloy DTD XXXA", in: "Advanced Materials Research and Developments for Transport", Eds. R.J.H. Wanhill, W.J.G. Bunk and J.G. Wurm, pp. 63-70, Les Editions de Physique, Les Ulis Cedex, France, 1986.

30. M.A. Reynolds, A. Gray, E. Creed, R.M. Jordan and A.P. Titchener, "Processing and Properties of Alcan Medium and High Strength Al-Li-Cu-Mg Alloys in Various Product Forms", in [4], pp. 57-65.

31. M. Peters, J. Eschweiler, K. Welpmann, "Strength Profile in Al-Li Plate Material", Scripta Metallurgica 20 (1986), pp. 259-264.

32. S. Fox, D.S. McDarmaid and H.M. Flower, "Anisotropy of Mechanical Properties of Al-Li Based Alloy Plate", in: "Aluminium Technology '86", pp. 72.1-72.6, The Institute of Metals, London, 1986.

33. M.J. Bull and D.J. Lloyd, "Textures Developed in Al-Li-Cu-Mg Alloy", in [4], pp. 402-410.

34. B. Dubost, "Closing Address", in [5], pp. 913-919.

35. Y. Watanabe, M. Toyoshima and K. Itoh, "High Purity Aluminium-Lithium Master Alloy by Molten Salt Electrolysis", in [5], pp. 85-91.

36. D.S. McDarmaid, S. Fox and H.M. Flower, "Fatigue of Medium and High Strength Al-Li-Cu-Mg-Zr Alloys in Plate and Sheet Form", in: "Advanced Materials Research and Developments for Transport/Light Metals", Eds.: R.J.H. Wanhill, W.J.G. Bunk and J.G. Wurm, pp. 93-100, Les Editions de Physique, Les Ulis, Cedex, France, 1985.

37. M. Peters, V. Bachmann and K. Welpmann, "Fatigue Behaviour of the Al-Li Alloy 8090 Compared to 2024", Zeitschrift für Werkstofftechnik 18 (1987), pp.277-283.

38. R. Tintillier, H.S. Yang, N. Ranganathan and J. Petit, "Near Threshold Fatigue Crack Growth in a 8090 Lithium Containing Al Alloy", in [5], pp. 777-784.

39. M. Peters, V. Bachmann and K. Welpmann, "Fatigue Crack Propagation Behaviour of 8090 Plate Material Compared to 2024", in [5], pp. 785-791.

40. M. Peters, R. Braun, K. Welpmann and H. Buhl, "Die neuen Leichtbaulegierungen für die Luftfahrt auf der Basis Aluminium-Lithium", in: "Neue Werkstoffe", Vol. II, pp. 539-553, VDI-Verlag, Düsseldorf, 1988.

41. W.G.J. 't Hart and L. Schra, "Properties of the Al-Li Plate Alloy DTD XXXA-T651 (8090-T651) in Comparison with Two Damage Tolerant 2000 Series Plate Alloys", NLR TR 86115, NLR, The Netherlands, 1986.

42. F.S. Lin, Y. Moji, W.E. Quist and D.V. Badger, "Corrosion Resistance of Aluminium-Lithium Alloys", in [5], pp. 905-911.

43. R. Braun and H. Buhl, "Corrosion Behaviour of Al-Li-Cu-Mg Alloy 8090-T651", in [5], pp. 843-849.

44. R. Braun and H. Buhl, "Korrosionsverhalten der Legierung Al-Li-Cu-Mg", Z. Werkstofftechnik 18 (1987), pp.258-265.

45. A. Gray, "Factors Influencing the Environmental Behaviour of Aluminium-Lithium Alloys", in [5], pp. 891-904.

46. M. Reboul and P. Meyer, "Intergranular and Exfoliation Corrosion Study of Al-Li-Cu-Mg-Zr Alloys", in [5], pp. 881-889.

47. N.E. Paton, "Superplasticity in Titanium Alloys", in "Titanium Science and Technology", Eds. G. Lütjering, U. Zwicker and W. Bunk, Vol. 2, pp. 649-672, DGM, Oberursel, 1985.

48. M. Peters, P.-J. Winkler and W. Bunk, "Superplasticity of fine grained textured Ti-6Al-4V",ibid., pp. 681-688.

49. J.A. Wert, N.E. Paton, C.H. Hamilton and M.W. Mahoney, "Grain Refinement in 7075 Aluminium by Thermo-Mechanical Processing", Metall. Transactions 12A (1981), pp. 1267-1276.

50. C.H. Hamilton, C.C. Bampton and N.E. Paton, "Superplasticity in High Strength Aluminum Alloys", in "Superplastic Forming of Structural Alloys", Eds. N.E. Paton and C.H. Hamilton, pp. 173-189, TMS-AIME, Warrendale, PA, 1982.

51. R. Grimes, W.S. Miller and R.G. Butler, "Development of Superplastic 8090 and 8091 Sheet", in [5], pp. 239-249.

52. C.W. Cho, B.A. Cheney, D.J. Lege and J.I. Petit, "Superplasticity of 2090 SPF Sheet at Hot Rolled Gauge", in [5], pp. 277-283.

53. R. Grimes, C. Baker, M.J. Stowell and B.M. Watts, "Development of Superplastic Aluminium Alloys", Aluminium 51 (1975), pp. 720-723.

54. W.R. Wilson, J. Worth, E.P. Short and C.F. Pygall, "Recycling of Aluminium-Lithium Process Scrap", in [5], pp. 75-83.

55. S.J. Cieslak, R.M. Hart, P.L. Mehr and L.N. Mueller, "Alcoa Alithalite Alloy 2090 Technical Information", Proc. 17th International SAMPE Conf., Kiamesha Lake, NY, 1985.

56. J.E. Heany, Aviation Week & Space Technology, Oct. 12, 1987, pp. 71-106.

57. Aviation Week & Space Technology, July 6, 1987, p. 32.

58. J. Odorico and G. Leiba, "Evolutions des matériaux sur les structures d'avions civils et d'hélicoptères", Matériaux et Techniques, 76, N. 1-2 (1988), pp. 1-13.

59. W. Zink, MBB, private communication, 1988.