ReINTEGRA project: Innovative End of Life procedures for recycling integral welded Al-Li Aerostructures

GA No. 886609 — H2020-CS2-CFP10-2019-01

New EoL routes of Al-Li aircraft integral LBW and FSW welded panels including new Cr-free coatings

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12th EASN International Conference on Innovation in Aviation and Space for opening New Horizons

18 October to 21 2022 Barcelona, Spain

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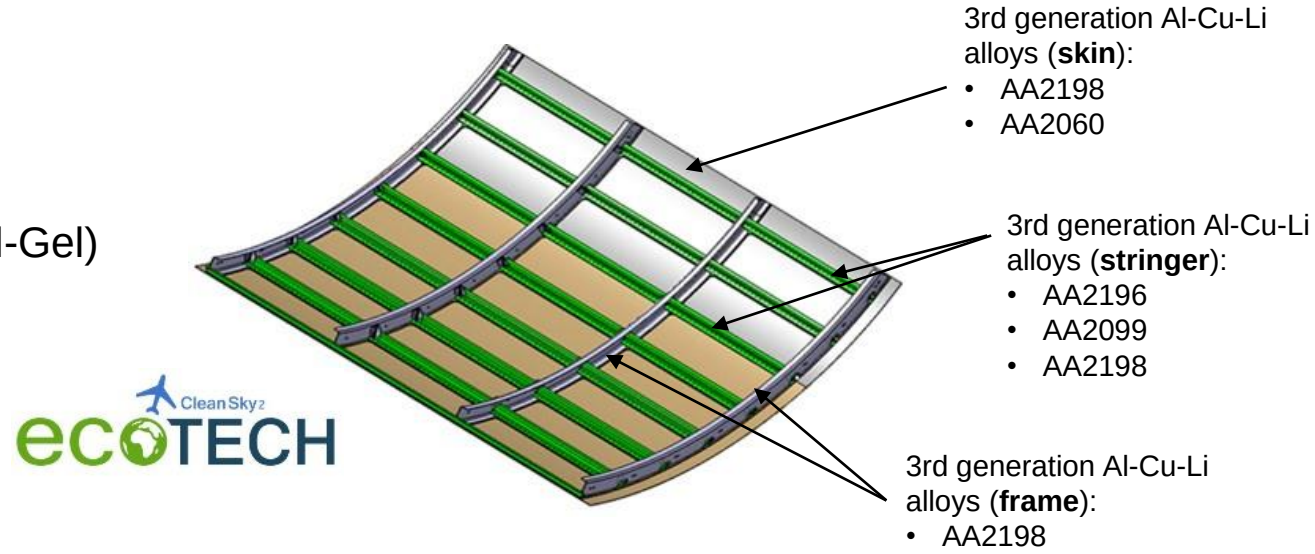
Introduction and objectives

- **Are new generation of integral welded panels recyclable to Al-Li aircraft alloys?:**
  - **integral welded panels made with different Al-Cu-Li alloys?**
  - **stringers and sheets welded by FSW and/or LBW including FSW sealants and LBW filler wires?**
  - **integral panels coated using new Cr-free surface treatments: TFSAA and Sol-Gel) plus Cr-free primers + topcoats?**

Manufacturing technologies:

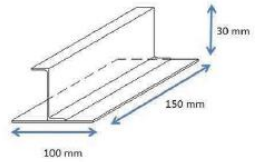
- Forming, extrusion, machining…
- Welding technologies (FSW, LBW)
- Cr-free surface treatments (TFSAA, Sol-Gel)
- Cr-free primers



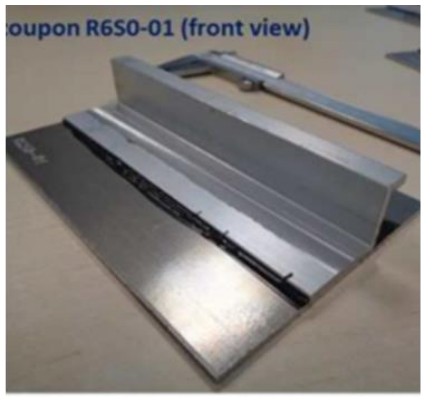
Introduction and objectives

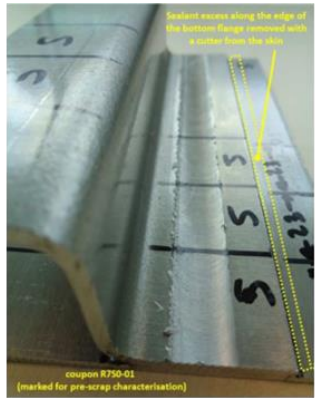
ReINTEGRA project studies the **recyclability** of new generation of integral welded panels recyclable **into Al-Li aircraft alloys :**

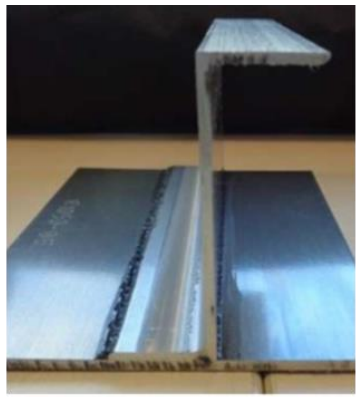
- first, **theoretically**;
- then, experimentally, **single-stringer coupons at laboratory scale**;



- Finally, refining the theoretical analysis thanks to "**compatibility software tool**"







Extruded Z-30mm: R6 & R8 *Formed Z-30 mm: R7&R9* *Extruded Z-70mm: R10&R11*

1 stringer type: L formed: R1, R2, R3, R4 & R5

- **Avoid downcycling.** Contribute to reduction of CO2 emissions in through **closed-loop recycling**

- 95% energy saving vs aluminium primary production + savings from **recovering other alloying elements** (Li, Ag, Zr, Cu, etc.)

