Deliverable Report

Deliverable Title:

Alloy specifications for partially recycled alloys

Deliverable No.	Deliverable 1.1
Deliverable nature	Report
Work Package (WP)	WP 1
Task	Task 1.1
Dissemination level [1]	Public
Number of pages	50
Keywords	Critical raw materials, HPDC, Extrusion, Stamping, Aluminium, Magnesium, Silicone
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Due date of deliverable	July 31st 2021
Actual submission date	July 30th, 2021, resubmitted 14.04.2023 after reviewer feedback

Technical References

Project acronym	SALEMA
Project full title	Substitution of Critical Raw Materials on Aluminium Alloys for electrical vehicles
Call	H2020-SC5-2020-2
Grant number	101003785
Project website	salemaproject.eu
Coordinator	Fundacion Eurecat

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
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Document history

V	Date	Author (Affiliation)	Actions& Approvals
V1.0	02.07.2021	Manel da Silva (EUT)	First draft for HPDC section to request input from key contributors
V2.0	13.07.2021	Manel da Silva (EUT)	Content outline of the other sections (stamping and extrusion) requesting inputs to write them
V3.0	16.07.2021	Manel da Silva (EUT)	Draft of extrusion section to be validated and completed by key extrusion partners
V3.1	20.07.2021	Jaume Pujante	First draft of the stamping section
V4.0	23.07.2021	Manel da Silva (EUT)	Update of template format
V4.1	26.07.2021	Jaume Pujante (EUT)	Update of stamping section including missing information
V4.2	28.07.2021	Manel da Silva (EUT)	Generation of final version including inputs from all the partners
V4.3	06.03.2023	Jaume Pujante (EUT)	Update of stamping section including evaluator feedback
FINAL	14.04.2023	Hannah Arpke (EUT)	Finalisation

Summary

The present document defines the relevant properties to take into account in the development of the partially recycled alloy of SALEMA project. The document is divided in 3 sections, one for each processing technology: HPDC, stamping and extrusion.

The content of each section differs a little from each other, as the approach for each technology is not the same. However, the main structure and procedure followed in all of them to define the final alloy requirements has been to:

1. The respective end-users in agreement with the alloy producer and the processing company, established the requirements of their demonstrators
2. The alloy producers select the alloys that can better fulfil the necessities of the corresponding demonstrators
3. Define the tests that will be conducted in each stage of development (WP1 and technology development, WP4-6) and the required threshold or criteria to assess the alloy performance for each test

Deliverable 1.1 should be a guide to take into account in the development of SALEMA partially recycled alloys and not a comprehensive and rigid rulebook with properties.

Disclaimer

Abbreviations

Abbreviation / Acronyms	Description
(A)MGA	(Annotated) Model Grant Agreement
CA	Consortium Agreement
CFS	Certificate of Financial Statement
EAB	External Advisory Board
EC	European Commission
EU	European Union
FP	Framework Programme
GA	Grant Agreement
PSB	Project Steering Board
PMT	Project Management Team
PC	Project Consortium
WP	Work Package
WPL	Work Package Leader
HPDC	High Pressure Die Casting
YS or ReH	Yield Strength
UTS or Rm	Ultimate Tensile Strength
A	Elongation at break

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1. Introduction and Background

The use of aluminium in vehicles has been steadily growing over the last decades, substituting steel and cast iron and making vehicles more efficient and less fuel demanding. As a reference, weight reduction potential of up to 20-30 % has been estimated by making use of high-performance aluminium grades. However, these high-performance parts need to be produced in primary aluminium alloys requiring alloying elements classified as sensitive by the CRM alliance, the most common of those being Silicon metal (Si) and Magnesium (Mg).

While aluminium recycling is spread in the industry, recycled alloys are currently not able to fulfil structural applications due to limitations in their formability and mechanical performance. Moreover, the parts traditionally produced with recycled aluminium (motor blocks, gear boxes, oil pans, valve covers) are not present in electrical vehicles. Detailed information about the possible parts and their requirements can be found in ANNEX 1: Aluminium Alloys for Electric Cars: base-line concepts, together with an exhaustive analysis of the current state of the art for the 3 SALEMA processing technologies. The development of new high performance, environmentally and strategically sustainable aluminium grades and their forming processes is fundamental for the electrification of the transportation industry.

WP1 sets the basis for the development of partially recycled aluminium alloys for high performance applications, one of the main objectives of SALEMA project, while Task 1.1 select the aluminium alloys to be further developed and define the criteria to assess its performance, according to the requirements of the different demonstrator components.

1.1. Objectives of task and deliverable

Task 1.1 defines the methodology to be followed within the project to develop the partially recycled alloy of SALEMA project:

- Define the 2 demonstrators that will be used to assess SALEMA alloys for the different transformation processes and establish the main requirements of each of them
- Select the 2 aluminium alloys used as reference for further development within SALEMA project
- Establish the methodology, tests and preliminary criteria used to assess the alloy performance for each processing route

2. Specifications of SALEMA HPDC alloys

2.1. State of the art in aluminium alloys for high performance HPDC

High pressure die-casting (HPDC) has been considered as a simple but effective method for the fabrication of aluminum alloy parts [1,2]. Due to its advantages of high efficiency and short production cycle, HPDC has been widely employed by automotive industries. Today’s casts are getting thinner and larger with more and more functions integrated. In addition, there is an increasing requirement to offer higher strength and ductility for these crash relevant parts and the riveting process.

Classic applications are served by the Al-Si family in the range of 7 to 11% Silicon. Varying amounts of Mg (for Mg_2Si hardening), low contents of Fe and Mn for die soldering resistance are added as well. If elongations of 10% or higher are required, then a T7 heat treatment is mandatory. Among aluminum-silicon and aluminum-silicon-magnesium based alloys, AlSi10MnMg alloys, designated as EN AC-43500 usually have good castabilities and excellent mechanical properties [3], and therefore, they are widely used to make automotive structural components by HPDC process [4–7].

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2.2. Definition of HPDC demonstrator' requirements

2.2.1. Requirements of demonstrator 1 (Shock Tower)

2.2.1.1. Mechanical properties (tensile test)

The Shock Tower has, as structural part, high requirements in terms of mechanical properties. Thus, the mechanical requirements of the material from which this demonstrator is produced are the following ones:

- Yield Strength (ReH) = 120 MPa
- Ultimate Tensile Strength (Rm) = 180 MPa
- Elongation at Break (A) = 10 %

In general, the results obtained with tensile tests are quite similar, independently of the standard use, and similar values can be obtained with different standards. Nevertheless, in order to unify the procedure, in SALEMA project all tensile tests will be conducted following EN ISO 6892-1 standard.

2.2.1.2. Bending test

An additional mechanical property measured by FORD is the resistance of the material to a 3-point bending test according to the VDA 238-100 standard, with samples with 60 mm length and 30 mm width.

2.2.1.3. Crash performance

As structural component, crash performance is a very important issue. FORD uses a methodology to model the crash performance of an aluminium alloy from tensile tests conducted at different strain rates. This methodology will be used to predict the crash performance of HPDC SALEMA alloys.

In addition, TEF tests, a methodology developed at Eurecat, will be used, to compare the results obtained with FORD's methodology.

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2.2.1.4. Corrosion properties

The Shock Tower shall be resistant to corrosion. As FORD has not a defined requirement to assess corrosion resistance, it will be followed the same methodology defined by CRF-Stellantis for the Frontal Frame demonstrator.

2.2.1.5. Riveting

Self-piercing riveting (SPR) is a widely used mechanical joining process in the automotive industry due to its ability in joining any combinations of materials without leading to material mixing. This technology is suitable for high volume productions, as in the case of FORD's F-150 trucks, which require between 2200 and 2700 rivets per vehicle.

Flat specimens of the alloy in their final treatment condition will be delivered to FORD for conducting this test. The specimen will be riveted together with a 1.3 mm DP600 steel sheet.

2.2.2. Requirements of demonstrator 2 (Frontal Frame)

2.2.2.1. Mechanical properties (tensile test)

The Frontal Frame has, as structural part, high requirements in terms of mechanical properties. The mechanical requirements of the material from which this demonstrator is produced are the following ones:

- Yield Strength (ReH) = 180 MPa
- Ultimate Tensile Strength (Rm) = 230 MPa
- Elongation at Break (A) = 10 %

As discussed above, the results obtained with tensile tests are quite similar, independently of the standard use, and similar values can be obtained with different standards. Nevertheless, in order to unify the procedure, in SALEMA project all tensile tests will be conducted following NF EN ISO 6892-1 standard.

2.2.2.2. Fatigue requirements

The Frontal Frame is a component with fatigue requirements. Thus CRF-Stellantis will conduct a fatigue test at samples level. However, not minimal fatigue specifications are defined to the alloy or even separated components.

2.2.2.3. Corrosion properties

The Frontal Frame is a component with corrosion requirements. In order to assess the corrosion resistance of SALEMA alloys CRF-Stellantis proposes to use a combination of 6 hours of corrosion test according to ASTM B638 standard, followed by a stay of 672 hours in a climatic chamber under the testing conditions defined by ASTM D1375. The tests will be done at samples level.

In addition, some of the welded samples will be subjected to an SAE J 2334 test and they should resist a minimum of 120 days under this test conditions.

2.2.2.4. Weldability

The HPDC part of the frontal frame will be weld to the extruded profile and therefore, SALEMA HPDC alloy should be weldable, and weldability will be a property that will be assessed during alloy development. CRF-Stellantis will conduct welding tests over specimens with an arc weld robot equipped with Cold Metal Transfer system.

The weld beads will be validated with a micrographic inspection to see if the weld areas are in compliance with FCA specifications and with tensile tests of specimens machined with the weld beam within its calibrated section, in order to verify that the failure take place outside the joint area.

2.2.3. General process requirements

2.2.3.1. Process requirements: castability

A fundamental property for any casting alloy is its ability to flow and fill a complex part shape, easing the forming a quality casting. Material properties that influence the alloy castability are fluidity, solidification pattern and tendency to form dross.

2.2.3.2. Tool wearing

Die life and tool wearing is an important issue in HPDC. There are different mechanisms that induce damage into the die, but the mechanism more related to alloy composition is the tendency to react with the Fe present in the tool material, commonly known as die soldering.

2.3. Selection of reference alloys

Two alloys have been selected as reference for further development in SALEMA project. These alloys will be used as:

- Alloy base for developing the addition of high scrap ratios and the potentially required micro-additions to compensate the high impurity level
- Reference in terms of properties and performance for the rest of HPDC alloys developed in SALEMA project

Currently, AlSi10MnMg is the alloy most used in the production of structural parts and other parts with high mechanical requirements by HPDC by far and the only that can reach the exigent requirements of SALEMA HPDC demonstrators. For that reason, it has been agreed between Raffmetal, the end-users (CRF-Stellantis and FORD) and the demonstrator producers (Fagor and Endurance). To focus the development of the partially recycled alloy on this alloy, trying different levels of Mg (around 0.2 % and 0.45 %, respectively) in order to get different final mechanical properties (strength and elongation).

2.3.1. Main properties of AlSi10MnMg alloy

Raffmetal has started to produce this alloy recently, in 2020, and it is interested in further improvement of the alloy characteristics as well as increase the amount of recycled material used for its production. Raffmetal is currently producing industrially such alloy with a content of approximately

40-45 % of end-of-life scrap material. The target will be to increase the amount of end-of-life scrap using the selected post-shredded scrap from COMET to at least 60 %.

According to Raffmetal alloy datasheet (ANNEX 2), the mechanical properties of AlSi10MnMg alloy in T6 condition are the following:

- Yield Strength (ReH) = 200-280 MPa
- Ultimate Tensile Strength (Rm) = 290-350 MPa
- Elongation at Break (A) = 6-12 %

These properties met well the requirements of Yield Strength and Ultimate Tensile Strength requested by both demonstrators but can struggle by reaching the minimum Elongation at Break required by both demonstrators.

Alternatively, the alloy can be subjected to a T7 treatment, in order to improve the material elongation in exchange of some strength lost. In this case the following mechanical properties can be obtained:

- Yield Strength (ReH) = 120-170 MPa
- Ultimate Tensile Strength (Rm) = 200-240 MPa
- Elongation at Break (A) = 15-20 %

The properties of the alloy in this thermal condition will safely met the requirements of the Shock Tower demo component, but the strength is too low to reach the Yield Strength and will struggle with the UTS value demanded by the Frontal Frame.

A development of an optimized intermediate treatment between T6 and T7 may be required in order to reach the high mechanical requirements of the Frontal Frame.

In Raffmetal alloy datasheet (ANNEX 2) it also stated that this alloy has GOOD general resistance to corrosion and EXCELLENT castability.

2.4. Final alloy requirements and validation criterion

2.4.1.1. Mechanical properties (tensile test)

In order to validate SALEMA project alloys tensile test according to EN ISO 6892-1 standard will be conducted to a minimum of 3 specimens. The minimum requirements that all 3 specimens shall meet are those from the most selective demonstrator (the Frontal Frame):

- Yield Strength (ReH) = 180 MPa
- Ultimate Tensile Strength (Rm) = 230 MPa
- Elongation at Break (A) = 10 %

2.4.1.2. Bending test

The assessment of mechanical properties in WP1 will be done exclusively with tensile test, as the available amount of material will be very reduced.

Bending resistance will be evaluated in WP4, with the specimen parts cast by Eurecat and, subsequently, in the final Shock Tower demonstrator component.

SALEMA alloys will be subjected to a 3-point bending test according to the VDA 238-100 standard, with samples with 60 mm length and 30 mm width.

2.4.1.3. Fatigue requirements

The assessment of fatigue requirements will be done in two stages:

- In WP1 alloys only tensile tests will be conducted, due to the small amount of material that it is going to be available. Fatigue behaviour is often related to the mechanical properties of the material. Thus, in HCF (High Cycle Fatigue) materials with high mechanical strength generally exhibit greater resistance to fatigue. On the other hand, in LCF (Low Cycle Fatigue) the best behaviour is obtained in materials that have a high plastic deformation capacity. Fatigue behaviour will also be affected by component porosity.
- In WP4 fatigue tests will be conducted in the Shock Tower moke-up that is going to be cast in EURECAT HPDC machine to validate the performance of HPDC alloys. LCF fatigue tests will be performed according ISO12106 standard (Metallic materials – Fatigue testing – Axial-strain controlled method). Around 21 specimens will be used: 7 specimens by strain amplitude with 3 repetitions for each strain level. The strain rate will be 0,008 s^{-1} and strain ratio will be -1 (fully reversed). A life range from 500 to 1.000.000 cycles will be analysed. Strain control will be used the first 50.000 cycles, and, after stabilization, control mode will be changed to load control with a frequency of 10Hz. The results will be the εN curve parameters (Basquin and Coffin-Manson coefficients) and the monotonic and cyclic stress-strain curves.

