Engineering Notes

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Low Density, High-Stiffness, Aluminum-Lithium Materials

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I. 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, e.g., increased strength or stiffness. 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 nonmetallic materials, e.g., carbon fiber reinforced composites that reveal certain improved specific properties when compared to conventional high-strength aluminium alloys. The aluminium industry has however taken up this challenge by developing a new generation of superlight weight Al alloys with lithium as a major alloying addition.

What makes these new Al-Li aloys so attractive? Figure 1a shows the influence of various chemical elements on density when alloyed to aluminium. It is obvious that Li reveals an outstanding behavior. Since it is the lightest metallic element known, 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, for example, 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%.

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. Again, Li takes an outstanding position in that it is the alloying element that most effectively increases stiffness. Every weight percent of Li added to Al raises the Young's modulus by about 4%.

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Compared to carbon fiber 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 in a manner very similar to conventional high strength Al alloys. Essentially no new investments are required by the aircraft manufacturers.

There are, however, drawbacks associated with 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. Al-Li alloys are expected to be about two to four times more expensive than the conventional counterparts they are intended to replace. Reasons for this high price include the expensiveness of Li and the investments that 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 because of the high reactivity of Li.

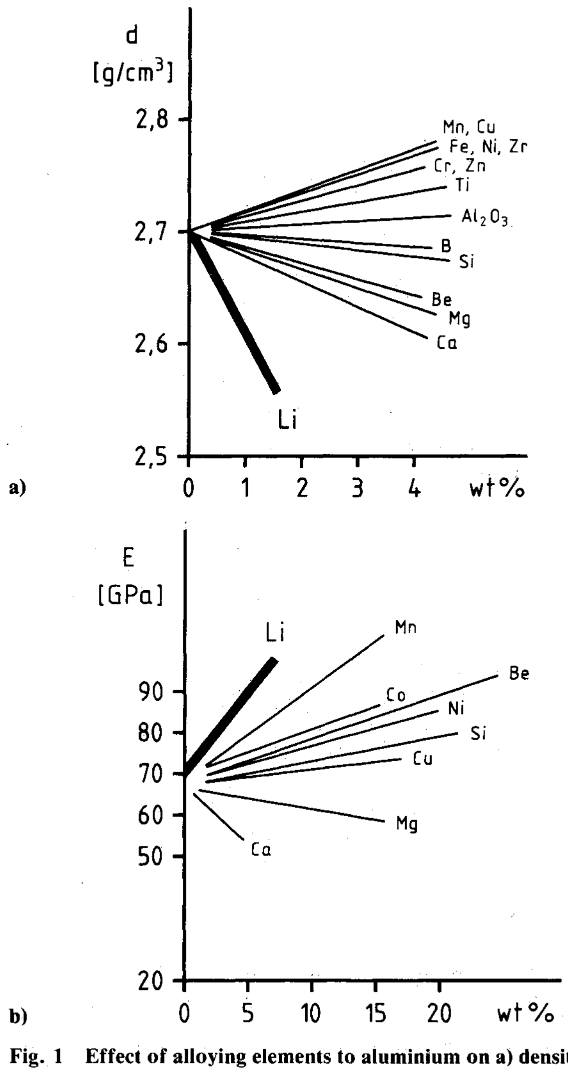

Fig. 1 Effect of alloying elements to aluminium on a) density and b) elastic modulus.

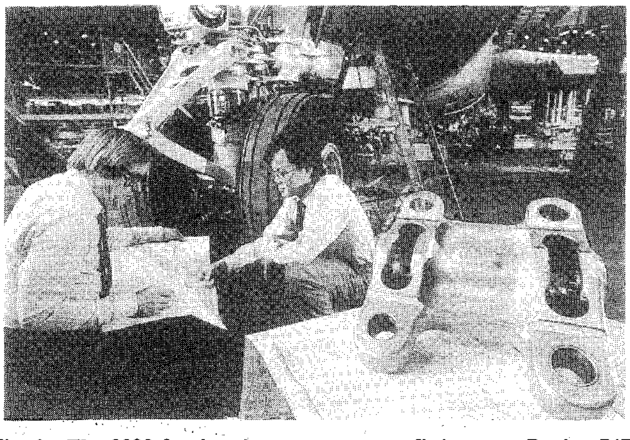

Fig. 2 The 2090 forging that serves as tow fitting on a Boeing 747 landing gear (courtesy Aluminum Company of America).

II. Historical Reflections

The first commercial Li-containing Al alloys were developed in Frankfurt, Germany, in 1924, by the Metallbank und Metallurgische Gesellschaft (today Metallgesellschaft). These alloys, named Scleron, contained only 0.1% Li. They did not become a success because at that time they had to compete against 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, for patent reason.