- Definition **of optimised EoL procedures** for each type of "integral" welded panel

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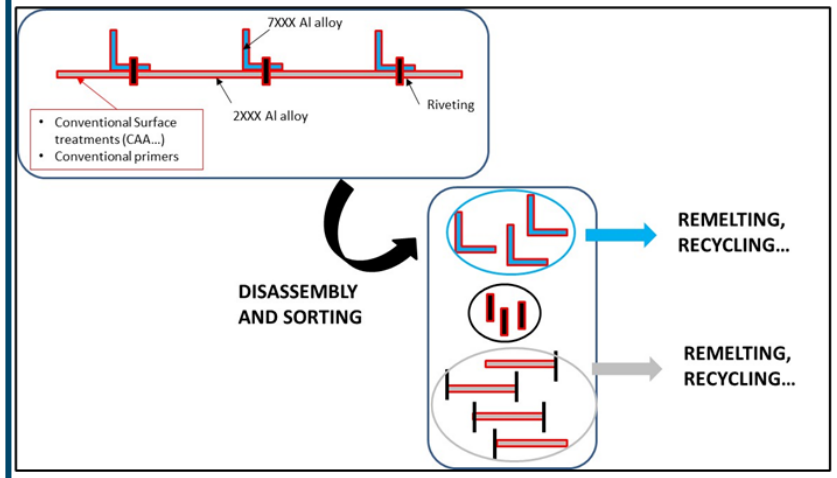
Design of Experiments

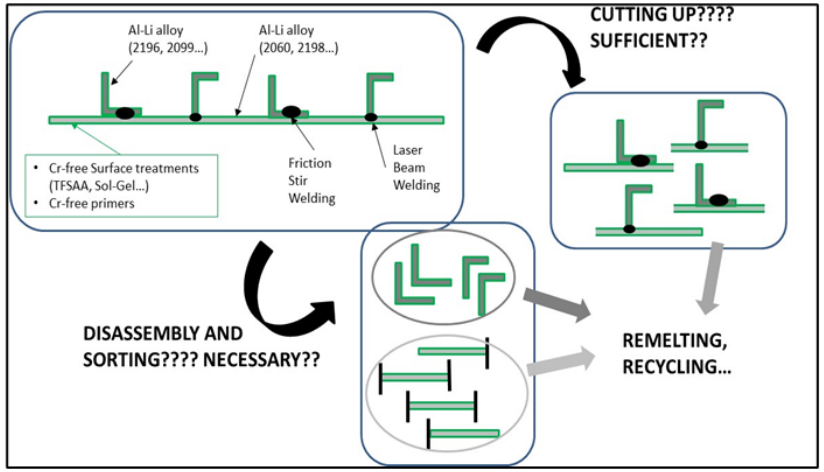
Reference Technology



SoA Recycling – **Riveted** panels (CS1-SENTRY):

- Dismantling
- Sorting
- Size reduction
- Decoating
- Remelting separated alloy families

CS2 ecoTECH Technology Innovation

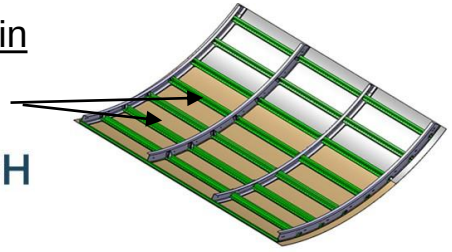


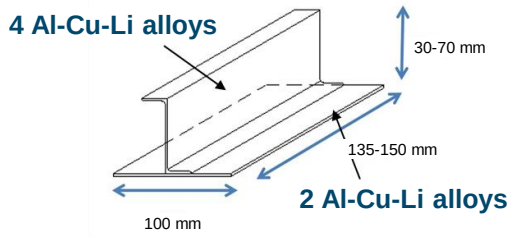
New EoL – **Welded** panels (CS2-ReINTEGRA):

- Dissasembly – needed?
- Sorting – needed?
- Size reduction
- Decoating
- Remelting separated/welded Al-Li alloys of 2XXX series

?

Stringer-Skin welds





10 different welded coupons:
- **4 LBW coupons with different filler wire**
- **6 FSW coupons with different skin/stringer alloys**

Cr- free coatings

TFSAA (Thin film sulfuric acid anodising)
AC-131 (sol-gel)
+ Cr-free Primer and topcoat