2.4.1.4. Crash performance

For the evaluation of the crash performance of SALEMA alloys 2 different methods will be used and compared:

1. Tensile tests conducted at different strain rates: FORD uses this approach to predict crash performance of HPDC aluminium alloy. Eurecat will use material from their HPDC trials conducted at industrial laboratory level at the final thermal conduction to conduct this test. Eurecat will conduct the tensile tests at the different strain rates defined by FORD and provide the information to FORD to predict the potential crash performance of the alloy and determine which of them are more suitable to produce the final HPDC demonstrators. The same approach will be also conducted in the Shock Tower demonstrator.

2. Alternatively, Eurecat will use the approach of the Essential Work of Fracture (EWF). In EWF methodology, DENT specimens with different ligament lengths (l0) are tested up to fracture (Fig. 1). Specimens will be tested up to fracture at a constant displacement rate of 1 mm/min. The load-line displacement will be measured by means of a video-extensometer, using two extensometer marks (initial calibrated length = 25 mm). The load vs load-line displacement will be recorded. Ligament lengths from 6 to 14 mm will be used and 2 specimens per ligament length will be tested. The experimental procedure for the determination of the specific Essential Work of Fracture (we) is schematized in Fig. 1. The total specific work of fracture (wf) is obtained by integrating the area under the load displacement curve and dividing by the cross section area. we is determined from extrapolation of wf vs l0 data to zero ligament length.

3.

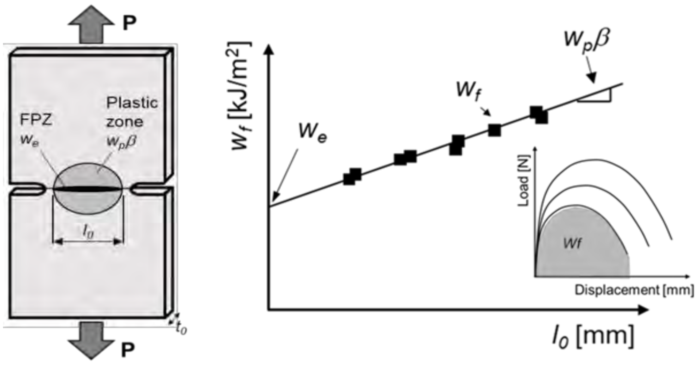

Figure 1: Experimental procedure for we determination

2.4.1.5. Corrosion properties

To assess the corrosion properties of HPDC SALEMA alloys, the parts casted by Eurecat in WP4 will be subjected to 6 hours of corrosion test according to ASTM B638-97 standard, followed by a stay of 672 hours in a climatic chamber under the testing conditions defined by SAE J2635. The acceptance criteria for SALEMA alloys will be, that after this double corrosion test, the cracks in the scratched area should have less than 2 mm of propagation.

The same procedure will be conducted over the 2 final HPDC demonstrator parts, which should also meet the same requirement described for the industrial laboratory trials.

2.4.1.6. Riveting

Riveting properties of SALEMA HPDC alloys will be also assessed in WP4. Flat specimens of the alloy in their final treatment condition, extracted from Eurecat HPDC validation specimens, will be provided to FORD in order to conduct this test. The specimen will be riveted together with a 1.3 mm DP600 steel sheet.

2.4.1.7. Weldability

CRF-Stellantis will conduct welding tests over specimens with an arc weld robot equipped with Cold Metal Transfer system.

The weld beads will be validated with a micrographic inspection to see if the weld areas are in compliance with CRF-Stellantis specifications, and with tensile tests of specimens machined with the weld beam within its calibrated section, in order to verify that the failure take place outside the joint area.

2.4.1.8. Tool wearing

In order to assess tool wearing, Eurecat testing die will be inspected before and after the production of each alloy. Replicas of the existing cracks will be extracted, and their profile will be measured with a confocal microscope. The crack progress during the alloy production will be determined and compared between them.

There will be a criterion that SALEMA alloys should met in order to assess this property, but tool wearing will be measured for all alloys and taken also into account to select the best candidates for the production of the final HPDC demonstrators.

Die damage will be also analysed in the demonstrator production tools, determining the presence and origin of any possible damage appearing in the trials during the part production.

2.4.1.9. Process requirements: castability

In order to assess alloy castability of the HPDC alloys developed in WP1 a mould with strips of different thicknesses will be used. The design will be based in a geometry reported in the literature (Fig. 2). To ease the control of the mould temperature an oil circuit will be added to both mould parts. The flow length of the different strips will be measured and compared with those obtained for the reference alloy.

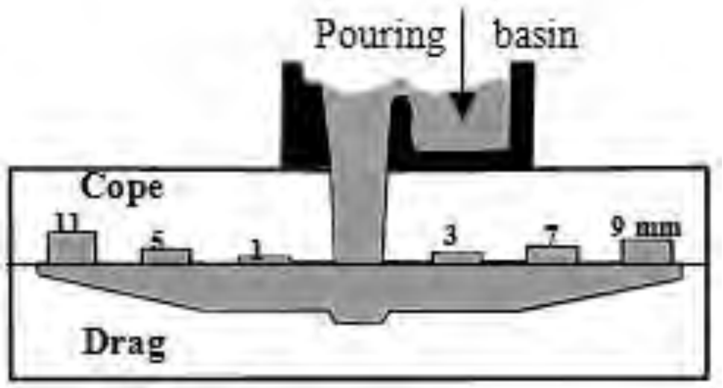

Figure 2: Scheme of SALEMA mould intended to assess alloy castability

2.4.1.10. Amount of recycled material: Alloy Criticality Index

The Criticality Index is a concept that considers the different aspects that European Commission takes into account to establish a material as a Critical Raw Material (CRM) and gives a value, pondering all these aspects.

For SALEMA partially recycled alloys, it will be considered that the end-of-life scrap has a Criticality of 0, at it is a material available in between European borders and which provision does not comport any risk or criticality.

The criticality index for AlSi10MgMn alloy calculated taking into consideration the present values given for the critical elements that are required by this alloy: Si (2.86) and Mg (3.82), is 0.298.

Raffmetal is currently producing industrially such alloy with a content of approximately 35-40 % of end-of-life scrap material. Therefore, the criticality of the alloy will be reduced in the same amount, being 0.119.

The target of the new SALEMA alloys would be to increase the amount of end-of-life scrap used in the alloy production to at least 80 %, by a more accurate selection of the scrap and a reduction of the scrap variability, reducing the current criticality index to, at least, 0.06.

3. Specifications of SALEMA Stamping alloys

3.1. State of the art in aluminium alloys for cold and hot stamping

Several sheet aluminium alloys are used in the automobile industry, with different implications in terms of processing route and mechanical properties. Ismail [1] presented in 2016 a good summary of the main uses of Aluminium sheet in the mainstream automotive industry; this work is still a valid overview despite the 5 years elapsed from its publication (Figure 3). In this regard, the main divide concerning the project is between 5000-series alloys, materials hardened by cold working during stamping; and 6000-series alloys, materials hardened by solution and aging heat treatments.

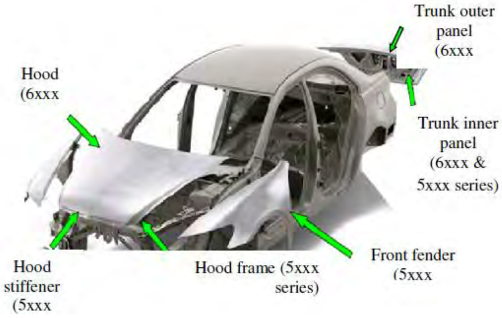

Figure 3: Use of Aluminium alloy sheet in the mainstream automotive industry [1]

In general terms, 5000-series alloys are used in applications with higher geometrical complexity and less stringent mechanical requirements, as these work hardening alloys generally present higher formability than 6000-series alloys.

It must be noticed, however, that sheet Aluminium grades with favourable mechanical properties present limited formability when compared to steel alloys, particularly in terms of Springback [1] and Forming Limit [2]. In all cases, combinations of strain path, strain rates and work hardening (for 5000 alloys) need to be carefully considered to obtain a successful component [3, 4]. Given that presence of inclusions and defects is detrimental to formability, this study is crucial in the development of recycled alloys in SALEMA. One additional limitation in 5000-series alloys, that could be improved with their substitution for 6000 series, is the appearance of defects such as slip bands or orange peel. Moreover, these defects are typically not clearly revealed until after component painting.

One way to circumvent limited formability is using temperature to aid the forming process [1,3, 5] (Figure). While other possibilities exist, a possible embodiment of this is a process analogous to hot stamping of sheet steel (*press hardening* [6]), in which sheet aluminium, would be brought to solubilization temperature in a furnace and stamped and quenched in a single step, to be later artificially aged to its final properties [2,7].

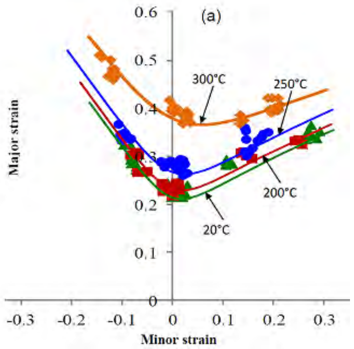

Figure 4: Simulated FLD curves for 5754 sheet; the material shows improved formability at temperatures above 250 ºC.

While still not widely adopted, this approach has been demonstrated as technically and industrially feasible by SALEMA partners Eurecat and Gestamp [7], and opens a possibility for obtaining components with high geometrical complexity and high mechanical properties using 6000-alloys with limited formability at room temperature and in final heat treatment state. This route will also be explored in SALEMA.

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3.2. Selection of reference alloys

From these, the following alloys have been considered as references, due to their wide implementation in the automotive industry:

3.2.1. 5000-series

These alloys acquire their final mechanical properties trough work hardening. They can be acquired in a range of pre-deformed states.

The main interest alloys are 5182 and 5754. The typical range of mechanical properties for these alloys can be found in Table 7 (5182) and Table 8 (5754).

From these two grades, 5754 has been selected as the main reference and for the first battery of tests including scrap in WP1. The reason is that 5754 is very widespread in the automotive, railway and general structural industry, and its chemical composition is more tolerant to the alloying elements typically found in traces in scrap aluminium.

Table 7: Range of properties achievable with 5182 sheet in different cold work states

State Designation	description	AA 5182		
		UTS [MPa]	YS [MPa]	A%
O	annealed	275	130-170	12-25
H22	1/4 hard	315-317	230-245	12
H24	1/2 hard	340-338	240-285	10
H26	3/4 hard			
H28	4/4 hard	390	320	1-6
H19	extra hard	420-421	360-395	1-4

Table 8: Range of properties achievable with 5754 sheet in different cold work states

State Designation	description	AA 5754		
		UTS [MPa]	YS [MPa]	A%
O	annealed	190-240	80-135	12-20
H22	1/4 hard	220-270	130-180	7-15
H24	1/2 hard	240-280	160-215	5-10
H26	3/4 hard	265-305	190-245	4-6
H28	4/4 hard	290	230-250	3-4
H19	extra hard			

3.2.2. 6000-series

6000 series mechanical properties strongly depending on the heat treatment state. The most common presentations for sheet metal are T4 (solubilized and naturally aged) and T6 (solubilized and artificially aged at moderate temperature).

Three grades have been chosen as reference: 6016, 6082 and 6111. The range of mechanical properties achievable with these alloys is presented in Table 9 (6016), Table 10 (6082) and Table 11 (6111).

From these grades, 6082 has been selected as the main reference for the first battery of tests including scrap in WP1. Similar to the case above, 6082 is a very commonplace alloy, and its chemical composition is more tolerant to the alloying elements typically found in traces in scrap aluminium, particularly when compared to 6016.

Table 9: Range of properties achievable with 6016 sheet in different heat treatment states

Heat Treatment	AA 6016		
	UTS [MPa]	YS [MPa]	A%
T4	170-250	80-140	24-26
T6	260-300	180-260	10 a 12

Table 10: Range of properties achievable with 6082 sheet in different heat treatment states

Heat Treatment	AA 6082		
	UTS [MPa]	YS [MPa]	A%
T4	205-240	110-140	12 a 23
T6	260-375	220-310	4 a 13

Table 11: Range of properties achievable with 6111 sheet in different heat treatment states

Heat Treatment	AA 6111		
	UTS [MPa]	YS [MPa]	A%
T4	270-290	150-180	20-26
T6	360-390	250-310	8a14

3.3. Definition of stamping demonstrators’ requirements

Two use case demonstrators are considered for sheet metal alloys: cold stamping of aluminium sheet and hot stamping.

3.3.1. Cold stamping demonstrator: car door

This demonstrator, corresponding to partner CRF-Stellantis, consists in a commercial car door. The production reference to be used will be selected in Task 5.3, choosing a geometry that is relevant to the state of the art at the moment of performing the pilot tests.

Cold stamping demonstrators will be produced in both 5000 and 6000 series alloys, as both use cases have place in the industry.

3.3.2. Hot stamping demonstrator: B-Pillar

The demonstrator for hot stamping is a B-pillar geometry, which is a representative example of the crash-resistant components where press hardening is typically applied.

Due to the thermal cycle applied in the process, only 6000 series are considered for this application.

3.3.3. Relevant properties for each demonstrator

While most properties are relevant for both use cases, some specific tests only apply to one of the demonstrators. This information is summarized in Table , and the resulting criteria for determining if requirements are met are summarized in section 0.

Table 6: Relevant properties for each of the demonstrator cases

	Cold Stamping	Hot Stamping
Format		
Mechanical properties	X	X
FLD	X	
Hot formability		X
Weldability	X	
Compatibility with adhesives	X	X
Corrosion resistance	X	X
Essential Work of Fracture	X	X
Surface finish (qualitative)	X	

3.4. Final alloy requirements and validation criterion

Requirements could not be expressed in terms of numeric values, but rather as a comparison with reference materials of a set of properties and performance indicators. The following points describe how these comparisons are to be established.

3.4.1.1. Format

Basic requirements for the applications include the format of the material itself. Relevant factors include:

- **Thickness:** ranges of 0.8-5 mm need to be possible

- **Passivation:** good passivation is required for cold forming applications
- **Surface finish:** Cold forming applications require good surface finish. This will be evaluated by means of light topography measurements.

3.4.1.2. Basic mechanical properties

Basic mechanical properties will be determined through tensile tests, as described in section **Error! Reference source not found.**. In addition of the conventional strength and elongation measurements, specific tests will be performed at 0, 45 and 90 degrees from the rolling direction to evaluate anisotropy, a very relevant parameter for sheet metal stamping and drawing. These tests will be performed according to standards such as ASTM E 517.

The alloys developed in SALEMA need to meet combinations of mechanical properties equivalent to those of the reference grades.

3.4.1.3. Formability: FLD

Formability of cold forming alloys will be evaluated by determining selected points of their Forming Limit Diagrams; the methodology followed will correspond to standards such as ASTM E2218.

The obtained FLD curves will be compared to the reference grades, to determine if the addition of scrap has resulted in decreased formability. Analyses of the FLD curves in task 5.3 together with Finite Element Modelling will determine if the results achieved are sufficient for the proposed demonstrator.

