Executive summary.

Aircraft manufacturers are looking for new materials offering lower operating and maintenance costs. For metallic aerostructures, weight reduction solutions and improvement of corrosion resistance are two strategic orientations. Al-Mg-Li type alloys are good candidates to meet these requirements as they are weldable (avoiding riveted structures that constitute corrosion initiation sites), present a low density and intrinsic good performance in corrosion resistance, in particular compared to 2024 alloy. The three years project "ECEFA" has permitted to prove the interest of using such type of material for environmental benefit:

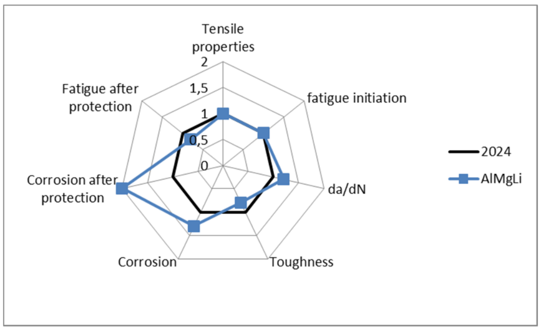
- During operating phases :

Light weighting estimated at least at 7.9 % in direct relation with the density reduction offered by AlMgLi.

- Out of operating phases :

Corrosion resistance of AlMgLi alloy here studied is significantly improved compared to incumbent 2024 T351. This improvement has permitted to allow the use of green treatment (CrVI free) with the same or better performance as existing CrVI protections. The development of more resistant alloys to corrosion like AlMgLi offers then the possibility to introduce green surface treatment more easily and should permit to fulfil the REACH compliance. Moreover, the better fatigue propagation compared to 2024 T351 could also offer opportunity for increasing inspection time interval.

These achievements fulfil the expected outcome of Clean Sky program to offer more eco-friendly solutions : the product should offer, through design adaptation, an excellent corrosion resistant product with the possibility to use green surface treatment and permitting a weight loss and a lower maintenance cost. However, some investigations are still needed to industrialise the product. Based on that we can draw a schematic spider diagram for the AlMgLi alloy in comparison with 2024, which illustrate the better performance in terms of corrosion and fatigue propagation, with however some limitations with regards to toughness (anisotropy, lower value in T-L and detrimental impact of 1000h 85°C) and impact of surface treatment on fatigue.



Comparison of properties between AlMgLi and 2024 T3 product (arbitrary unit)

Summary description of the project context and the main objectives.

ECEFA project (ECo-EFficient Aluminium for aircraft) aims at developing an aluminium alloy, primarily for fuselage skin application, that offers a step change in terms of corrosion resistance versus conventional aluminium alloys used for this application. As the overall purpose of Clean Sky is to offer more eco-friendly solutions, the proposed alloy must also offer properties that allow some weight saving versus the incumbent alloys. This is achieved through mechanical properties, which determine the component thickness, and through density reduction.

The option proposed is to develop an AlMgLi alloy that inherently offers 5 to10% weight saving by density versus conventional alloys. Constellium has already worked on such alloy and has developed it to a Technology Readiness Level 3: following lab trials, two campaigns at industrial scale were already performed, that demonstrate the capabilities of this alloy type to fulfil the above requirements. The prior art, a bibliographical survey and a roadmap proposal have been performed in the project.

To bring the alloy to TRL6, the project has first rolled and heat treated an existing slab to determine the properties according to the precise requirements of the airframers issuing the call and an appropriated test program has been set. Corrosion tests relevant to the application, with and without protection, fatigue before and after corrosion protection, damage tolerance tests, static mechanical properties have been performed. The results obtained for this first set of characterisation (C4 composition) have been reported.

A second step consisted in casting, converting and characterizing a slightly modified composition (C5 composition). In that second step, properties pertaining to the fabrication of components (formability, machinability) were assessed in addition to the material properties as described above. The results obtained for the second set of characterisation have also been reported.