Design of Experiments: raw materials

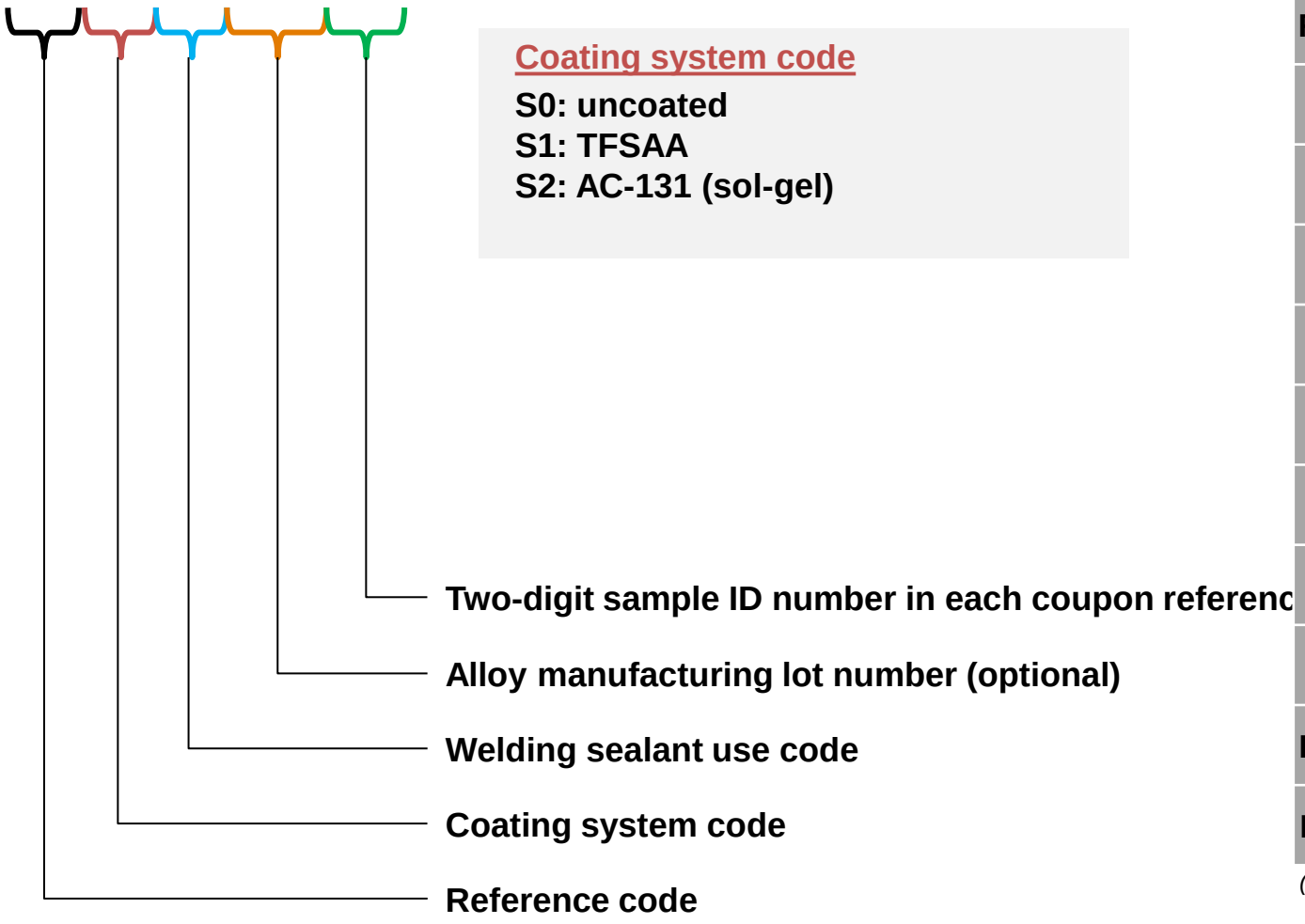
Raw material characterisation

Report No.		Reference	Type	Alloy	Chemical composition in wt. %													
					Main alloying elements in Al-Li alloys							Impurities to be controlled		Other impurities to be controled (bibliographic data, registration				Density (g/cm3)
					Li (*)	Cu	Mg	Ag (*)	Zr (*)	Mn	Zn	Fe	Si	Ti (*)	special	Other each	Other Total	
426642	1	SK-2060	Skin FSW	2060-T8E30	0,68	3,74	0,75	0,29	1	0,29	0,35	<0,03	<0,04	0,025		0,05	0,15	2,73
					-	±0,1	±0,03			±0,02	±0,02	-		±0,004				
426642	2	SK-2198 ST-L30F ST-Z30F	Skin LBW and FSW+ Stringer (L-30 forming for LBW) Stringer (Z-30 forming for FSW)	AA2198-T8	0,98	3,28	0,31	0,21	0,091	<0,03	<0,03	0,041	<0,04	0,027	Cr<0,03	0,05	0,15	2,70
						±0,09	±0,01					±0,005		±0,004				
428401, Ref,1	1	ST-Z30E	Stringer (Z extrusion-30 cm)	2196-T8511	1,62	3,08	0,33	0,24	0,12	0,35	0,047	0,053	<0,04	0,04		0,05	0,15	2,64
					-	±0,08	±0,02		-	±0,02	±0,008	±0,005		±0,005				
428401, Ref,2	2	ST-Z70E	Stringer (Z extrusion-70 cm)	2099-T83	1,65	2,45	0,25	<0,02	0,1	0,10-0,5	0,62	0,036	<0,04	0,03		0,05	0,15	2,64
					-	±0,07	±0,01		-	±0,02	±0,03	±0,004		±0,004				
426642	3	FW-4047	LBW filler wire: Al-Si	ER4047	<0,008	<0,04	<0,03	<0,02	<0,008	<0,03	<0,03	0,18	11,4	0,013	0,017 Sr	-	-	2,71
												±0,01	±0,4	±0,003	±0,001			
426642	4	FW-2319	LBW filler wire: Al-Cu	ER2319	<0,008	5,93	<0,03	<0,02	0,11	<0,03	<0,03	0,071	0,042	0,16	0,078 V	-	-	2,72
						-						±0,006	-	±0,01	±0,005			
426642	5	FW-2395	LBW filler wire: IAWAS 1	2395 (IAWAS)	1,2	3,73	0,34	0,23	0,085	<0,03	<0,03	0,046	<0,04	0,02				2,70
					-	±0,1	±0,02					±0,005	-	±0,004				
437485	2	FW-J300	LBW filler wire: IAWAS 2	J300 (IAWAS)	<0,03	6,32	<0,03	<0,02	0,11	0,31	<0,03	0,078	<0,04	<0,03				2,79
						±0,16				±0,02								

- **Four different Al-Cu-Li** alloys some of them with **Ag** other without it
- **4 different filler wires for LBW**: one Al11Si filler wire, two Al-Cu filler wires and one Al-Cu-Li filler wire.
- **Si < 0.04 wt. % and Fe < 0.06 wt. % admissible as impurities** for scrap in Al-Li aircraft alloys

Design of Experiments: coupon reference

R#S#Wsl(/L#)-##



Coating system code

S0: uncoated
S1: TFSAA
S2: AC-131 (sol-gel)