3.4.1.4. Hot Formability

Hot formability will be modelled by performing a series of tensile tests at different temperature ranges and strain rates. These data will allow determining if there are unexpected phenomena at high temperature (e.g. localized plasticity, loss of ductility), determining flow stress at different conditions and determining constitutive equations for FE modelling.

3.4.1.5. Bendability

Bendability tests offer an evaluation of the tightness at which a particular sheet metal can be bent without presenting defects, mainly cracking. Bendability will be tested based on standard VDA 238-100.

Cold Stamping materials need to display bendability equivalent to conventional alloys.

3.4.1.6. Weldability

Weldability tests will be performed in all the available materials. Procedures will be the same as described in section 2.4.1.7 for HPDC demonstrators, with the necessary adaptations to the sheet metal format.

SALEMA alloys need to show weldability equivalent to reference alloys.

3.4.1.7. Compatibility with adhesives

Compatibility with adhesives includes two different aspects of material performance. On the one hand, adhesion force as measured by standard tests such as ASTM D 1002-01.

On the other hand, and particularly critical for sheet aluminium alloys, compatibility of any heat treatment required for curing the adhesive with the heat treatment of the aluminium itself. This will be evaluated by comparing the curing cycles on common adhesive with the heat treatment window in the developed alloys.

3.4.1.8. Corrosion resistance

Cyclic corrosion tests will be run according to common auto industry standards. At the moment of writing this document, standard VDA 233-102 is proposed.

Corrosion performance is relevant for hot stamped material, as no passivation can be used on the sheet due to the thermal cycle of the forming process.

3.4.1.9. Essential Work of Fracture

EWF is a good indicator of crash performance, but it is also a good predictor for formability in sheet metal, specifically in operations generating severe and localized expansion of the material, such as flanging or hole expansion.

EWF will be measured in selected cases, using the methodology described for Eurecat in section 2.4.1.4.

3.5. Prediction of impact on alloy properties of higher use of scrap

The use of higher amounts of scrap is expected to impact the following aspects:

3.5.1. Precision of the chemical composition

Aluminium scrap contains a number of alloying elements, which may complicate achieving a precise composition in low-alloy grades. This is particularly true for alloys 5182 and 6016 which present a low amount of Mn, as the latter is a very common alloying element in aluminium scrap.

3.5.2. Material performance

Formability of the new alloys could be affected, particularly in cold forming of sheet with high strength and high % of scrap. In these conditions, the material may be sensitive to the presence of inclusions and defects detrimental to formability and display FLD curves (section 3.4.1.3) which are more restrictive than usual.

3.5.3. Criticality Index

Project targets include achieving a use of scrap in excess of 70 %. Considering that scrap metal from European origin is not subject to supply risks (essentially presenting a criticality risk of 0), the criticality index of the studied alloys will be reduced in a similar amount.

4. Specifications of SALEMA extrusion alloys

4.1. State of the art in aluminium alloys for extrusion

The main areas of aluminium expansion are the replacement of steel with aluminium alloys in the range of products for the transport, aviation, engineering and construction industries, which translates into lower operating costs and environmental benefits, as well as measurable economic benefits [1]. Therefore, currently a huge impact on the development of the aluminium industry is attributed to the development of the automotive industry, especially electromobility [2].

AlMgSi alloys are among the most commonly produced and used in practice aluminium alloys intended for extrusion processing. The basic features of these materials are very good deformability, corrosion resistance, and good weldability [3].

The currently designed electric battery housing systems are based on profiles made of AlMgSi alloys, eg 6063 with a strength in the range of 220-240 MPa, due to the necessary complex shapes of the profiles and the necessary mechanical properties [4]. For the front parts, 6082 series alloys are used with slightly higher strength properties of 280-320 MPa and an equally high plasticity of 10%, similar to 6063 alloys [5, 6].

In the case of changes in the chemical composition related to the reduction of critical elements and greater use of aluminium scrap in the production process, it will be crucial to characterize, apart from the strength properties, many functional properties of the tested alloys.

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6. C. Poletti, R. Bureau, P. Loidolt, P. Simon, S. Mitsche, M. Spuller: Microstructure Evolution in a 6082 Aluminium Alloyduring Thermomechanical Treatment: Materials 2018,11, 1319

4.2. Definition of extrusion demonstrators’ requirements

4.2.1. Requirements of demonstrator 1 (Battery Tray)

The first demonstrator used to validate SALEMA extrusion alloys is going to be the dies designed and fabricated in MARBEL project (where are also involved ASAS, EURECAT and CRF-Stellantis). SALEMA alloys will be also extruded with these dies and the obtained properties will be compared with the properties obtained with the commercial alloys used in MARBEL project.

Therefore, no fixed requirements are defined for this demonstrator, as the requirements are going to be achieve similar properties with SALEMA alloys extruded profiles, as those reached in MARBEL project.

4.2.2. Requirements of demonstrator 2 (Frontal Frame)

4.2.2.1. Mechanical properties (tensile test)

The requirements of the extruded part of the Frontal Frame are the same as for the HPDC components:

- Yield Strength (ReH) = 180 MPa
- Ultimate Tensile Strength (Rm) = 230 MPa
- Elongation at Break (A) = 10 %

As discussed above, the results obtained with tensile tests are quite similar, independently of the standard use, and similar values can be obtained with different standards. Nevertheless, in order to unify the procedure, in SALEMA project all tensile tests will be conducted following NF EN ISO 6892-1 standard.

4.2.2.2. Fatigue requirements

The Frontal Frame is a component with fatigue requirements. Thus CRF-Stellantis will conduct a fatigue test at samples level. However, not minimal fatigue specifications are defined to the alloy or even separated components.

4.2.2.3. Corrosion properties

The Frontal Frame is a component with corrosion requirements. In order to assess the corrosion resistance of SALEMA alloys CRF-Stellantis proposes to use a combination of 6 hours of corrosion test according to ASTM B638 standard, followed by a stay of 672 hours in a climatic chamber under the testing conditions defined by ASTM D1375. Tests will be carried out at samples level.

In addition, some of the welded samples will be subjected to an SAE J 2334 test and they should resist a minimum of 120 days under this test conditions.

4.2.2.4. Weldability

The extruded profile part of the frontal frame will be weld to the HPDC and therefore, SALEMA extruded alloys should be weldable, and weldability will be a property that will be assessed during alloy development. CRF-Stellantis will conduct welding tests over specimens with an arc weld robot equipped with Cold Metal Transfer system.

As for the HPDC alloys, the weld beads will be validated with a micrographic inspection to see if the weld areas are in compliance with FCA specifications and with tensile tests of specimens machined with the weld beam within its calibrated section, in order to verify that the failure take place outside the joint area.

4.3. Selection of reference alloys

Two alloys have been selected as reference for further development in SALEMA project. These alloys will be used as:

- Alloy base for developing the addition of high scrap ratios and the potentially required micro-additions to compensate the high impurity level
- Reference in terms of properties and performance for the rest of HPDC alloys developed in SALEMA project

4.3.1. Main properties of 6063 alloy

6063 is one of the most used alloy in the extrusion process…..

ASAS is commonly producing extruded profiles of this alloy and it is the alloy intended for the Battery Tray Part that is going to be targeted in MARBEL project.

According to ASAS, the mechanical properties of 6063 alloy in T6-T7 condition are the following:

- Yield Strength (ReH) = 200-240 MPa
- Ultimate Tensile Strength (Rm) > 215 MPa
- Elongation at Break (A) > 10 %

In addition to the tensile properties of the alloy, in ASAS alloy datasheet it is also stated that this alloy is able to stand an angle higher than 120° in 3-point bending test for 2 mm wt.

4.3.2. Main properties of 6082 alloy

In order to reach the high mechanical properties requested by the frontal frame the 6082 alloy has selected.

This is an alloy with higher mechanical performance than 6063 alloy, that ASAS is using for extruded profiles with high requirements of strength.

According to ASAS, the mechanical properties of 6082 alloy in T6-T7 condition are the following:

- Yield Strength (ReH) = 280-320 MPa
- Ultimate Tensile Strength (Rm) > 290 MPa
- Elongation at Break (A) > 10 %

In addition to the tensile properties of the alloy, in ASAS alloy datasheet it is also stated that this alloy is able to stand an angle higher than 90° in 3-point bending test for 2 mm wt.

4.4. Final alloy requirements and validation criterion

4.4.1.1. Mechanical properties (tensile test)

In order to validate SALEMA project alloys tensile test according to EN ISO 6892-1 standard will be conducted to a minimum of 3 specimens. The minimum requirements that all 3 specimens shall meet are the same as defined for HPDC, as the requirements of the common demonstrator (Frontal Frame) are the most restrictive:

- Yield Strength (ReH) = 180 MPa
- Ultimate Tensile Strength (Rm) = 230 MPa
- Elongation at Break (A) = 10 %

4.4.1.2. Bending test

The assessment of mechanical properties in WP1 will be done exclusively with tensile test, as the available amount of material will be very reduced.

Bending resistance will be evaluated in WP6, with the extruded profiles obtained at IMN and, subsequently, in the final Battery Tray and/or Frontal Frame demonstrator components.

SALEMA alloys will be subjected to a 3-point bending test according to the VDA 238-100 standard, with samples with 60 mm length and 30 mm width. This standard is intended to test materials bending characteristics to estimate their deformation and crush behaviours. The test operates with a bending knife which has got specific dimensions according to VDA 238-100 and applies force to the extracted plate which has been located up to two fixed rollers to bent the specimen. The test should be conducted applying a certain level of force defined on VDA 238-100 standard. The test should be stopped when a force loss has been occurred. After bending has been completed, flat plates turn into the V shape. The outer angle of bent plates (the angle that supplements to 180°) should be measured with goniometer. Generally the requirements of bending angles have been addressed according to the 2 mm wall thickness. If wall thickness of the extracted portion of sample is different from 2 mm. Outer angle should be normalised to make them comparable on macro level. The formula which has been given below should be used to calculate normalised angle.

$$\propto_{normalised} = \alpha_{measured} \times \frac{\sqrt{wt}}{\sqrt{2}}$$

The requirement requested for an alloy with a yield stress in the range of 200-240 MPa is 120° on normalised angle calculation.

4.4.1.3. Fatigue requirements

The assessment of fatigue requirements will be done in two stages:

- In WP1 alloys only tensile tests will be conducted, as described previously for HPDC requirements.
- In WP6 fatigue tests will be conducted following the same procedure described in section 1.4.1.3 for the HPDC parts.

4.4.1.4. Crash performance

For the evaluation of the crash performance of SALEMA extrusion alloys 2 different methods will be used and compared:

1. A quasistatic crush / crash (compression) test will be used. An initial extruded hollow profile of, normally, 2 mm thickness will be compressed at a rate of 100 mm/min to 200 mm of compression path. After the tests the specimens will be visually inspected to assess the appearance of cracks.
2. Alternatively, Eurecat will also use the approach of the Essential Work of Fracture (EWF) described in HPDC requirements.

4.4.1.5. Corrosion properties

To assess the corrosion properties of extrusion SALEMA alloys, the profiles extruded by IMN in WP6 will be subjected to 6 hours of corrosion test according to ASTM B638-97 standard, followed by a stay of 672 hours in a climatic chamber under the testing conditions defined by SAE J2635. The acceptance criteria for SALEMA alloys will be, that after this double corrosion test, the cracks in the scratched area should have less than 2 mm of propagation.

The same procedure will be conducted over the 2 final extruded demonstrator parts, which should also meet the same requirement described for the industrial laboratory trials.

4.4.1.6. Thermal stability test

In order to assess the effect of paint bake and the resistance to the exposure at high temperatures tensile tests following the same EN ISO 6892-1 standard will be conducted in specimens after being subjected to an exposure at hight temperature for a certain time:

- 45 min at 195°C or 1 h at 200°C (to be determined later). The minimum mechanical properties after the high temperature exposure should be:
    - Yield Strength (ReH) = 180 MPa
    - Ultimate Tensile Strength (Rm) = 230 MPa
    - Elongation at Break (A) = 10 %

- 500 h at 120°C or 1000 h at 150°C (to be determined later). The minimum mechanical properties after the high temperature exposure should be:
    - Yield Strength (ReH) = 180 MPa
    - Ultimate Tensile Strength (Rm) = 230 MPa
    - Elongation at Break (A) = 10 %

4.4.1.7. Weldability

CRF-Stellantis will conduct welding tests over specimens with an arc weld robot equipped with Cold Metal Transfer system.

The weld beads will be validated with a micrographic inspection to see if the weld areas are in compliance with FCA specifications, and with tensile tests of specimens machined with the weld beam within its calibrated section, in order to verify that the failure take place outside the joint area.

4.4.1.8. Process requirements: extrudability

In order to assess alloy extrudability IMN will conduct tests in two stages.

First, compression tests at elevated temperatures (400°C - 500°C) and the strain rate similar to the industrial plastic working processes will be performed. The results of the tests performed will be the input data for determining the parameters of the extrusion process for the tested materials.

In the second stage, the tests of the extrusion process based on the results of the compression tests will be carried out on a semi-industrial technological line consisting of a horizontal 5MN press with (direct/indirect) equipped with a runout with a cooling system, and an induction heater.

Parameters of the extrusion process will be developed (such as temperature, extrusion speed and elongation factor) allowing to obtain profiles with assumed mechanical properties.

4.4.1.9. Amount of recycled material: Alloy Criticality Index

The Criticality Index is a concept that considers the different aspects that European Commission takes into account to establish a material as a Critical Raw Material (CRM) and gives a value, pondering all these aspects.

For SALEMA partially recycled alloys, it will be considered that the end-of-life scrap has a Criticality of 0, at it is a material available in between European borders and which provision does not comport any risk or criticality.

Currently ASAS is using about 20 % of end-of-life scrap to produce 6063 and 6082 aluminium alloys. The objective of SALEMA project will be to increase this amount to 60-70 % with better aluminium scrap selection.

5. Conclusions and Outlook

The present document summarizes the required properties and stablishes the criteria for assessing the performance of SALEMA alloys for the different processing technologies. The general overview of the document can be summarized as:

- The general requirements for the 5 demonstrators have been defined, establishing the required mechanical properties, as well as any further specific requirement for its application
- The base alloys for further analysis and development have been stablished for each processing route, defining the current performance of those alloys reached by the corresponding alloy developer
- The tests and assessing criteria used to evaluate alloy performance have been defined, stablishing which tests will be done at the different alloy development stages

Annex 1: Aluminium Alloys for Electric Cars: base-line concepts

1. Metallic alloys for car structure

1.1. Design requirements for car structure

With the aim of assessing the best alloys required in a car body production, to obtain the maximum weight reduction, a clever strategy consists in evaluating the design requirements of each part (crash performance, stiffness and so on), analysing the suitability of actual used alloys and finding alternatives. If two or more alloys are found to fulfil the design requirements for a certain body car part, the lightest one will be the optimal choice.