The formability and the machinability of the product have been investigated. Machinability has only be studied on the first composition C4.

ECEFA project provided sheets of C5 for the demonstration activity which has been achieved with the B2 demonstrator at a full scale range. Dassault and HAI have integrated C5 sheets (and extrusions) on their barrel.

Description of the main S & T results/foregrounds.

Within ECEFA project, two compositions (C4 AW551.35 and C5 AW551.38) have been evaluated and two gauges have been tested for each composition.

- C4 AW551.35 4.5 mm and 2.1 mm
- C5 AW551.38 3.5mm and 1.6 mm

C5 composition is a derivative of C4 with the same major elements Mg and Li content but with no Cu and addition of Mn. These adjustments are based on our intent of improving corrosion (Cu was considered as detrimental) and improving residual strength (Mn addition)

Review of the results:

Density

Both compositions C4 (density 2.547) and C5 (2.552) are below 2.55.

Tensile properties

In Table 1 below are listed typical values obtained. The material is anisotropic : lower values of UTS and YS and a higher elongation at 45°.

		direction	UTS (MPa)	TYS (MPa)	E%
T8	Typical value from C4 4.5 mm	LT	447	316	14,6
		45°	387	257	22,3
		LL	441	339	7,1
	Typical value from C4 2.1 mm	LT	447	330	12,5
		45°	385	265	22,4
		LL	431	342	6,1

Table 1 : Typical tensile properties values

Formability

AlMgLi behaviour is anisotropic due to the mainly unrecrystallized structure compared to the recrystallized structure of a 2024 T3 sheet. It presents the lowest formability when it is deformed in the rolling direction (lowest elongation value in the rolling deformation).

Using T3 temper permits to improve its formability : it permits to achieve 2t bending at 180° in the transverse direction. In the rolling direction, 4t bending is achievable on all the products in T3 and 2t is possible on the thinnest products 1.6 mm and 2.2 mm (only at 90°).

The properties of formability of AlMgLi are listed in the table below

<table>
<tr><th></th><th>AlMgLi
characterised in T8</th><th>AlMgLi
characterised in T3</th></tr>
<tr><td>Effect of direction of shaping</td><td>L < LT < 45°</td><td></td></tr>
<tr><td>Effect of temper</td><td colspan="2">T8 < T3</td></tr>
<tr><td>Young Modulus</td><td>76 GPa
(average value in all directions C4 and C5 composition)</td><td></td></tr>
<tr><td>Elongation E%</td><td>6 to 22%
depending on orientation</td><td>12 to 20%
depending on orientation</td></tr>
<tr><td>Bending</td><td>4t only in the rolling direction</td><td>4t bending at 180° for all products.
2t bending achievable on thinner gauges (2.5 and 1.6 mm)</td></tr>
<tr><td>Strain hardening
n (2-E necking)</td><td>Anisotropic
Between 0.13 to 0.18
depending on orientation</td><td>Less anisotropy
Between 0.15 to 0.18
depending on orientation</td></tr>
<tr><td>Lankford coefficient</td><td>Anisotropic
Average R= 1.29</td><td>Average R= 1.18</td></tr>
<tr><td>Bearing</td><td>NA</td><td>In L direction<table><tr><th colspan="2">e/D = 1.5</th><th colspan="2">e/D = 2</th></tr><tr><td>Fbru</td><td>Fbry</td><td>Fbru</td><td>Fbry</td></tr><tr><td>589</td><td>445</td><td>762</td><td>548</td></tr></table></td></tr>
</table>

LDH (panel 500 x 500 mm – Punch diam 250 mm	NA	Comparable to 6056 T6, T78 .

Toughness

Table below present typical toughness values. Residual strength of AlMgLi is better in T-L than 2024 T3 clad and lower than 2024 T3 clad in L-T (120MPa√m for both direction for 2024T3clad).