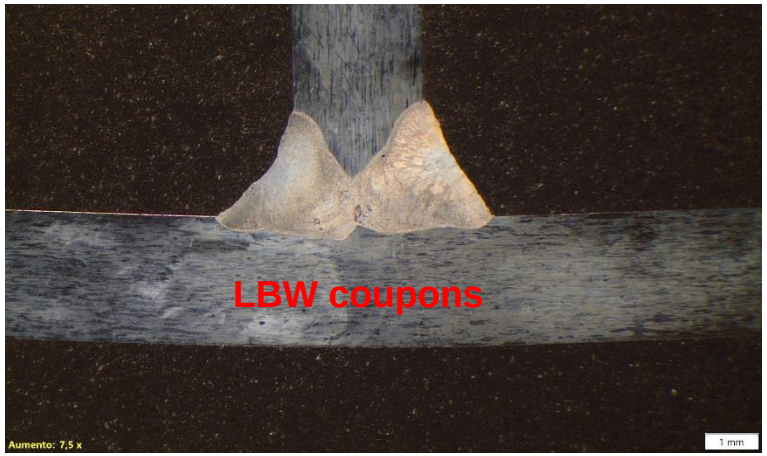
Coupon Reference code

Ref.	ecoTECH w/coating	Skin alloy	Stringer alloy	Stringer type	Welding technology	Welding joint
R1	LBW-coupon 1 & 4	AA2198-T8	AA2198-T8	L-30 mm (formed)	LBW - ER4047	T
R2	LBW-coupon 2 & 5	AA2198-T8	AA2198-T8	L-30 mm (formed)	LBW - ER2319	T
R3	LBW-coupon 3 & 6	AA2198-T8	AA2198-T8	L-30 mm (formed)	LBW - IAWAS 2395	T
R5	LBW-T.B.D.	AA2198-T8	AA2198-T8	L-30 mm (formed)	LBW - IAWAS J300	T
R6	FSW-coupon 1 & 3	AA2198-T8	AA2196-T8511	Z-30 mm (extruded)	FSW	Overlap
R7	FSW-coupon 2 & 4	AA2198-T8	AA2198-T8	Z-30 mm (formed)	FSWt	Overlap
R8	FSW-coupon 5 & 7	AA2060-T8E30	AA2196-T8511	Z-30 mm (extruded)	FSW	Overlap
R9	FSW-coupon 6 & 8	AA2060-T8E30	AA2198-T8	Z-30 mm (formed)	FSW	Overlap
R10	FSW-coupon 9 & 10	AA2198-T8	AA2099-T83	Z-70 mm (extruded)	FSW	Overlap
R11	FSW-coupon 11 & 12	AA2060-T8E30	AA2099-T83	Z-70 mm (extruded)	FSW	Overlap

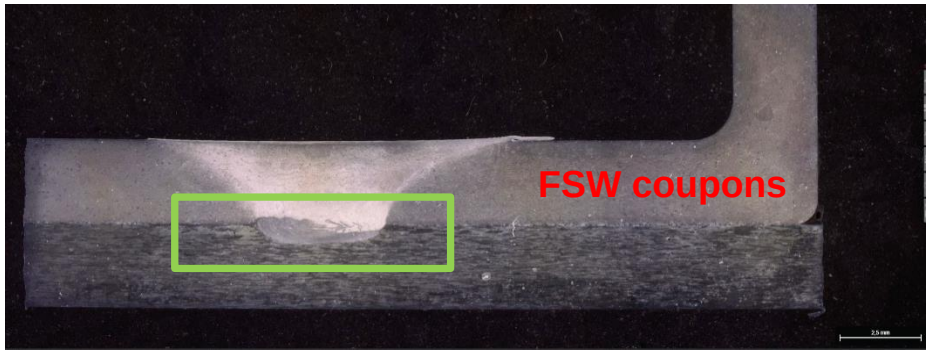
(*)R4 was not manufactured due to a low quality of the welding wire

Design of Experiments

Pre-scrap characterisation of each coupon



The filler wire material is concentrated in the weld seam.



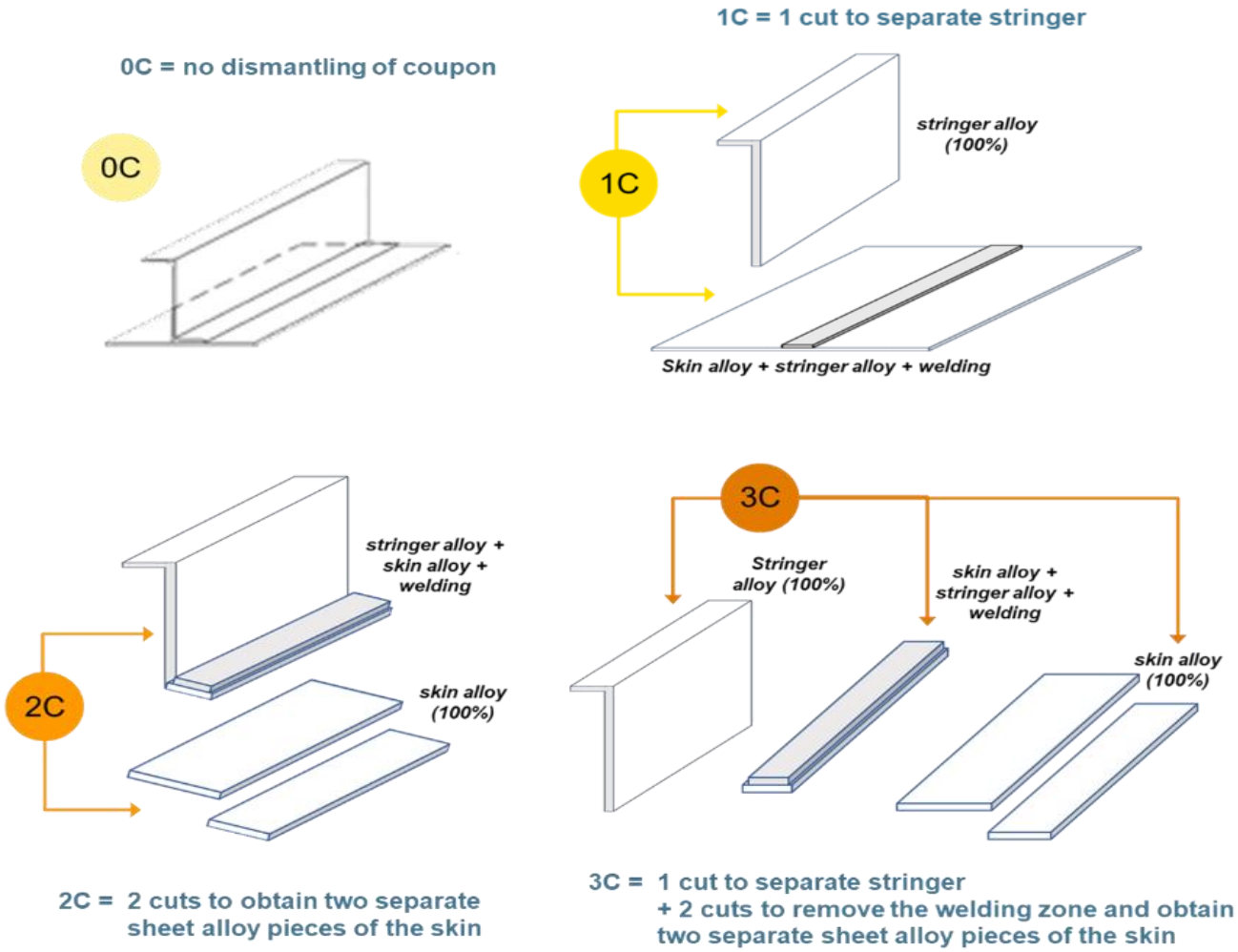
The green rectangle indicated full mixed area. However full overlap area should be removed to assure weld seam separation.