Naturally, the car components requirement will depend, among the others, by the car class. Therefore, in this review it was chosen, as reference vehicle, the one described in the EC-project "SuperLightCar" (SLC) (Fig. 1) [1].

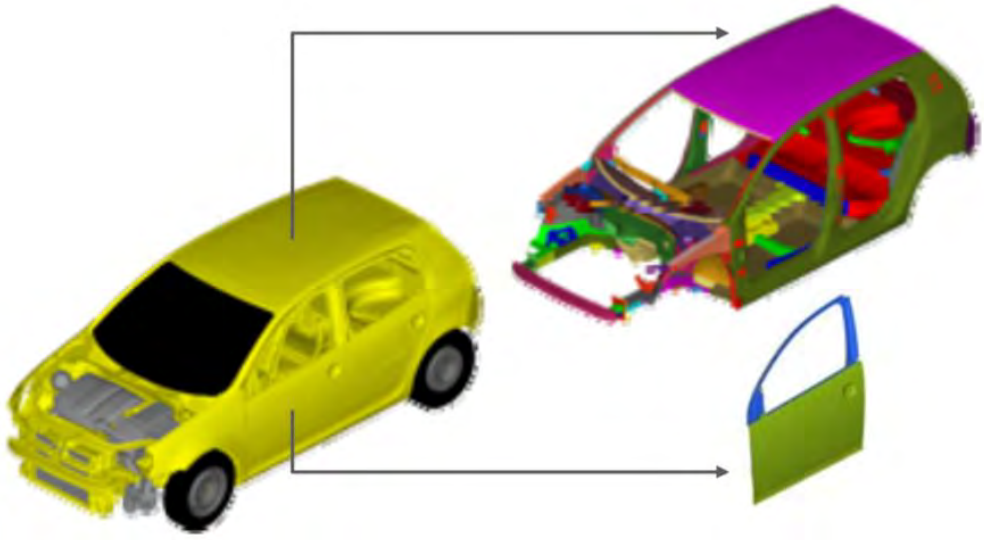
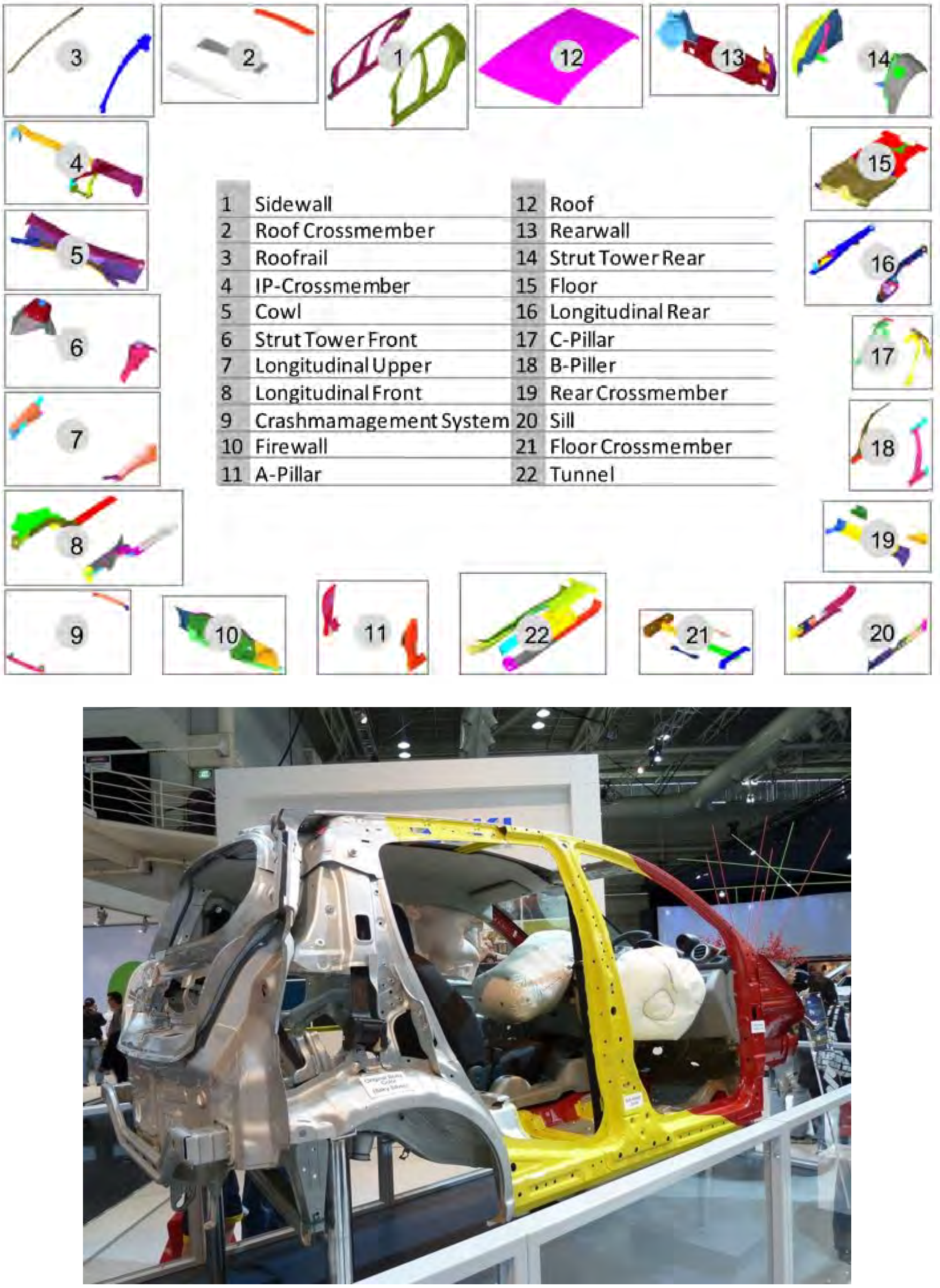


Fig. 1 – SLC-reference FE-model [1]

The target properties considered by designers are stiffness and strength for their specific relevance in crash performance. The parts requirements are quantified in literature by numerical simulation using a proper body-in-white subdivision as shown in Fig. 2.

Fig. 3 summarizes the stiffness relevance of the body-in-white components combining bending stiffness relevance with torsional stiffness relevance. The stiffness relevance of each component is represented by a value between 0 and 1 with 1 meaning highest stiffness relevance. In general, the results are according to expectations. Components that are typically known to have a strong influence on the static body stiffness like the suspension strut towers or the sill, show high relevance values.

Similarly, it is possible to evaluate, by numerical simulation, the relevance of the strength on crash test. Fig. 4 summarized the results found in literature.



1	Sidewall	12	Roof
2	Roof Crossmember	13	Rearwall
3	Roofrail	14	Strut Tower Rear
4	IP-Crossmember	15	Floor
5	Cowl	16	Longitudinal Rear
6	Strut Tower Front	17	C-Pillar
7	Longitudinal Upper	18	B-Piller
8	Longitudinal Front	19	Rear Crossmember
9	Crashmamagement System	20	Sill
10	Firewall	21	Floor Crossmember
11	A-Pillar	22	Tunnel

Fig. 2 – Subdivision of body-in-white into 22 components [1]

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003785

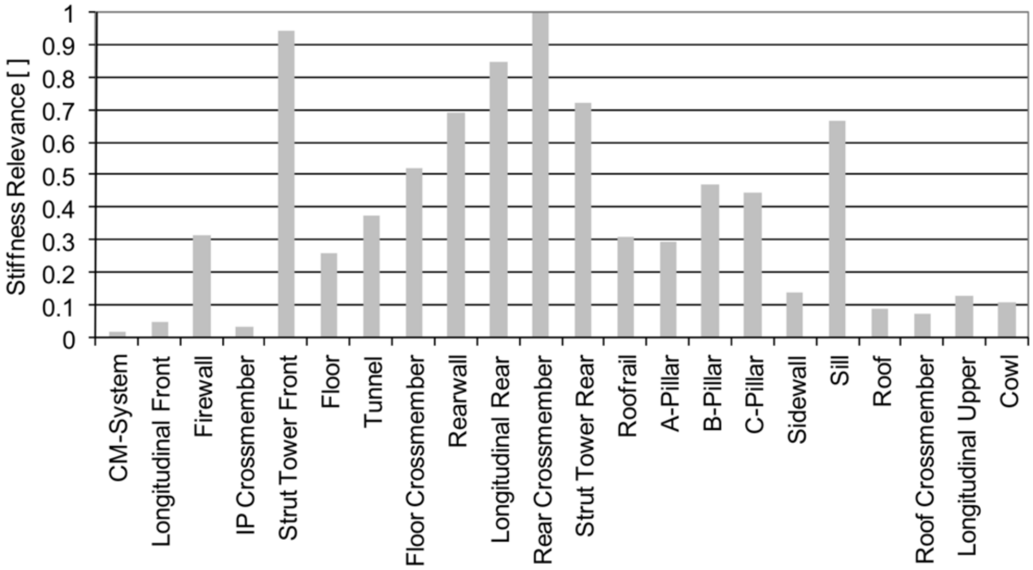


Fig. 3 – Stiffness relevance of body-in-white components for all load cases [1]

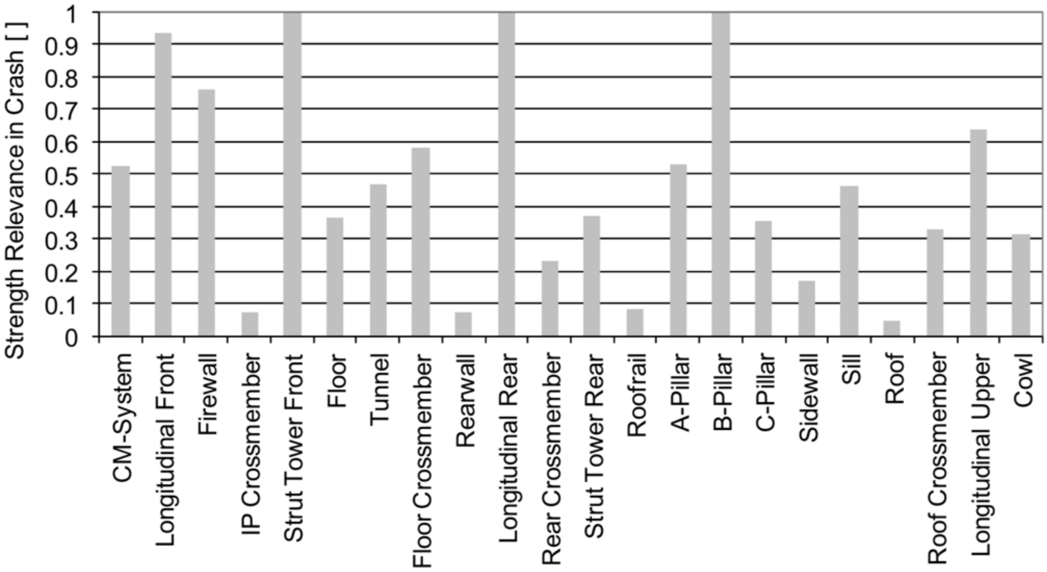


Fig. 4 – Strength relevance in crash of door components [1]

As expected, it is interesting to note that components that are typically known to have a strong influence on the structural crash performance like the B-pillar, the longitudinal members, the CM-system but also the strut towers, show high relevance values. Using datasheets of today cars producers, the alloy yield stress chosen for each component is summarized in Fig. 5 as a function of the class. Components made of ultra-high strength steels (UHSS) are highlighted in blue, while those ones made out of conventional steels are marked in red. Results of Fig. 5 can be compared with those obtained by numerical simulations in order to verify their suitability (Fig. 6). Components typically made of conventional steel have low yield strength. In addition, they also have low demands on stiffness and crash, except in the strut tower front. That might be a reason, why this component is already realised as an aluminium part in vehicles like the BMW X5. On the other side all components that are highlighted as parts typically made from UHSS have higher values for the yield strength. In most cases, these components have high demands on strength in case of a crash. Finally, data can be summarized in a graph that combines the stiffness relevance and the strength relevance in crash (Fig. 7). The diagram is separated in three areas. Components in the upper left part of this diagram have high stiffness relevance and low strength relevance in crash. The components in the lower right part have low stiffness relevance and high strength relevance in crash. In the middle area components can be found that are important concerning stiffness as well as strength in case of a crash.

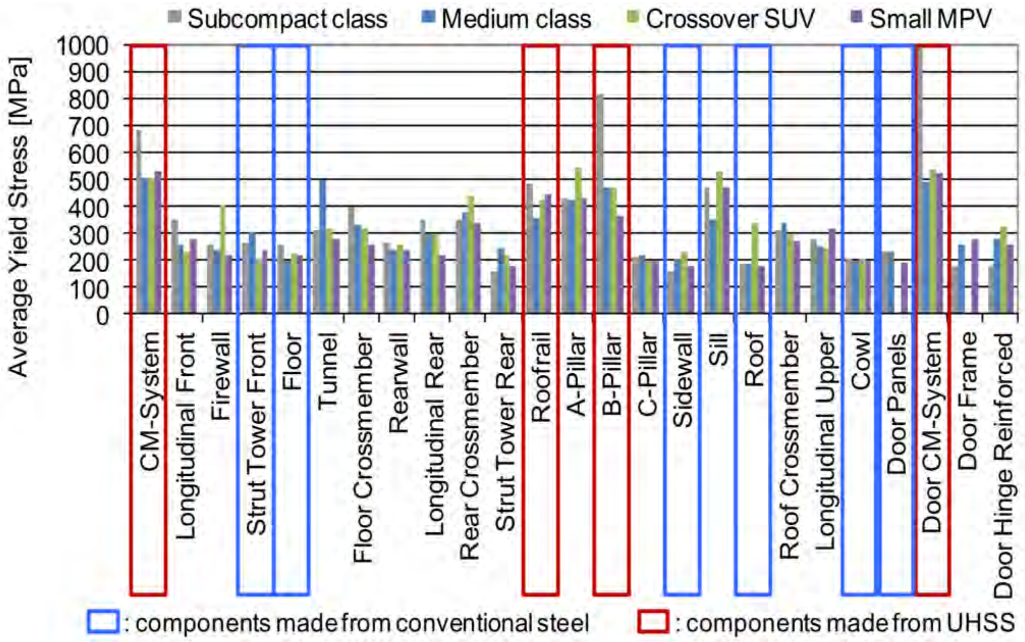


Fig. 5 – Comparison of material usage in all classes [1]