After thermal exposure (1000h 85°C), we observe a decrease of residual strength of order 20%

Table 2 : Typical toughness properties obtained on CCT 760

	Temper		K_{app} (MPa√m)
C5 27822 3.5 mm Typical	T8	L-T	119
		T-L	125
	T8 + 1000h @ 85°C	L-T	100
		T-L	102

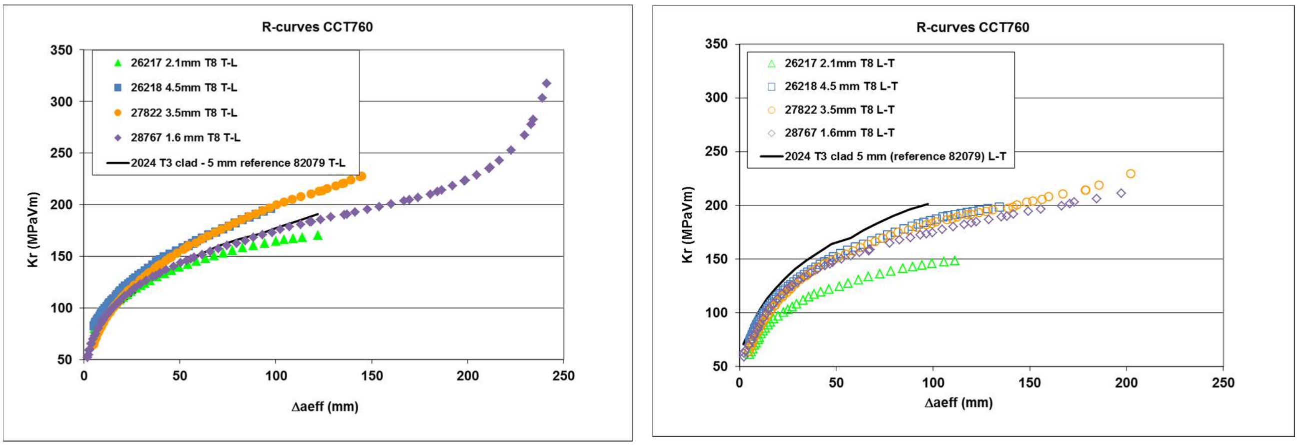


Figure 1 : R- curves of AlMgLi –composition in T8 – Comparison with 2024 T3 clad

Left : T-L propagation. Right : L-T propagation

(Invalid points beyond Δa_{eff} 150 mm)

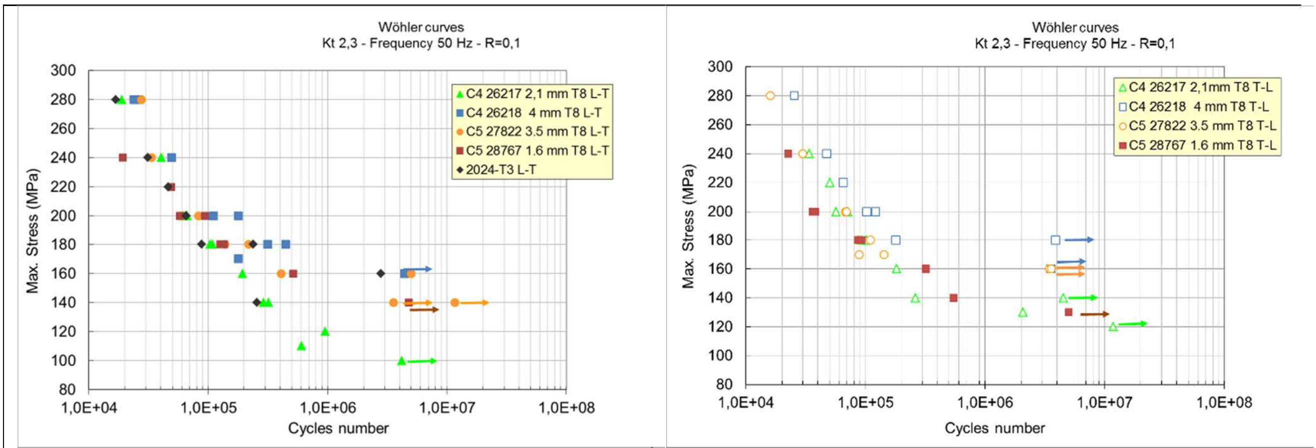
Fatigue initiation

Table 3 : Typical fatigue properties obtained on Woehler curves - Kt 2,3 - Frequency 50 Hz - R=0,1