Remelting tests at laboratory scale (~ 28 g)

A slice of each coupon was remelted in a small laboratory furnace at AZTERLAN and casted in a metallic mold.

The chemical composition of the remelted sample was analysed by ICP.

EoL Strategies: 4 scrapping options



- 0C — No separation, just size reduction
- 1C — Complete separation of the stringer fraction from the skin + weld seam
- 2C — Complete separation of the skin fraction from stringer + weld seam
- 3C — Complete separation of each material (skin, stringer, and weld seam fractions)

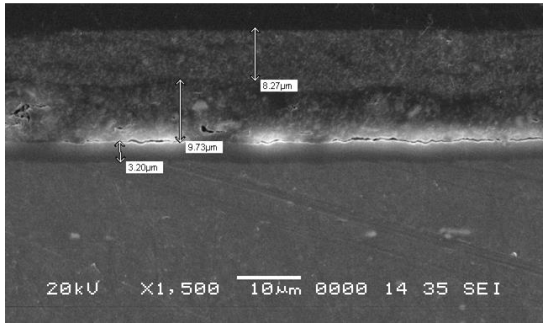
Schematic representations of cutting configurations for different EoL strategies

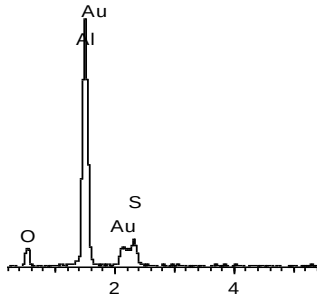
1. Introduction and objectives
2. Design of experiments
3. Results:
    - Coating effect on recyclability
    - Testing of different EoL routes
    - Compatibility software development
    - Best EoL route
4. Main conclusions

Results: Coating effect on recyclability

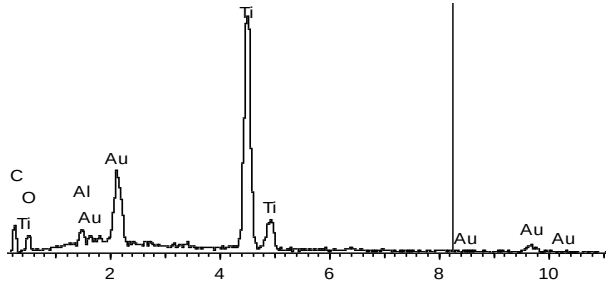
Analysis of the effect of coating and de-coating in the remelting tests: Thin coatings < 25 µm

TFSAA (+ primer + topcoat) coating over 2060 alloy

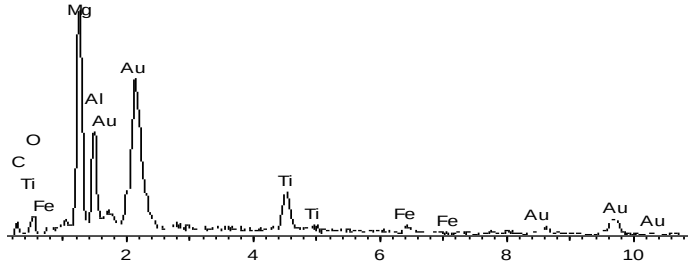




TFSAA layer (Al+S)



Topcoat (Ti-rich particles)



Primer (Mg and Ti-rich particles+ Fe)

Reference	Metal yield (%) at remelting tests
Uncoated coupon	93.5-95.3 %
TFSAA coated	90.0 %
Sol-gel coated	86.4 %

- **Dark fume and higher amount of scrap** is observed in the coated samples. That means a lower yield in the coated samples.
- **C is little bit higher in the sol-gel** coated sample after remelting.
- **No other contamination** or increased loss of the usual alloying elements or impurities are observed with the TFSAA coated sample **even in Ti, Mg and S.**

De-coating was necessary previous to remelting tests

Blasting with corundum was defined by Cidetec as the best de-coating process for both Cr-free coatings

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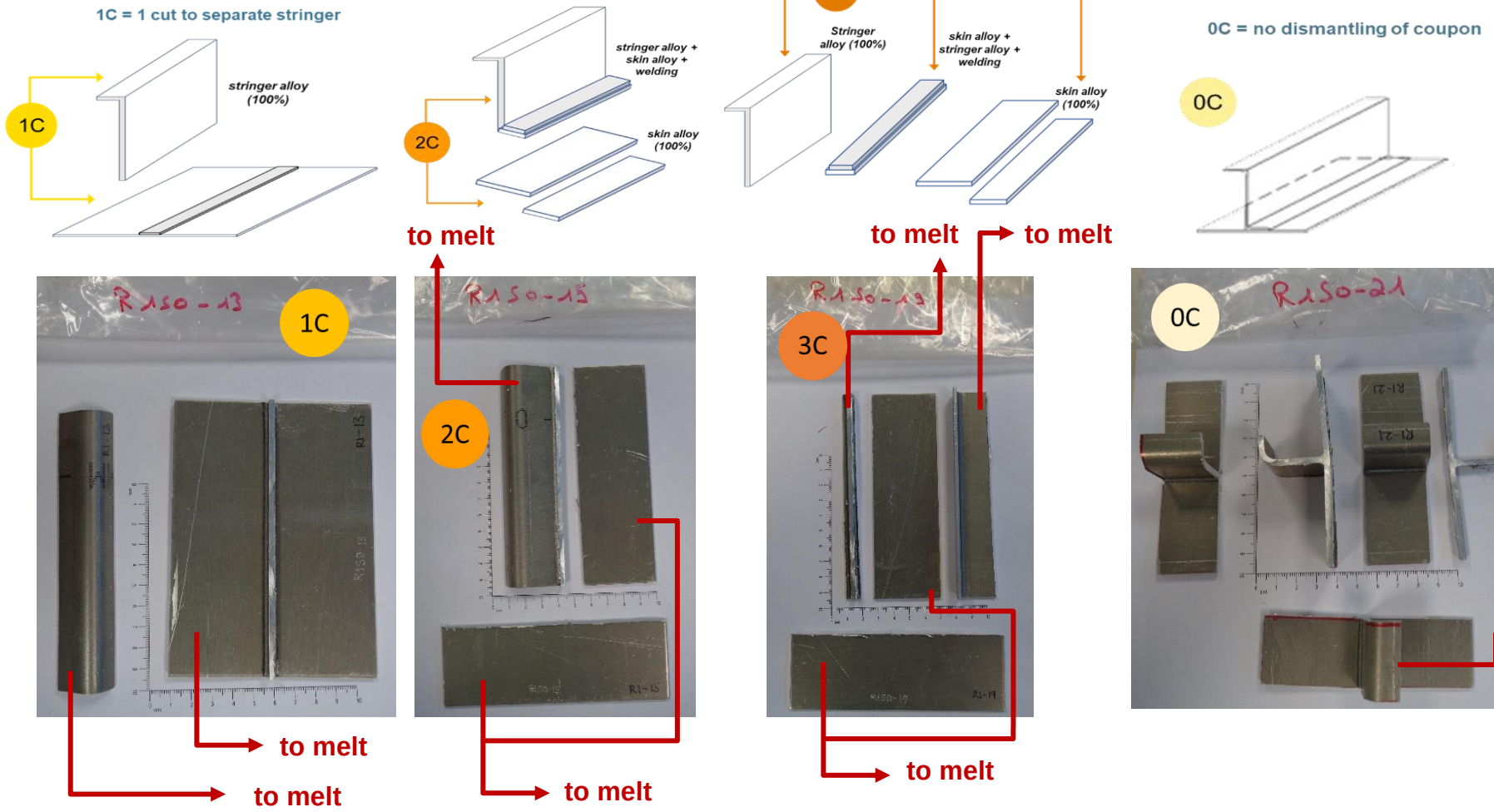
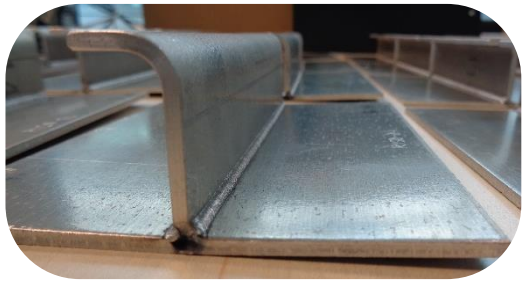
Results: Testing of different EoL routes