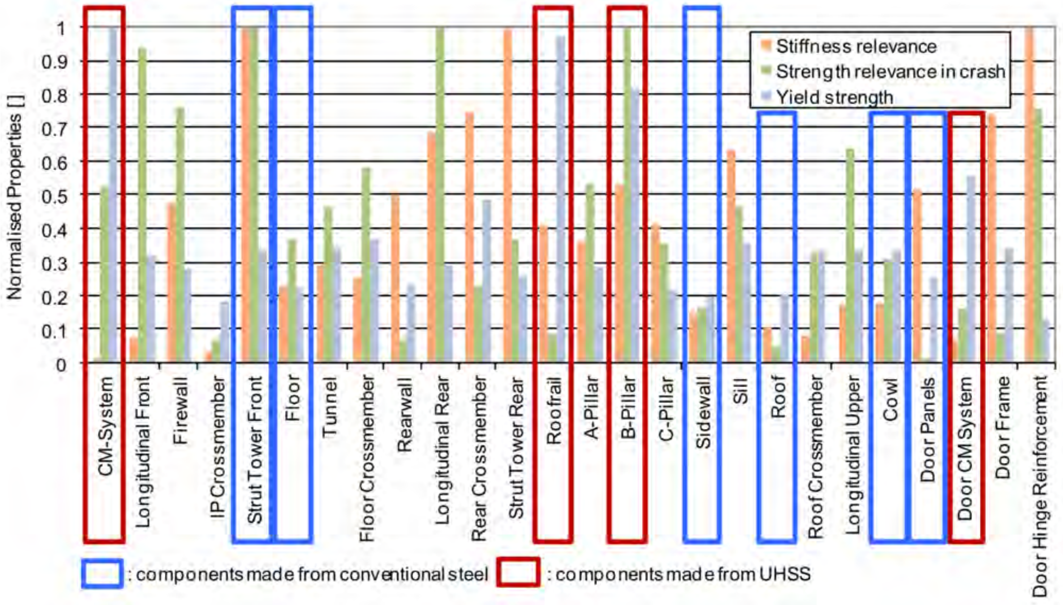


Fig. 6 – Overview of the evaluation results [1]

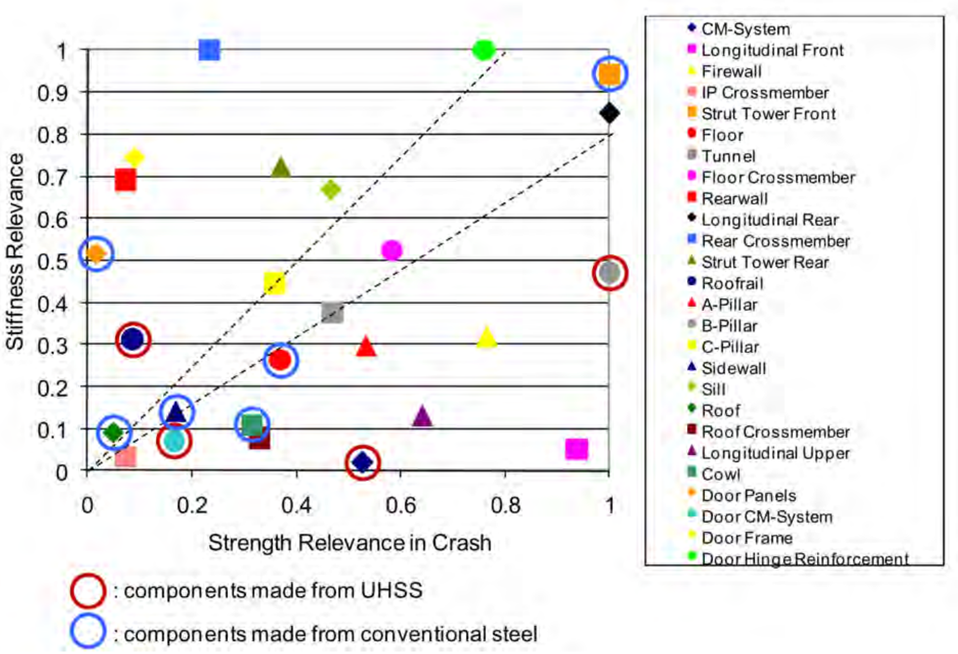


Fig. 7 – Evaluation of the UHSS body components [1]

1.2. Moving from steels to Aluminium alloys

Moving from steels to aluminum alloys should follow the same strategy that differentiate the alloy grade according to its capability in fulfilling the single component requirements (stiffness versus strength relevance in crash performance). The re-design of the electric vehicle using aluminum alloys only is the new challenge in the automotive sector [2]. It is addressed to all parts of the body-in-white, the front and rear armatures and the hang-on parts such as doors, closures and front fenders. The previous analysis regarding loads and constraints to be considered in design can be maintained. The bill of aluminum alloys the designer can account for is summarized in Table 1; while the corresponding specific parts of the vehicle are schematized in Fig. 8.

Alloy	Function	R_{p02} value [MPa]
5xxx	Structural sheet	150
6xxx	External skin sheet	250
6xxx	Structural sheet	200
6xxx	Structural sheet	250
7xxx	Structural sheet	400
6xxx	Extrusion for beam parts	280
6xxx	Extrusion for beam parts	320
6xxx	Extrusion for crushed parts	200
6xxx	Extrusion for crushed parts	280
AlSi10Mg	Die casting	140 MPa

Table 1 – Overview of used aluminum alloys [2]

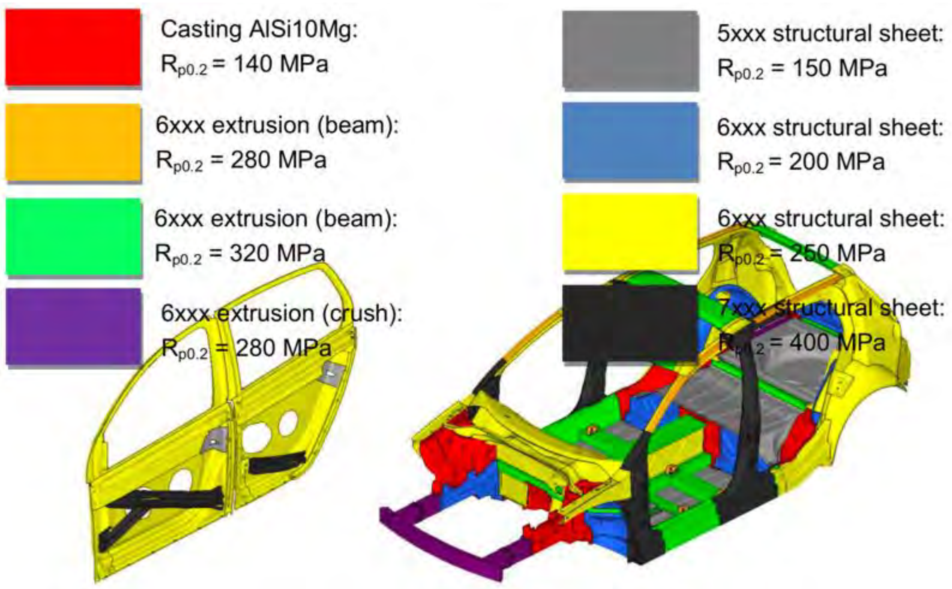


Fig. 8 – Material attribution to body-in-white, armatures and doors for target vehicle model [2]

Fig. 9 differentiates the aluminum alloy components of a car produced via sheet forming, extrusion and casting. For the sake of simplicity, compared to the previous analysis that used AHSS, only the thickness of the sheets was changed to take into account the different alloys mechanical properties. On the other hand, the car frame was completely redesign with the aim to improve the crash performances, as schematized in Fig. 10.

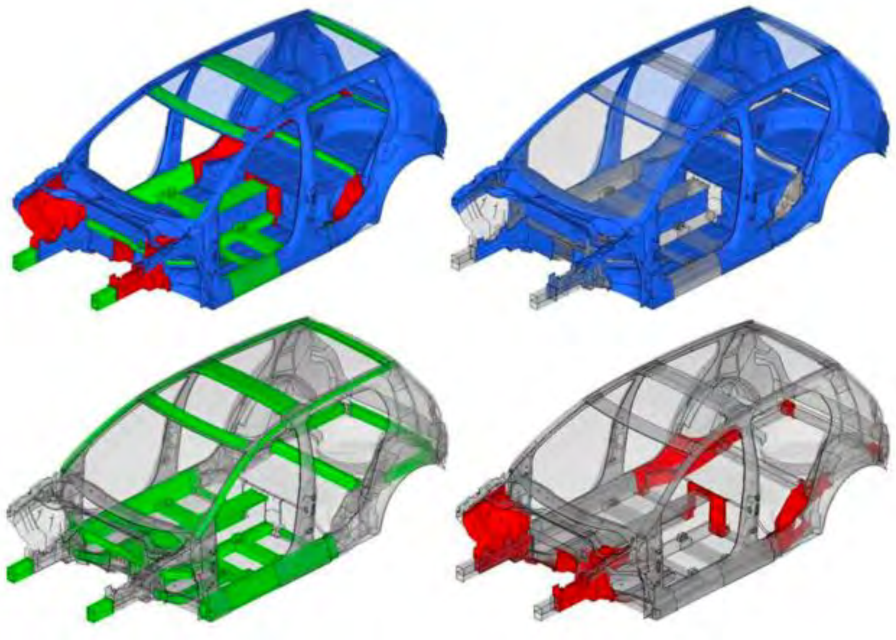


Fig. 9 – Application of aluminum manufacturing methods to the target vehicle model (blue: sheet, green: extrusion, red: casting) [2]

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003785

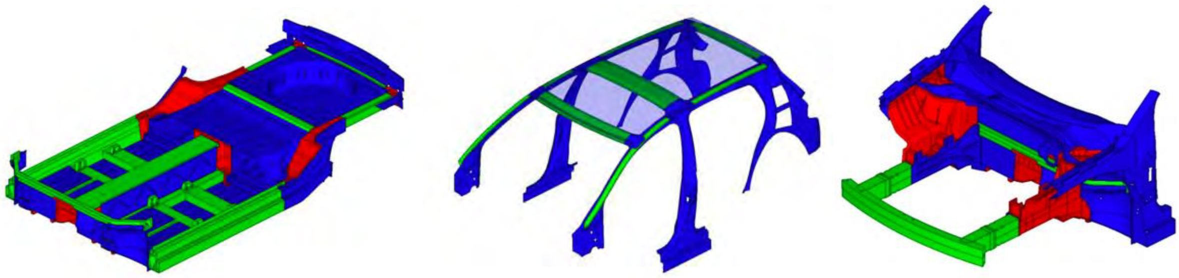


Fig. 10 – Schematic of target vehicle model floor, target vehicle model roof and target vehicle model front, respectively [2]

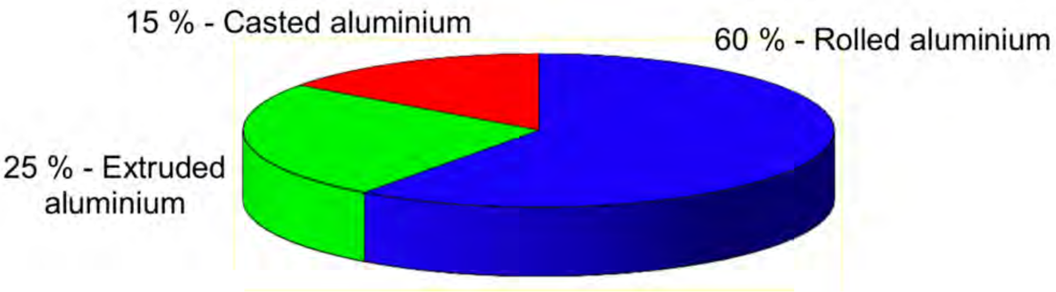


Fig. 11 – Distribution of aluminum manufacturing methods over the target vehicle body [2]

The complete body structure involves 213 kg of aluminum, distributed over the different Aluminium manufacturing methods (Fig. 11)

Considering only the crash performances and the electric reference vehicle made out of HSS and AHSS, a considerable weight saving can be reached by replacing steels with aluminum alloys as described in Table 2.

	Electric reference vehicle [kg]	**Target vehicle model [kg]**	**Weight reduction [%]**
Body-in-white	272	151	-44
Doors (one side)	30.2	19.2	-36
Fenders (one side)	2.40	1.28	-47
Armatures	12.5	7.53	-40
Closures	24.8	14.0	-43
Total body structures	375	213	-43

Table 2 – Involvement of steel in electric reference and of aluminum in target vehicle structure [2]

1.3. Cost and sustainability issues

Keeping these good results in mind, cost estimation is mandatory to assure a successful use of Aluminum alloys in e-vehicle production. A first analysis, made in 2015, resulted in a production cost increment of about +1000 € if the electric reference vehicle made out of HSS/AHSS is completely re-built using aluminum alloys only. However, this cost increment should be compared to the battery cost saving induced by weight reduction coming from the use of aluminum alloys. This cost saving is estimated to be about 1600 €, which makes the aluminum alloy eclectic car more convenient compared to steel electric vehicles. These concepts introduce to the life cycle assessment topic. In this analysis, the metal supply for the steel parts as well as for the aluminum parts is supposed to correspond to the European average, i.e. *40 % from recycling and 60 % from primary production* for both metals. The use phase assumes a total mileage of 150,000 km, corresponding to 1000 charging cycles while only the recycling of the two vehicle structures (steel and aluminum vehicles) is considered at the end of life. The LCA results are summarized in Table 3.

Results for the full life cycle		**Electric reference vehicle [kg]**	**Aluminium target vehicle [kg]**	**Difference [kg]**
Greenhouse Gas Intensity (kg CO_2-Equiv)	Production	735	1105	+370
	USE	14086	12901	-1185
	EoL benefits	-300	-980	-680
	Total	14521	13026	-1495

Table 3 – Greenhouse Gas (GHG) emission balance summary for the electric reference and the aluminum target model [2]

Even if benefits from the end-of-life (EoL) stage of the vehicle are not considered, the break even point is at about 47,000 km. This means that the higher greenhouse gas intensity resulting from the production phase of the aluminum target vehicle is rapidly recovered over the use phase, due to the lower energy consumption than for the heavier electric reference vehicle (Fig. 12)

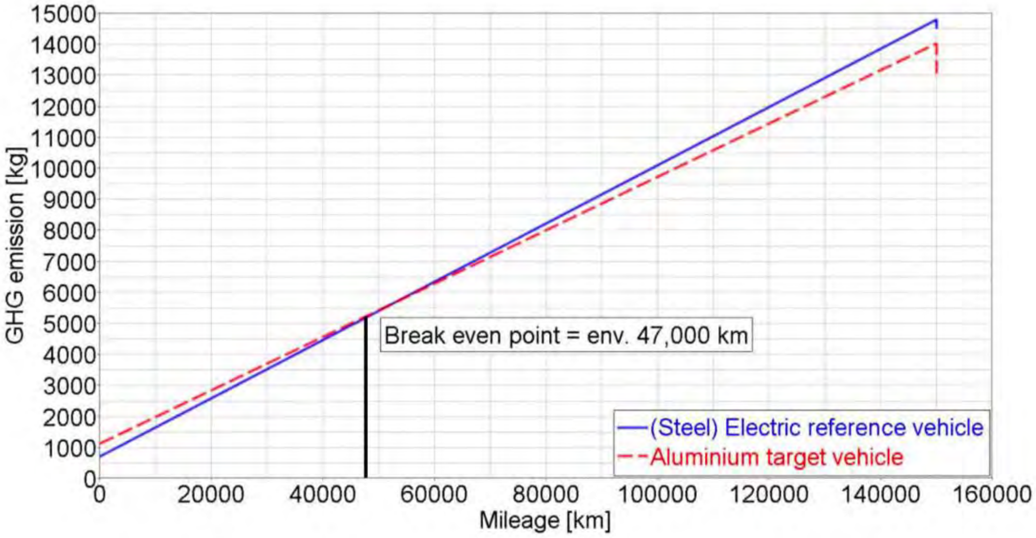


Fig. 12 – Comparison of Greenhouse Gas (GHG) emission over full life cycle for aluminum target and electric reference vehicles [2]

It is easy to observe, by a simple sensitivity analysis, that a possible greenhouse gas intensity reduction of electricity production by 50 % will still result in a more advantageous use of aluminum alloys as described in Table 4.