The first Al alloy to which Lithium was deliberately added to save weight was 2020. This alloy, developed in the 1950s by Alcoa, USA, contained about 1.3 wt% Li. For more than 15 years, it was used on a U.S. military airplane. It was eventually withdrawn because it did not fulfill the damage tolerance requirements established in the 1970s. 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 nonmetallic 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) Farnborough, England, in the first half of the 1970s. It led to the development of the first of the current generation of Al-Li alloys: originally designated F92, the name of the alloy was first changed to DTD XXXA/C and then to Lital A/C with the Aluminium Association registraiton number 8090, once the British Aluminium Co.—now Alcan International Ltd.—became involved in 1977. These activities in Europe revitalized commercial interest in Al-Li alloys all over the world, particularly at the Aluminum Company of America, Alcoa, and at Cégédur Pechiney in France.

III. 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 (United States) and Pechiney (France). All of the alloys that thus far have been internationally registered were developed by these three companies.

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. All alloys are either of the Al-Cu-Li-Mg-Zr type (2X9X) or Al-Li-Cu-Mg-Zr type (8X9X). The only exception is Alcoa's Al-Cu-Li-Zr alloy 2090, which does not contain Mg.

Table 1 Proposed new Al-Li alloys

Producer	Trade name	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	—	—	—	—	—

Table 2 Alloy categories for new Al-Li alloys according to conventional high-strength Al alloys to be replaced

Alloy category (replaced alloy)	Al-Li alloy	Trade name	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
(2014-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

For all alloys, the lithium contents varies between 1.7 and 2.9 wt%. Densities range from about 2.52 to 2.58 g/cm³. Compared to conventional high-strength aluminium alloys such as 2024 (2.77 g/cm³) or 7475 (2.80 g/cm³), this represents a decrease in density of about 7–10%.

Of all the alloys listed in Table 1, only four have been registered to date by the Aluminum Association: 2090, 2091, 8090, and 8091. It is obvious from Table 1 that only Alcan has registered all of its alloys so far, whereas both Alcoa and Pechiney still have 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.

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 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. First, the table does not distinguish between product forms such as sheet, plate, extrusions, or forgings. Second, the category can very well change with product form. Third, the same alloys might be found in several categories because the table does not distinguish between different tempers. Finally, the classification of the various new Al-Li alloys is not definite since some alloys listed in Table 2 are still undergoing extensive development, e.g., X 8092, X 8192, or CP 277.

Most advanced, and at the edge of widespread commercial 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 is jointly registered by Alcan and Pechiney and slightly modified by Alcoa (see Table 1).

Sticking to the least 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 commoness has come in sight. Furthermore, these alloys still need to undergo extensive development, as does the category of very low density alloys. Due to their high strength and/or high lithium content, they often do not yet meet the ductility or toughness goals required to match the properties of the corresponding conventional Al alloys they intend to replace.

IV. 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: First, the confidence in the new material attesting it a sufficient degree of maturity and, second, 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, whereas use in civil aircraft shows that they can fly *economically*.

The Boeing Commercial Airplane Company announced the first use of an Al-Li alloy on a commercial airplane. The Alcoa alloy 2090 was chosen as the material for tow fittings on four B-747 front landing gear struts (see Fig. 2). 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 takeoffs 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, and the rest is a result of the improved mechanical properties.

Airbus Industrie has announced that the new A330/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. In a first step, stringers and parts of the secondary structure will be made out of Al-Li alloys. Then use of Al-Li sheet material for the fuselage skin will be attempted.

V. 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 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 has been raised whether the aluminium companies can produce enough Al-Li to meet the quantity and schedule requirements of aerospace programs. 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 the extended use of Al-Li alloys is, however, a solution to the scrap problem.

The future is already directed toward 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.

Takeoff Characteristics of Turbofan Engines

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Nomenclature

AR = aspect ratio, $=(2s)^2/A_s$
A,B,C = constants in Eqs. (6) and (8)
A_s = span area
C_D = drag equation, $=C_{D0}+\phi K C_L^2$
D = drag
D_A = aerodynamic drag
e = Oswald's wing efficiency
f = fuel-air ratio
g = gravitational acceleration
h = span height above ground
K = $(\pi ARe)^{-1}$
L = lift
L_r = lapse rate of troposphere
$\dot{m}_{C,H}$ = air-flow rate (cold/hot), $\dot{m}_C=\beta\dot{m}_H$
$\dot{m}_{in}$ = intake air-flow rate, $=\dot{m}_C+\dot{m}_H$
S_{TO} = takeoff ground-rolling distance
s = half-span

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