EoL Strategies: 4 scrapping options. Cuts performed at SONACA



Each fraction is tested in remelted tests at AZTERLAN



R1 coupons cut following 1C, 2C, 3C strategies and in transverse direction (0C).

Results: Testing of different EoL routes

Experimental screening of recycling approaches at coupon level. LBW with Al11Si filler wire (R1 coupon)

EoL R1 coupon (LBW with Al11Si filler wire)		Alloy	Main alloying elements in Al-Li alloys							Impurities to be controled		Other impurities	Compatibility results
Type	Cutting strategy	Materials	Li (*)	Cu	Mg	Ag (*)	Zr (*)	Mn	Zn	Fe	Si	Ti (*)	
Sheet+ Stringer (L-30	Skin and stringer Raw material	2198	0,98	3,28	0,31	0,21	0,091	<0,03	<0,03	0,041	<0,04	0,027	Raw material
LBW filler wire: Al-Si	Filler wire	ER4047	<0,008	<0,04	<0,03	<0,02	<0,008	<0,03	<0,03	0,18	11,4	0,013	Filler wire
EoL scrap	0c	2198 +weld	0,69	3,32	0,2	0,23	0,13	<0,03	<0,03	0,041	**0,07**	0,03	Si over 0.04 % impurity limit
EoL scrap	1c	2199 +weld	0,78	3,22	0,23	0,23	0,11	<0,03	<0,03	0,04	**0,11**	0,031	Si over 0.04 % impurity limit
EoL scrap	2c	2198+ weld	0,66	3,26	0,2	0,22	0,1	<0,03	<0,03	0,042	**0,17**	0,03	Si over 0.04 % impurity limit
EoL scrap	3c	weld	0,66	3,12	0,19	0,21	0,11	<0,03	<0,03	0,045	**0,71**	<0,03	Si over 0.04 % impurity limit

- ER4047 filler wire with a **11.4% of Si** is incompatible with Al-Li alloys from the recycling point of view to close-loop recycling
- High dilution is necessary in all EoL strategies for the fraction containing the weld seam → *downcycling to low grade casting alloys, but for those alloys Li content is also detrimental*

Full separation of the weld seam (3C EoL strategy) is necessary for R1- LBW coupon with Al11Si filler wire to avoid downcycling