Results for the full life cycle		Electric reference vehicle [kg]	Aluminium target vehicle [kg]	Difference [kg]
Greenhouse Gas Intensity (kg CO_2-Equiv)	Production	735	1105	+370
	USE	7043	6451	-592
	EoL benefits	-300	-980	-680
	Total	7478	6576	-902

Table 4 – GHG emission balance summary for the electric reference and the aluminium target model after 50 % reduction of use phase GHG intensity [2]

If the GHG intensity of the electricity production is reduced by 50 %, the breakeven point between the aluminium target and the electric reference vehicle is delayed to mileage values around 94,000 km, i.e. corresponding to double the distance. Still, the advantage of intensive aluminium use in electric vehicle's structure is visible already during the vehicle's use phase (Fig. 13).

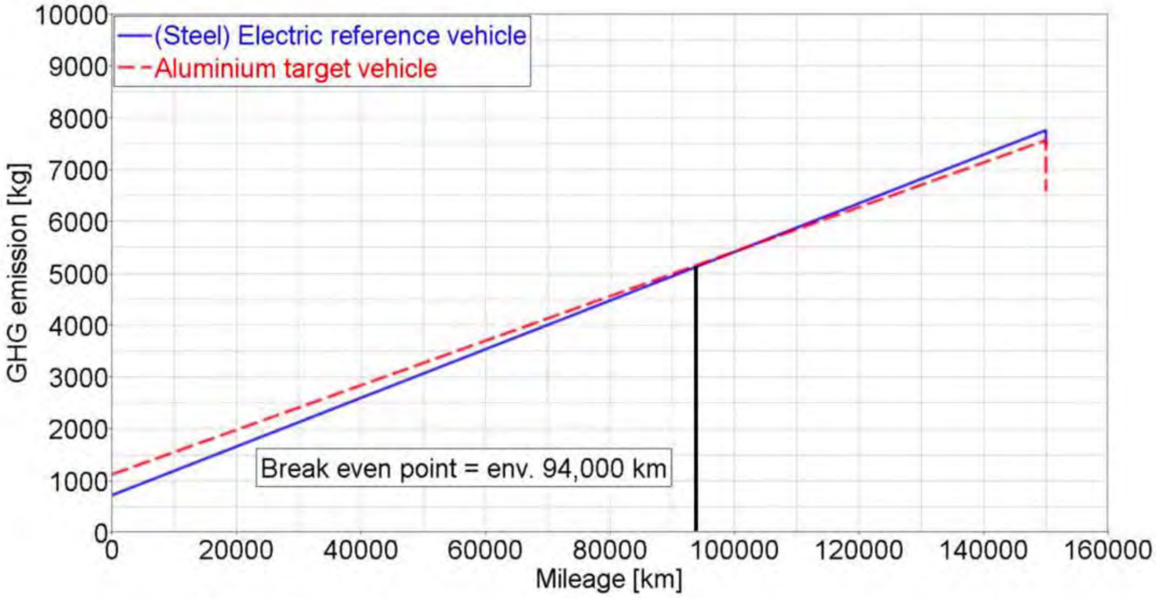


Fig. 13 – Comparison of GHG emission over full life cycle for aluminium target and electric reference vehicles with 50 % emission reduction over use phase [2]

1.4. The role of Critical Raw Materials

Focusing on Aluminium alloys, it is noted that they can suffer from a criticality issue, according to European Community (EC) [3]. As a matter of fact, the European Commission is used to investigate which raw material is considered critical according to different criteria or indicators that quantify the economic importance (EI), the supply risk (SR), the recyclability input rate, the substitutability issue, etc. The critical raw materials list is updated every three years and the last report dates September 2020. The impact of these aspects on Aluminium-based alloys development is the main focus of WP2, and will be fully described and evaluated in the Deliverables associated to this WP.

1. Casting Aluminium alloys: processing & properties

1.1. Castability

Castability is the ability of an alloy to be cast without formation of defects such as cracks, segregations, pores or misruns. Alloy dependent phenomena that determine castability are fluidity, macro-segregation, hot tearing and porosity. These phenomena have been known for a long time but have only recently become well understood and work is underway to develop predictive castability models. These models require input of physical properties, such as solidification path, dendrite coherency, solidification shrinkage and interdendritic permeability [4-6]. Some of these properties are difficult to determine experimentally, and two approaches can be followed:

- Evaluation of viscosity, based on models taking into account thermos-physical properties of pure metals and combining them to predict behaviour of alloys,
- Experimental test of fluidity, based on well-known systems.

Viscosity is used to describe the fluid resistance to flow, and it is the ratio of the shearing stress to the velocity gradient. Therefore, viscosity is a very important physical property of melts for the solidification simulation of the industrial cast metals and the modelling associated with fluid flow. In general, viscosity varies with the temperature and composition of the liquid and it can be measured using experimental techniques, such as the capillary and oscillating vessel methods. However, it is time-consuming and expensive to realize the viscosities of ternary or multi-component melts.

Various testing methods have been developed to evaluate fluidity of alloys. Such methods and related procedure have to monitor all the variables affecting the fluidity, with the aim to limit undefined fluctuations of them, which decrease results' comparability. These variables are listed below: pouring and mould temperatures, geometry and cross section of the mould cavity, surface tension, thermal conductivities of both metal and mould, metal-mould heat transfer coefficient, chemical composition and solidification range, cleanliness of the bath (inclusions, oxides), flow rate, metallostatic pressure, environmental conditions (temperature, humidity).

Spiral Fluidity Test

Liquid metal whose fluidity is to be determined is poured into a cylinder which terminates in a long thin cavity shaped like a spiral. The walls of this cavity might be sand or coated metal, heated or

unheated. Fig. 14 shows the principle of Spiral Fluidity Test, while Fig. 15 illustrates the typical realization for a laboratory spiral test [7]. The components of the equipment are:
- quartz sand cope and drag, with the cavity reproducing the spiral geometry;
- quartz sand pouring basin, which is placed over the cope;
- stopper, made by steel and equipped with a thermocouple.

The cope, drag and pouring basin are made by coldbox sand, which is compacted through mechanical force and catalysed with sulfur dioxide.

The stopper can be coated with a refractory paste in order to reduce the heat loss and to facilitate the cleaning operations after each pouring.

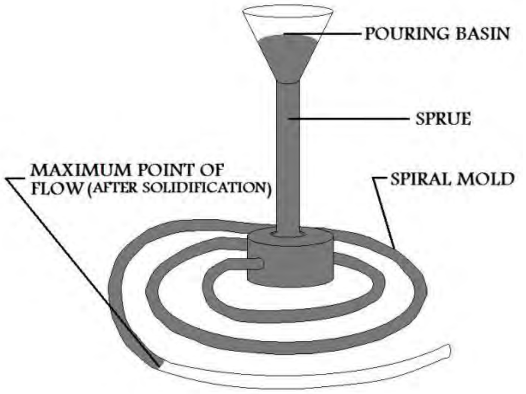


Fig. 14 — Description of the principle of Spiral Fluidity Test [7].

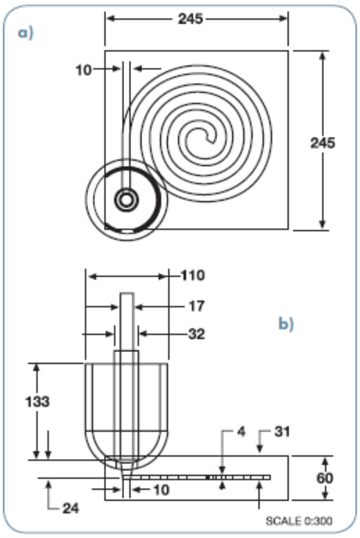


Fig. 15 — a) Top and b) side views of the spiral-shaped fluidity test [7].

<u>Vertical and Horizontal Vacuum Fluidity Test</u>

This method consists in measuring the length of the metal flow inside a narrow channel when sucked from a crucible by using a vacuum pump, according to the principle shown in Fig. 16. Velocity will be constant in both vertical and horizontal suction tests until the forces of gravity and pressure begin to

equalize. The vertical test is preferred over the horizontal test because the experimental setup is seen as being simpler to assemble, as the glass (or metal) tubes do not need an L shaped bend.
The graphite crucible can be placed into a ceramic container and internally coated by a boron nitride film; the system is located into an electric resistance furnace. The homogeneity of heating is controlled by means of two thermocouples (K-type), one inside the furnace wall, the other into the molten metal. A typical apparatus used for this test is shown in Fig. 17, with all the needed devices.

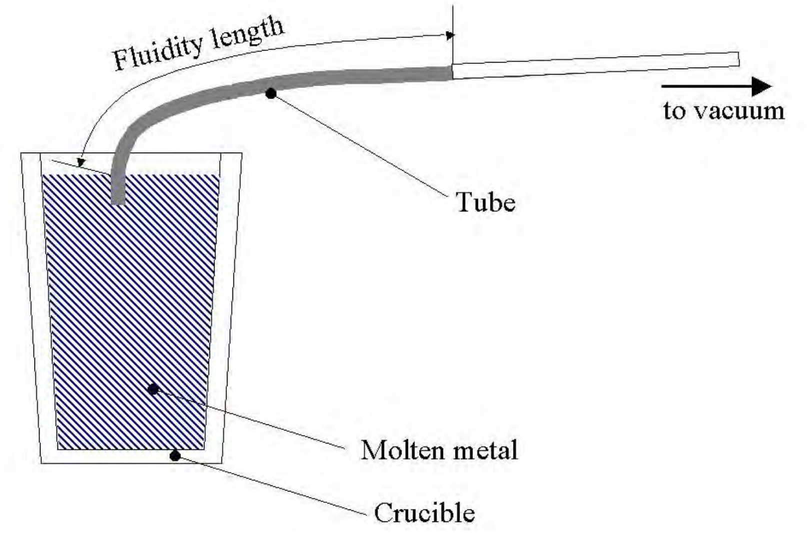


Fig. 16 — Description of the principle of Horizontal Vacuum Fluidity Test [7].

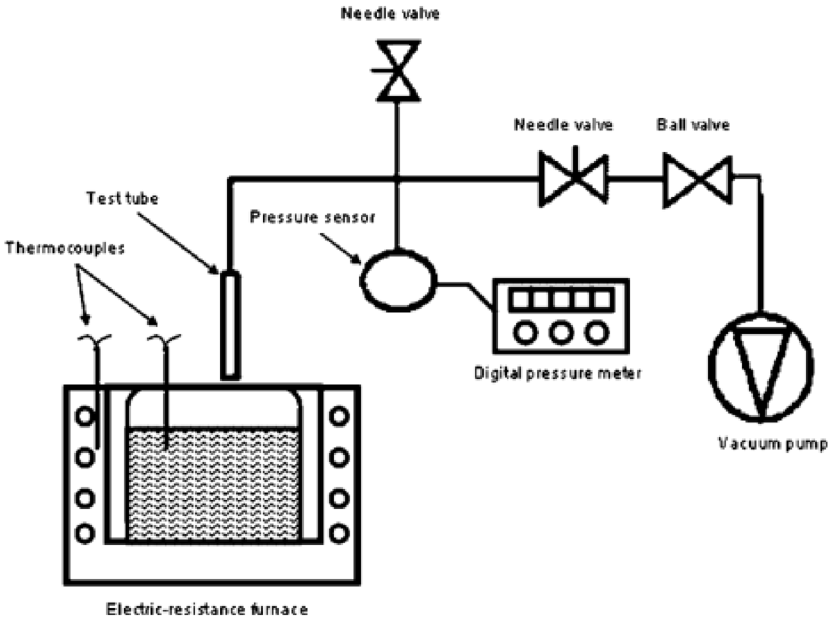


Fig. 17 — Description of the Vertical Vacuum Fluidity Test apparatus [7].

The project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003785

Fluidity strip mould Test

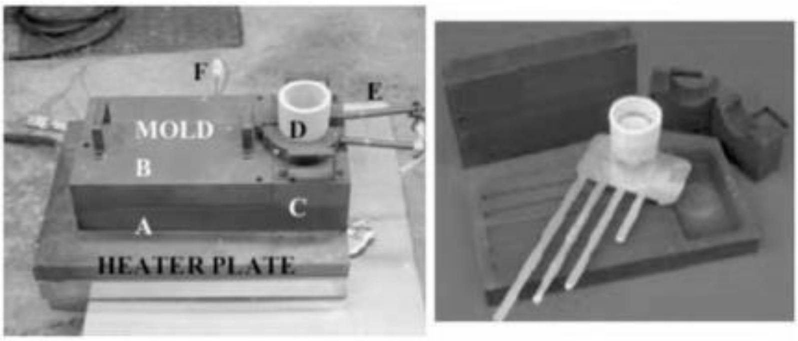
The fluidity mold (Fig. 18) consists of the following parts :

- drag consisting of five channels (fingers) of identical lengths and different cross sectional areas (Fig. 19);
- flat mold cope;
- gating system split in two semi-cylinders;
- KalpurTM sleeve, held in place by a clamp ring on the top of the gating system.

The fluidity mold has to be placed on a heater plate in order to pre-heat the mold and precisely control the temperature cycle of the mold during the experiments. The mold temperature has to be measured by a calibrated 'K' type thermocouple placed in the middle part of the drag. The total volume of the solidified alloy in the five channels must be calculated and reported as a fluidity index:

$$V = \sum_{1}^{5} A_i \cdot L_i \qquad (1)$$

where V is the total volume (mm^3), A (mm^2) and L (mm) are the cross sectional area and the length of each channel, respectively.



a) b)

Fig. 18 — Components of the commercial Fluidity strip mould (A-drag, B-cope, C-gating system split into two semi-cylinders, D-Kalpur sleeve, E-clamp ring, F-thermocouple); and b) view of the open mould with a fluidity test sample [7].