	Estimated maximum stress (MPa) to achieve 10^5 cycles	
	L-T direction	T-L direction
C5 27822 3.5 mm T8	194	181
C5 27822 3.5 mm T8 + 1000h 85°C	179	181

Fatigue initiation of AlMgLi is considered similar to 2024 T3.

After thermal exposure (1000h 85°C), decrease of fatigue of order 5% in L-T.



L- T	T-L

Figure 2 : Wöhler curves of AlMgLi alloy in T8.

Left L-T propagation – Right T-L propagation

Open Hole Kt 2.3 ; R=0.1, 50 Hz.

Fatigue propagation

Fatigue propagation has been measured using different CCT geometry (CCT50, CCT200 and CCT400, 50, 200, 400 being the total width of the sample) on C5 and C4 (see more details in D3.3 CTEC 2014-297 report).

Here below, some typical values

Wt 400 (T-L)

ΔK = 15 MPa√m → da/dN = 4.10^{-4} mm/cycle

ΔK = 30 MPa√m → da/dN = 10^{-3} mm/cycle

Fatigue propagation is better for AlMgLi at high ΔK (>20 MPa√m) compared to a 2024 clad . However, at low ΔK (<15 MPa√m) it tends to be worse than 2024.

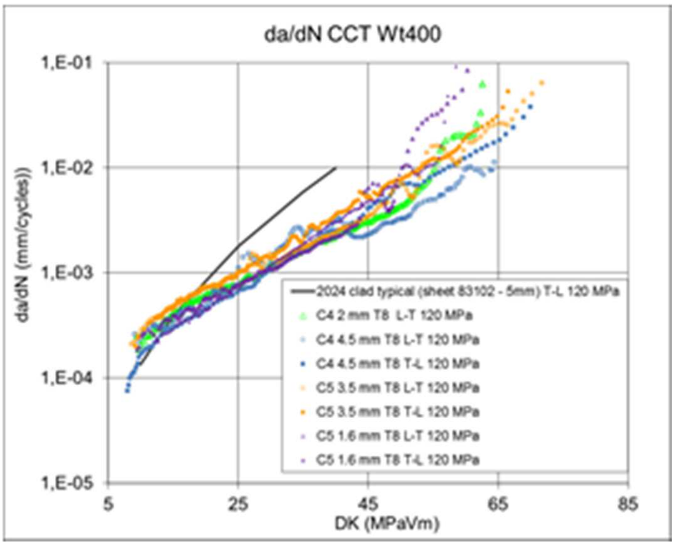
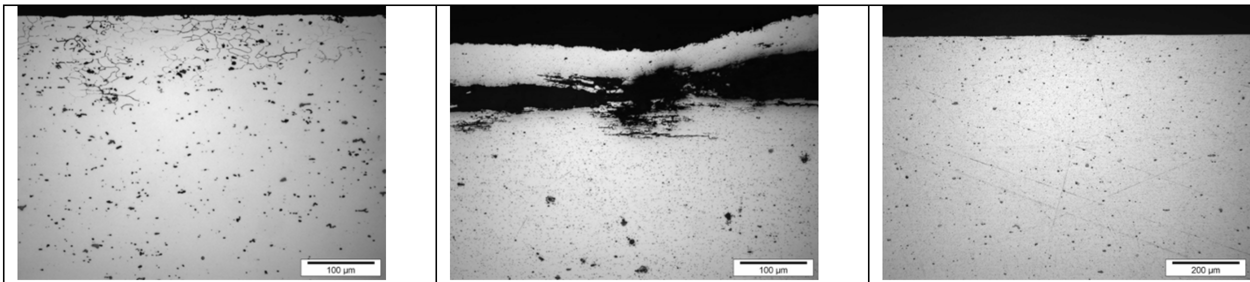