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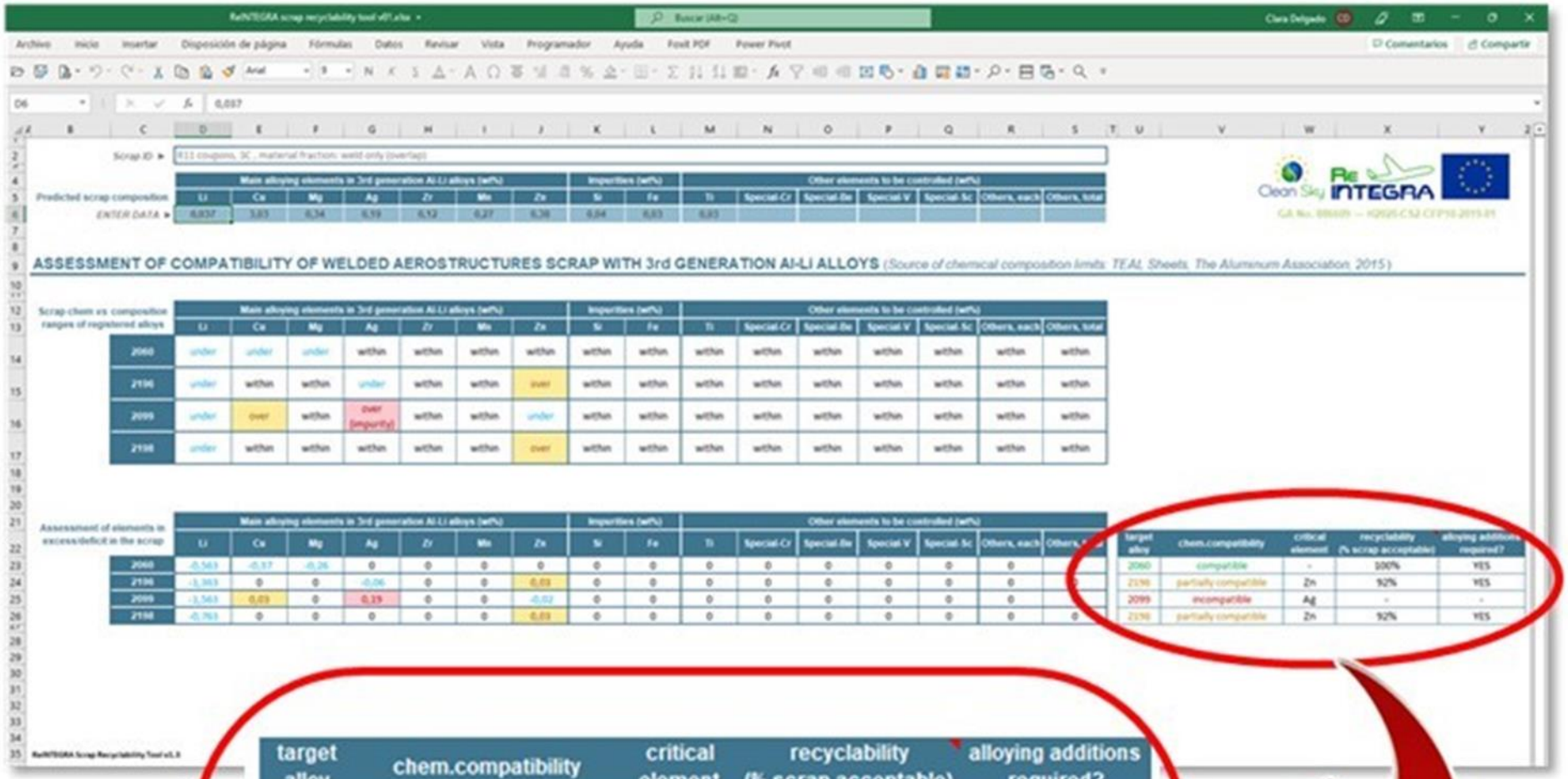
Results: Compatibility software development

COMPATIBILITY tool: 4 possible compatibility situations: scrap vs registered Al-Li alloy:

- SOLUTION: 100% compatible: The contents of all the chemical elements (alloying elements & impurities) in the scrap are within the formulated content ranges of an alloy or below the lower limits
  a) Alloying elements within ranges → **no addition needed**
  b) Alloying element(s) below lower limit → **addition needed for deficient elements**
- SOLUTION: partially compatible: The alloying element(s) in excess is an element with a content range specified for the alloy → **dilution**
- SOLUTION: above impurity limits (incompatible): The % excess of the impurity could be used as a criterion to decide between → **dilution or downcycling options.**

For partially compatible results with several Al-Li alloys → cost and environmental impacts calculations will help to select the most eco-efficient recycling option

Results: Compatibility software development



target alloy	chem.compatibility	critical element	recyclability (% scrap acceptable)	alloying additions required?
2060	compatible	-	100%	YES
2196	partially compatible	Cu	99%	YES
2099	incompatible	Ag	-	-
2198	compatible	-	100%	YES

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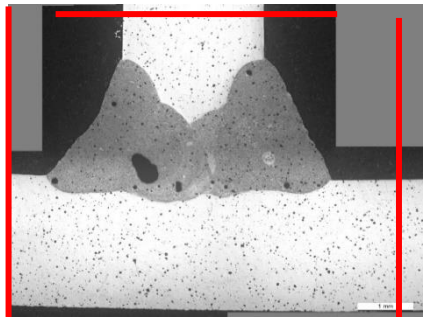
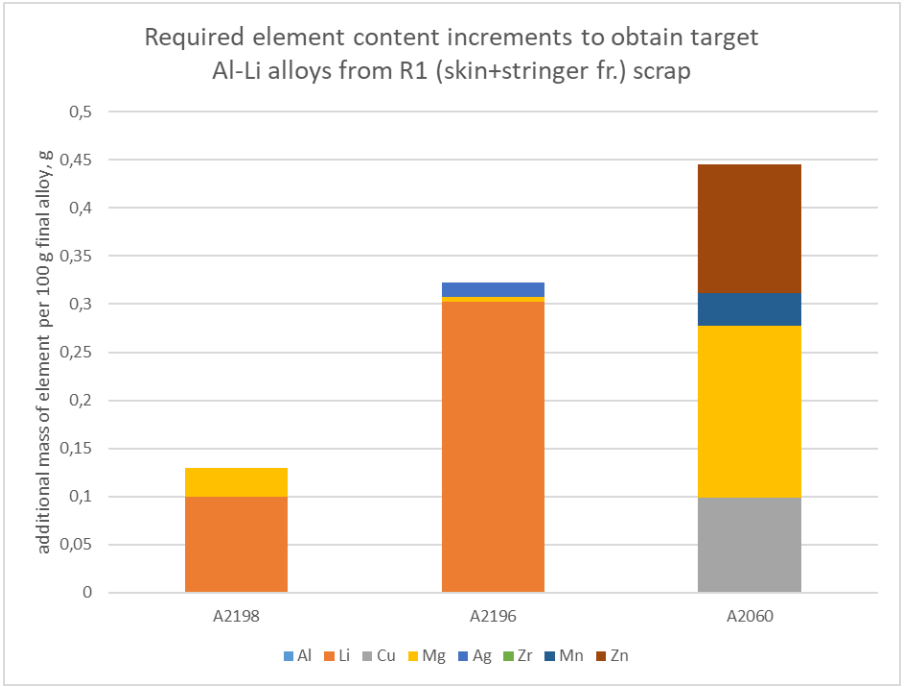
Results: Best EoL route for R1 – 3C

R1 LBW coupon – 3C cutting strategy

			(TEAL sheets)			
wt% total coupon scrap	COUPON scrap fraction	metal yield	AA2198	AA2196	AA2060	AA2099
88,74%	R1 3C-AA2198 fr	92,61%	100%	100%	100%	
11,26%	R1S2d 3C-weld fr	93,60%	0%	0%	0%	0%
63,46%	*R1S2d 3C-skin (AA2198)*	92,30%	*100%*	*100%*	*100%*	
25,29%	*R1S2d 3C-stringer (AA2198)*	93,40%	*100%*	*100%*	*100%*	