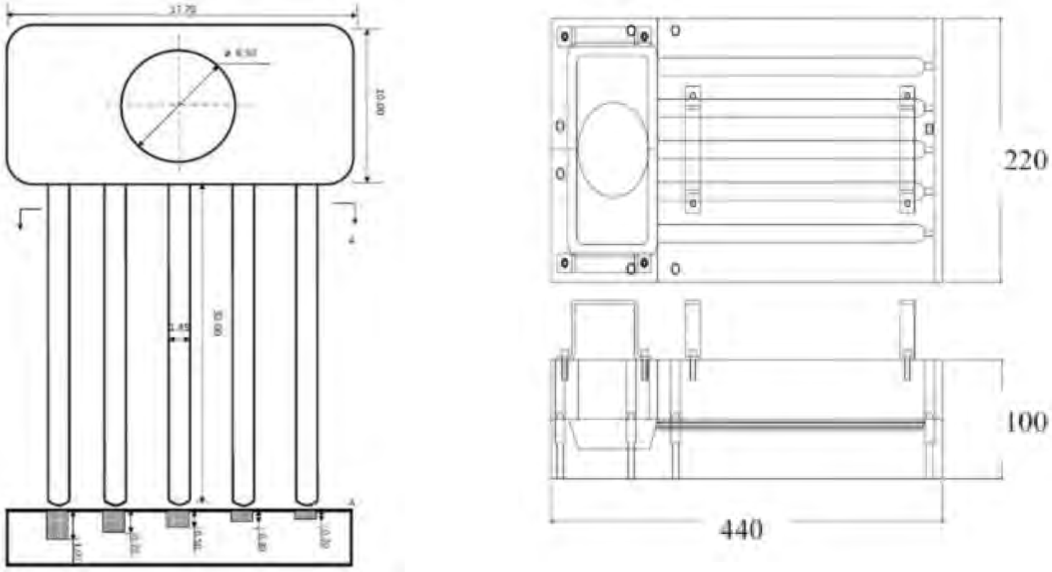


Fig. 19 — Design of Fluidity strip mould test configurations [7].

1.2. Avoiding die soldering phenomena

A relevant problem in HPDC processes is the genesis of die soldering phenomena, i.e. the formation of intermetallic compounds among Fe (from the steel die) and Al (from the alloy). Such compounds may

- Stick on the die surface (generating roughness in diecastings surface)
- Stick of the diecastings surface (damaging the die surface and making easier thermal fatigue phenomena).

Die soldering can be limited by a certain content of Fe in the alloy (but this is detrimental for the casting toughness and ductility). An alternative to Fe, to minimise die soldering risks, is the introduction of Mn in the alloy. The effect of Mn content on die wear has been studied in [8], where average wear on steel pins was used to calculate a die soldering index (DSI). The variation of this index with the manganese content is shown in Fig. 20 (lower DSI numbers correspond to longer die life). Commercial experience tends to confirm the results shown: the Mn-containing die casting alloys (such as AA 352 and 365) do offer improved die life compared to the first generation of low-Fe alloys. However, die life is still less than desired, when compared to that obtained with conventional, high Fe alloys. Particularly problematic is wear of the shot sleeve, caused by washout under the pouring hole.

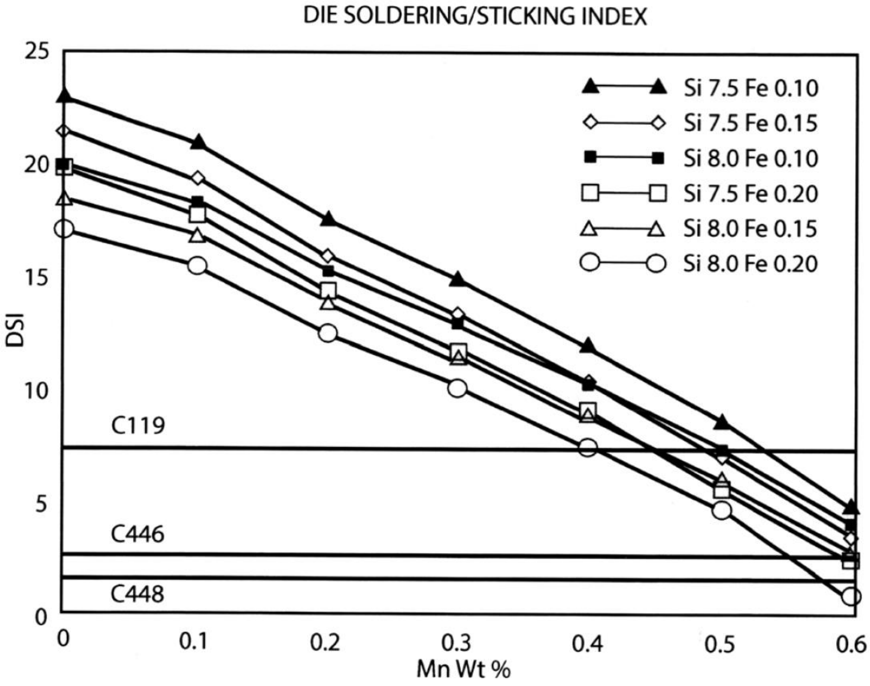


Fig. 20 – Die soldering index in several die casting alloys [8]

1.3. Distribution of properties

Unlike forging or other thermo-mechanical processes, the properties of shape Al alloy castings are almost entirely dependent upon the filling and solidification conditions, which should be considered during the design chain. For instance, from a stress-engineering viewpoint, thickening up a section of a component will lead to increased load-bearing capacity at that location. During casting, a thicker region will solidify more slowly and, for Al alloys, coarser microstructures will result in lower mechanical strength. Problems with feeding and shrinkage defects may also arise in thicker sections.

While the combination of high speed casting and high cooling rate can give the possibility of thin walled castings and high production rate, the associated turbulence remains a great source of inner and surface casting defects, which have deleterious effects on mechanical properties.

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In gravity and high-pressure die-casting, if a number of parameters is not adequately determined and adjusted, the quality of the die cast part results rather poor. Macro-segregation of eutectic, primary intermetallic and α-Al crystals, porosity, oxide bi-films and confluence welds are addressed as typical casting defects [9].
When designing and developing die cast components and process parameters, a great number of optimisation goals must be taken into consideration, e.g. dimensional accuracy, distortions of the component, casting defects. A useful approach in the development of die casting optimisation is the correct definition of the casting problems and their importance towards quality. Considering HPDC, casting defects are mentioned by foundrymen at first. Therefore, in case of a single optimisation goal, such as minimizing casting defects, an interactive optimisation cycle should be adopted to combine the changes of the die design, including the runner system and overflows, and the variations of injection parameters, such as the plunger speeds, the commutation point between the first and second phase (Figs 21-22).

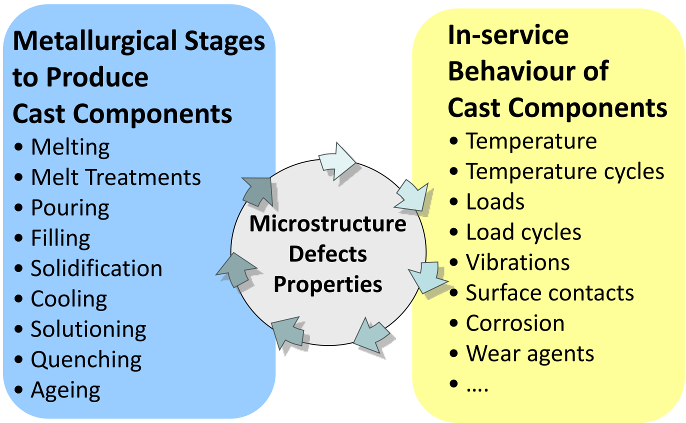

Fig. 21 – General approach to optimisation in design of Aluminium castings

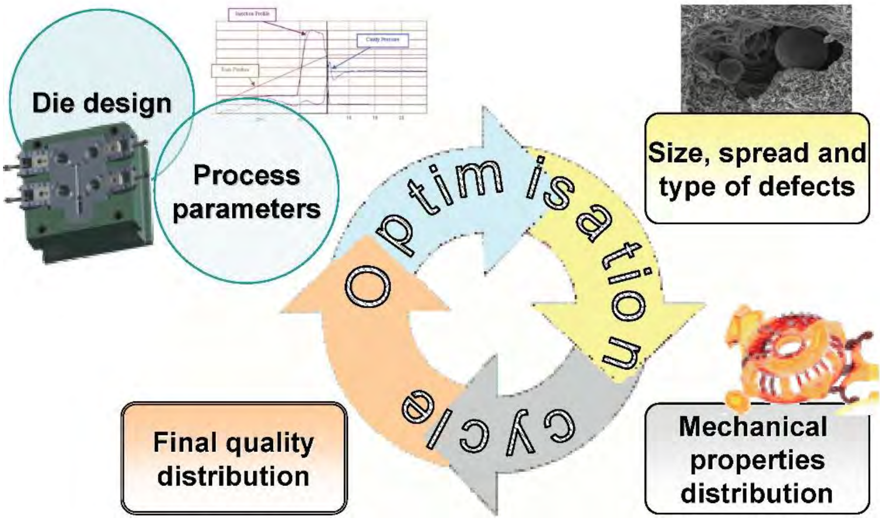

Fig. 22 – Specific optimisation cycle of a die cast component [9].

This is done in order to improve the final integrity of castings. If more optimisation goals are defined, different "good solutions" can be obtained. This however does not mean that the selected solution will be the best. With reference to the defined optimisation goals, it only represents the best compromise. On the other hand it cannot be completely concluded that there is not any solution that would fulfil the optimisations goals in full.

From another point of view, the variation of the casting parameters allows a more easy change of the casting quality, if compared to the expensive and time consuming machining operations of the die. Moreover, when speaking about traditional HPDC, it is common opinion that a certain amount of defects will be always entrapped within the die cast part, even if not optically revealed after subsequent machining. By means of the casting parameters' adjustments, foundrymen try to restrict and isolate the major part of defects into casting regions that will not be mechanically stressed during normal working. Further, thin-walled castings, like those produced by HPDC, are more affected by the presence of defects since a single macro-defect can cover a significant fraction of the cross-section area.

Quality of castings can be defined as being a measure of excellence or a state of being free from defects, imperfections and significant variations, where high quality is brought about by the strict and consistent adherence to measurable and verifiable standards to achieve uniformity of output that satisfies specific customer or user requirements [9]. The casting quality in engineering applications refers to reaching a suitable compromise drawn from among numerous factors which would produce minimum risk and maximum performance in conjunction with cost efficiency [9].

During the design stage of a component, the combined knowledge of the alloy expected strength, microstructure and presence of defects (an example is given in Fig. 23) is required. The knowledge of the expected strength of the alloys gives a view of the mechanical properties which can be achieved in optimized casting conditions. The way in which microstructure (which varies according to local solidification time in different regions of the cast components) influences mechanical behaviour constitutes another relevant issue. Lastly, the understanding of the way in which the expected strength of foundry alloys is limited by the negative effects of various kinds and amount of defects induced during the casting process is also fundamental. Often the formation of defects is sensitive to small variations in the casting conditions and the causes cannot be only connected to the process profile adopted, even if this variable results the main source of defects. Such a combined knowledge is matter of interest and interaction between foundry-men and mechanical designers.

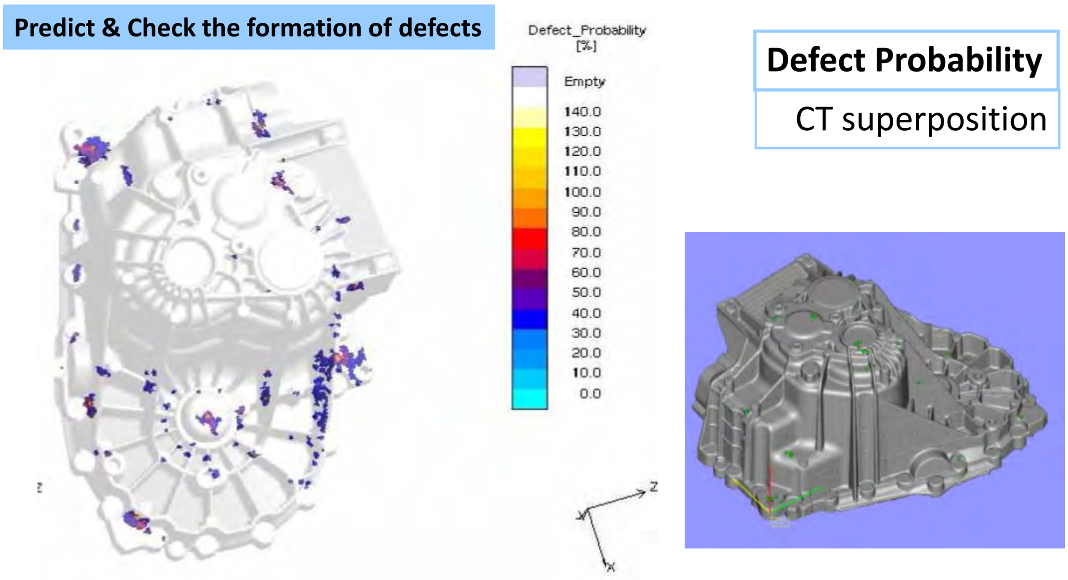

Fig. 23 – Example of defect distribution in an Al-alloy diecasting

However, the final mechanical behaviour of Al alloy die-castings is mainly controlled by defects size and amount; only when the presence of defects is avoided, microstructure (resulting from specific and local cooling conditions, see Figs 24-25) [10-11] becomes the controlling factor. This is because defect-containing regions in a tensile sample reduce load-bearing area and produce a concentration of strain. Particularly, castings with thin sections, such as those produced by high-pressure die-casting, are vulnerable to the effect of defects, since a single macro-defect could cover a significant fraction of the cross-sectional area [9].