Figure 3:Wt400 – Crack propagation. Comparison with 2024 T351 reference

Corrosion

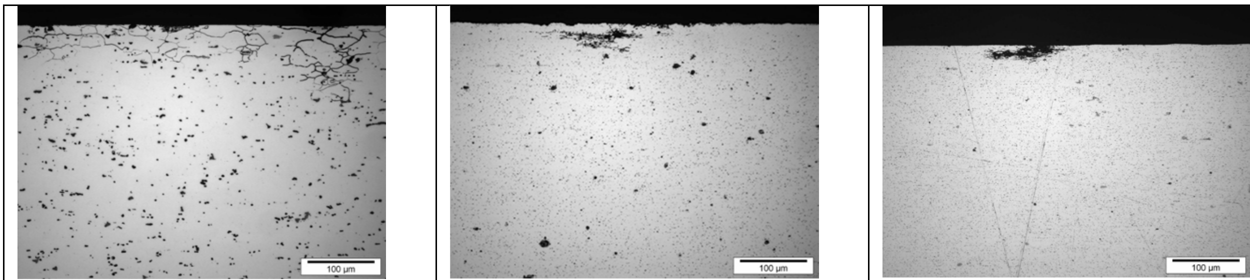
In seacoast, we observe on C4, a susceptibility of the wrought surface to generate blisters or pimples. This tendency seems to be avoided with the C5 – see Figure 4. On machined surface, we observe a tendency to intergranular corrosion, which does not cover the whole surface, and whose corrosion depth is below 100 µm. This extent is less than that observed on 2024 in similar conditions (fully covered by intergranular corrosion whose depth is approx 300 µm) – see Figure 5.



2024 T351 – 63487 (5mm)	C4 – 26218 (4.5 mm)	C5 - 27822 (3.5mm)

Figure 4 : Cross section after 1 year of seacoast exposure – comparison between 2024 T351 and AlMgLi (C4 and C5). wrought surface exposed, oriented sky face

Improvement of surface corrosion resistance with C5



2024 T351 – 63487 (5mm)	C4 – 26218 (4.5 mm)	C5 - 27822 (3.5mm)

Figure 5 : Cross section after 1 year of seacoast exposure – comparison between 2024 T351 and AlMgLi (C4 and C5). Machined surface exposed, oriented sky face. Better corrosion resistance of AlMgLi (very localized intergranular corrosion, less deep corrosion)

Effect of thermal exposure

Impact of thermal exposure on mechanical properties, toughness, fatigue initiation, fatigue propagation and corrosion has been evaluated in the project. The trends are captured in the table below

	tensile properties	toughness	fatigue initiation	fatigue propagation	corrosion
Effect of thermal exposure 1000h 85°C	↗	↘	↘	contradictory	= Or ↘ (depending on test)

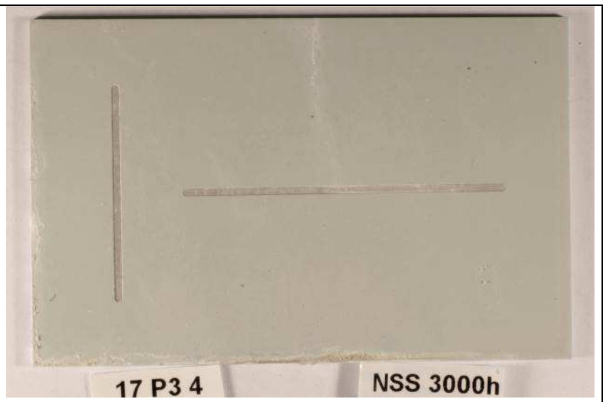
Surface protection

Impact of surface protection on fatigue and corrosion has been evaluated. Only C4 composition has been tested. Different surface treatments have been investigated and correspond to reference protection containing chromium and to “green” surface treatments without chromium VI. Each OEMs have defined their own systems. They are recalled in table below.