Apart from the base alloy AA2198 of R1 coupon, also possible recycling into AA2196 & AA2060, but environmental impacts are higher because it requires the addition of some alloying elements



Results: Best EoL route R2-R11

- **Experimental results and compatibility analysis**

max. % scrap into charge for target aeronautical Al-Li alloys (TEAL sheets)

EoL	COUPON scrap fraction	wt. % total coupon scrap	metal yield %	AA2198	AA2196	AA2060	AA2099
0C	R2 0C	100%		100%			
	R3 0C	100%		100%			
	R5 0C	100%		100%			
	R6 0C	100%	97,8%	100%	100%	84%	
	R7 0C	100%	95,5%	100%	100%	100%	
	R8 0C	100%	97,2%	100%	97%	92%	
	R9 0C	100%	97,4%	100%	95%	100%	
	R10 0C	100%	95,8%	95%	100%	78%	
	R11 0C	100%	94,5%	85%	85%	100%	

closed loop recycling into the base alloys of the coupon

scrap to downcycling (AlSi cast alloy)

0%

Results: Best EoL route for R11 – 0C

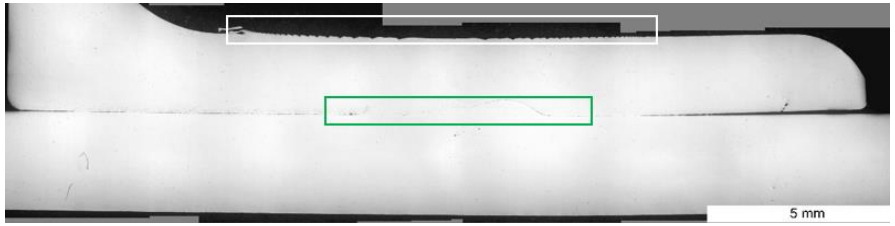
R11 FSW coupon – 0C cutting strategy

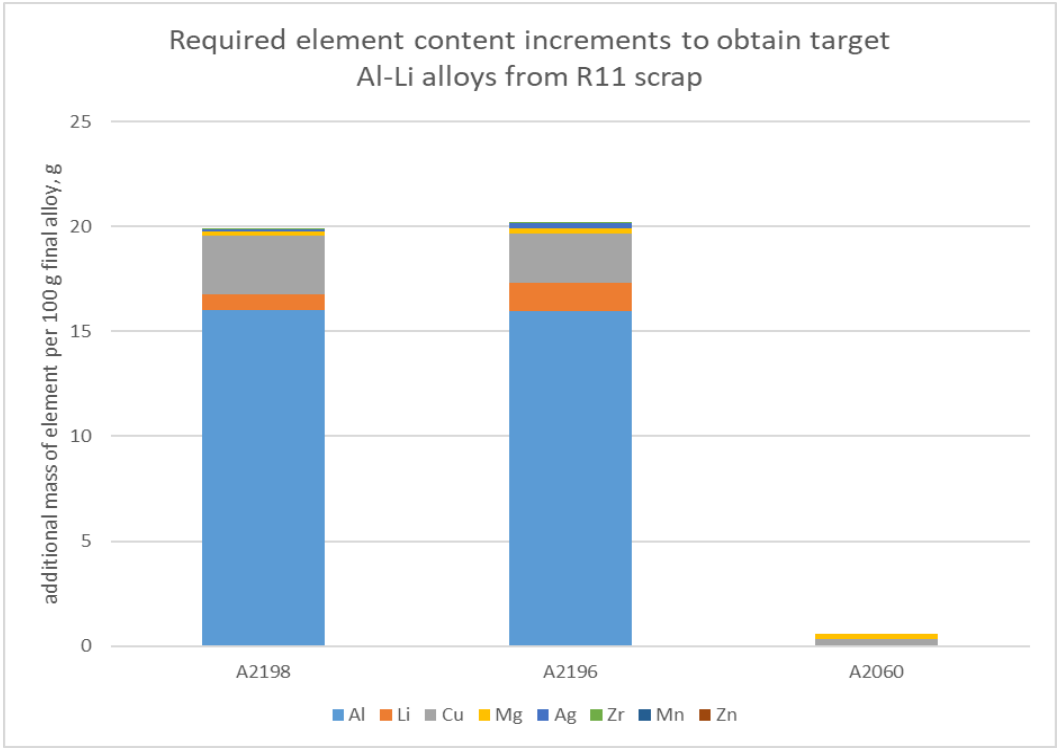
				max. % scrap into charge for target aeronautical Al-Li alloys (TEAL sheets)			
EoL	COUPON scrap fraction	wt. % total coupon scrap	metal yield %	AA2198	AA2196	AA2060	AA2099
0C	R11 0C	100%	94,5%	85%	85%	100%	

Only possible to recycle back into one of the two base alloys, 2060 but not for 2099

Recycling into 2196 and 2198 might be also possible, but with much higher impacts than towards the base alloy.

For recycling both into 2198 and 2196, dilution is needed





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    - Testing of different EoL routes
    - Compatibility software development
    - Best EoL route
4. Main conclusions

Main Conclusions

- **Aeronautical Al-Li alloys closed loop recycling of LBW coupons:**
  - **All filler wires except ER4047 (high %Si) compatibles with 2198 Al-Li alloy for closed loop recycling → no need of cutting for sorting into material fractions**
    - ✓ [R2, R3, R5] → 0C. No need of cutting for sorting into material fractions
    - ✓ R1 →3C:- skin and stringer fractions, free of weld seam for closed-loop
      - weld seam fraction downcycled to cast alloys
  - **Apart from the base alloy 2198, also possible into 2196 & 2060**
  - **No dilution needed (all cases)**
- **Aeronautical Al-Li alloys closed loop recycling of FSW coupons**
  - **No weld overlap separation needed: 0C**
  - **Possible back into their base alloys, except for 2099.**
  - **Note: If Ag in composition of one of the base alloys, recycling alloy should contain Ag (loss of valuable element that become an impurity)**

ACKNOWLEDGEMENTS

This research was supported by **Clean Sky 2 Joint Undertaking (JU) with the grant agreement No 886609**.

The JU receives support from the EU Horizon 2020 research and innovation programme and the Clean Sky 2 JU members.

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