	Pre-treatment	Protection
Reference DA	CAA without sealing	P60 primer
Green DA	Anodic Ecoat	None
Reference IAI	CAA + Dilute chromate sealing	Epoxy primer (chromated)
Green IAI	TFSAA + Water sealing	Epoxy primer (non-chromated)
Reference HAI	CAA + sealed with Potassium dichromate	Epoxy primer (chromated)
Green HAI	Solgel AC131	Epoxy primer (non-chromated)
Reference EADS		
Green EADS	TSA	Chrome free primer not defined

On corrosion, we obtained excellent results on AlMgLi which was seen better or similar to a 2024. These results are confirmed by seacoast exposure.

2024 T351 + solgel (HAI specifications)



AlMgLi + solgel (HAI specifications)

Figure 6 : Example of aspect of coated samples with green surface treatments after 3000h of neutral salt spray showing the better resistance of AlMgLi. (left : 2024 T351 - right AlMgLi)

On fatigue, it was observed that fatigue knock-downs induced by surface treatment are much higher on AlMgLi C4 than on 2024 T351 which leads in many cases to a worse behaviour of AlMgLi compared to 2024. For instance, AlMgLi is more affected by anodizing process than conventional 2024. This phenomenon is not well understood because it is not linked with pits as sites of initiation. For all AlMgLi (C4) treated with the different green (Ecoat, TFSAA) and reference (CAA) solutions, fatigue initiation occurs at the interface coating/substrate. Additional characterization would be needed to better understand the behavior (coating characterization). We expect that an improvement could be found if an attention is paid in developing adapted surface preparation process parameters for AlMgLi which likely need to be treated differently from a 2024.

		FATIGUE					CORROSION		
Protection	Partner	2024-T351		AlMgLi C4 (4mm)		C4 vs 2024 %	Neutral Salt Spray (3000h)	Filiform test (1000h)	Seacoast exposure (6 months)
		Max. stress at 10E5 cycles	Protected vs bare (%)	Max. stress at 10E5 cycles	Protected vs bare (%)		C4 vs 2024 + = -		
Bare		196		217		11%			
Ref CAA	DAV	173	-12%	144	-34%	-17%	+	+	+
	IAI	167	-15%	No data			=	+	=
	HAI	153	-22%	132	-39%	-14%	=	+	=
Green	DAV (Ecoat)	183	-7%	188	-13%	3%	+	+	+
	IAI (TFSAA)	167	-15%	123	-43%	-26%	+	+	+
	HAI (AC131)	190	-3%	194	-11%	2%	+	+	+
	EADS (TSA)	No data		No data			+	+	+

Description of the potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results.

ECEFA project has permitted to develop a product permitting environmental benefit :

- During operating phases :

Light weighting estimated at least at 7.9 % in direct relation with the density reduction offered by AlMgLi

- Out of operating phases :

Corrosion resistance of AlMgLi alloy here studied is significantly improved compared to incumbent 2024 T351. This improvement has permitted to allow the use of green treatment (CrVI free) with the same or better performance as existing CrVI protections. The development of more resistant alloys to corrosion like AlMgLi offers then the possibility to introduce green surface treatment more easily and should permit to fulfil the REACH compliance. Moreover, the better fatigue propagation compared to 2024 T351 could also offer opportunity for increasing inspection time interval.

These achievements fulfil the expected outcome of Clean Sky program to offer more eco-friendly solutions.

Sheets of metal produced during ECEFA project has been supplied to OEMs participating to the program (Dassault, HAI, IAI and EADS) to offer them the possibility to evaluate the benefit. Dassault and HAI have selected this material to incorporate it in the B2 demonstrator of Eco-Design ITD of Clean Sky.