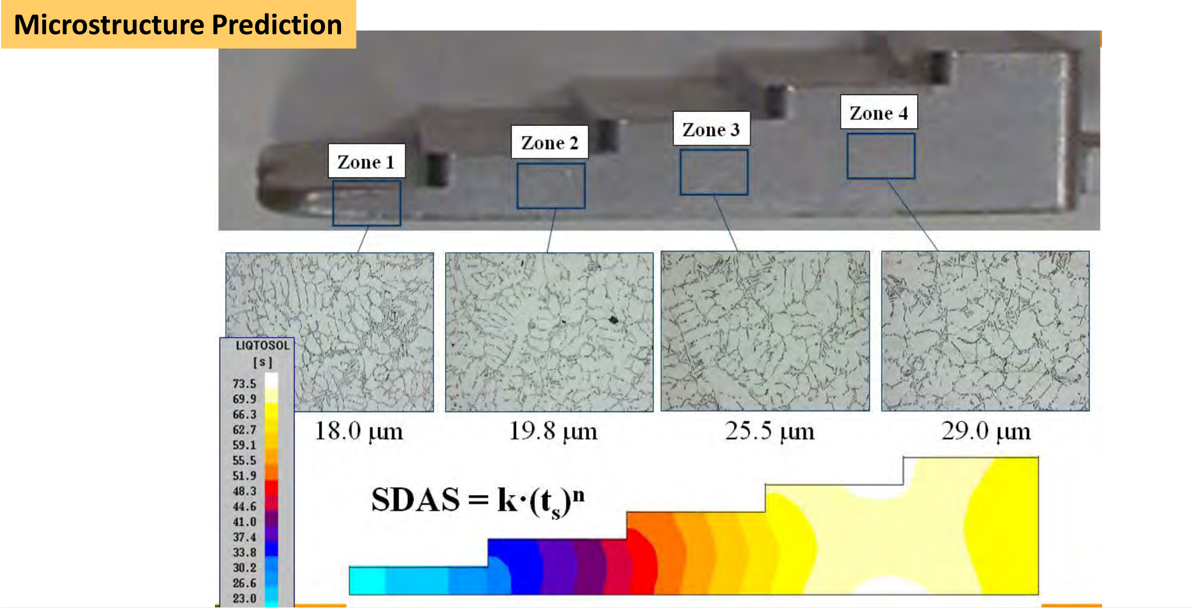

Fig. 24 – Example of correlation among casting thickness, cooling rate and microstructure (by SDAS, Secondary Dentrite Arm Spacing) [10]

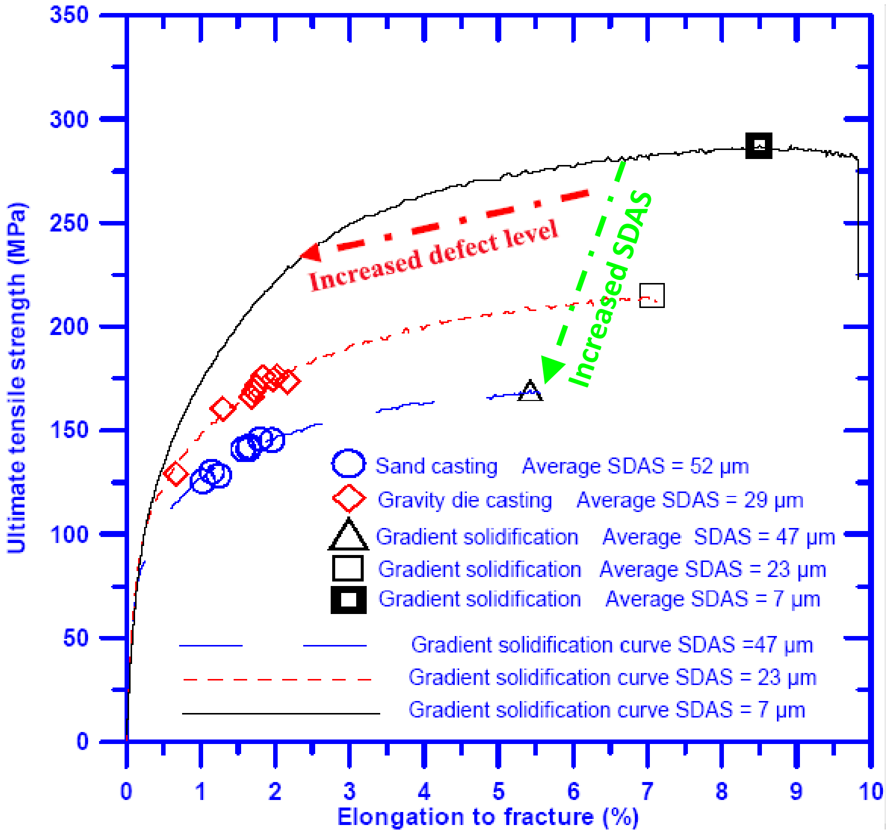

Fig. 25 – Example of correlation among casting process, cooling rate, microstructure (by SDAS) and mechanical behaviour [11]

The key-consequence of these complex interactions is that a multi-scale approach has to be considered when designing a component to be produced by casting of Aluminium alloys.

As shown in Fig. 26a-b, once considered macro-thermal and fluid-dynamics fields during filling and solidification, their effect on micro- and nano-structure evolution has to be taken into account, as well as the generated microstructural features (and defects) affect the mechanical behaviour. Furthermore, the role of heat treatment in modifying/improving properties is part of the discussion.
However, since different thicknesses in castings are generating different thermal fields, and thus different microstructure and properties, it appears clear than a HPDC components will be always characterised by a distribution of properties.

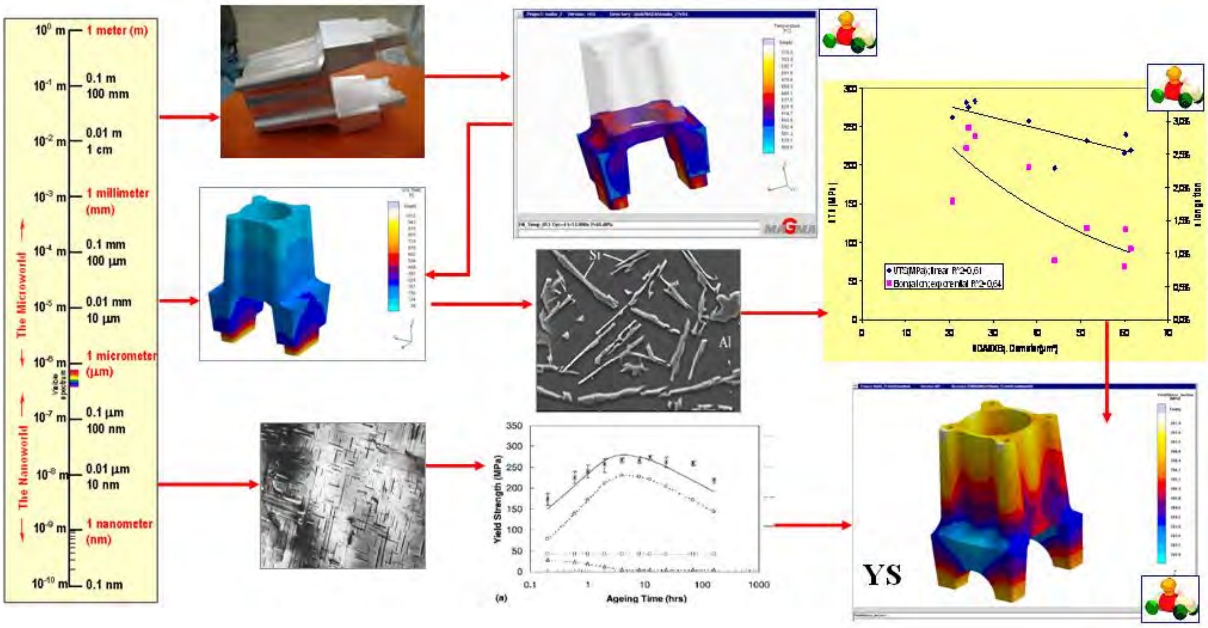

Fig. 26a – Multi-scale approach in designing Aluminium alloys castings

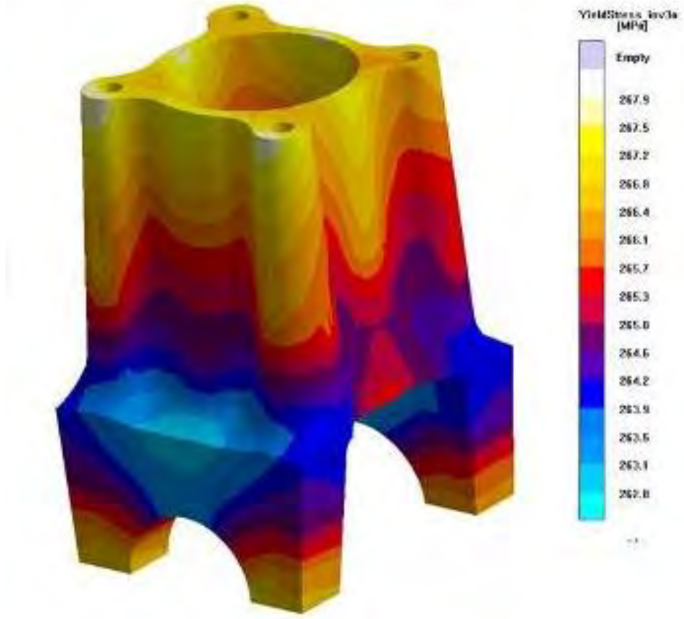

Fig. 26b – Example of YS distribution, as predicted in an Aluminium alloy casting, by means of the multi-scale design approach

A good experimental example of this situation is offered by the results reported below. On a structural HPDC casting (shock tower) tensile specimens have been achieved from different positions (with

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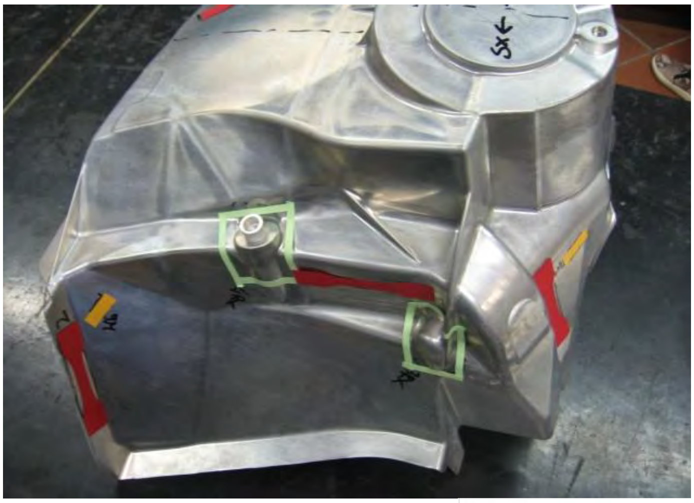
various size according to the local thickness), as shown in Fig. 27. Results of tensile tests are reported in Table 6 and in Fig. 28, showing relevant differences especially in terms of elongation.



Specimen	L_0	Thickness [mm]	Length [mm]
1	25	2,3	10
2	25	1,85	10
3	35	2,8	10

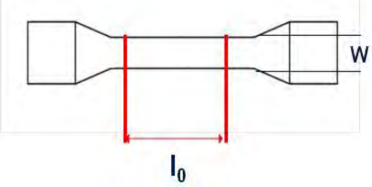


Fig. 27 – Specimens extraction form a structural HPDC casting

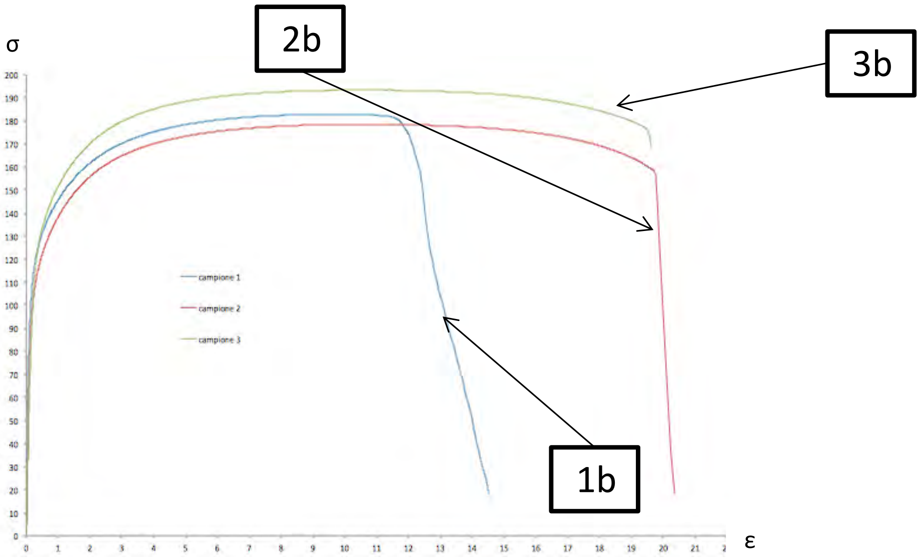


Fig. 28 – Results of tensile tests

Specimen #	YS (MPa)	UTS (MPa)	Elongation (%)
1a	121	184	10.5
1b	120	182	11.5
2a	111	181	12.5
2b	129	178	19.8
3a	124	187	13.0
3b	125	193	19.3

Table 5 – Results of tensile tests

This means that it is fundamental, when defining reference properties for castings targeted by SALEMA project, do not consider single values for YS, UTS and elongation, but indicate a reasonable range of variation for them.
This concept is strengthened by the fact that final assessment of mechanical properties may be performed by means of heat treatment (T4, T5, T6 or T7, according to alloy composition and casting characteristics), which also determines some variations in properties (Fig. 29) [8].

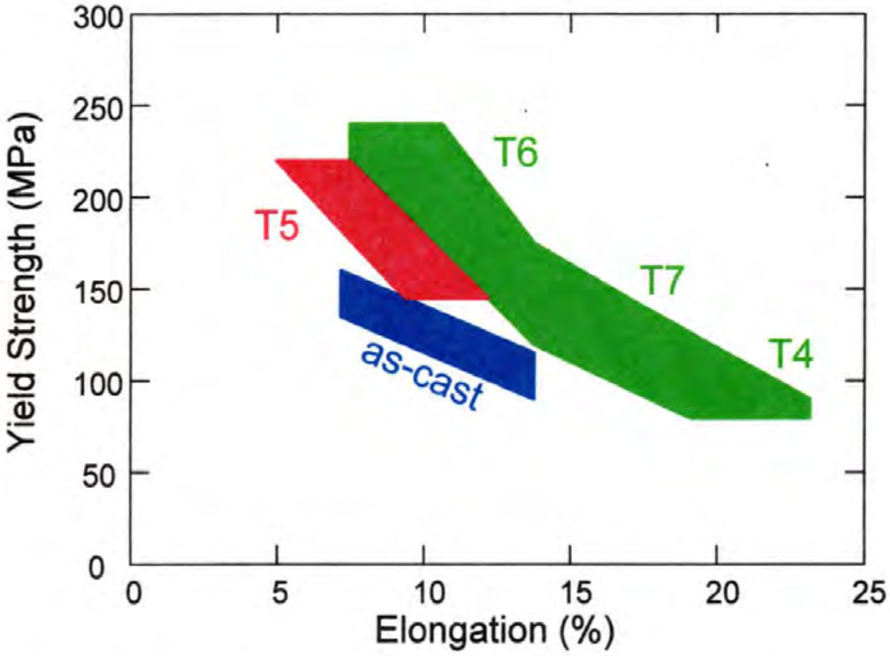


Fig. 29 – Range of properties available in structural diecastings, as a function of heat treatment

2. Aluminium alloys for extrusion, rolling and stamping: processing & properties

2.1. Wrought Aluminium alloys for automotive

The most used Wrought Aluminium alloys for automotive belong to 5000 and 6000 families, as already evidenced in Chapter 1.

5000 Alloys
These alloys are typical Al-Mg non-hardenable alloys, whose final mechanical behaviour is the result of work hardening (during the last stages of rolling or during final stamping operations).

6000 Alloys
These alloys are typical Al-Si-Mg hardenable alloys, whose final mechanical behaviour is the result of precipitation hardening (performed by means of various codified treatments, e.g. T4, T5, T6 and T7, see Table 6).

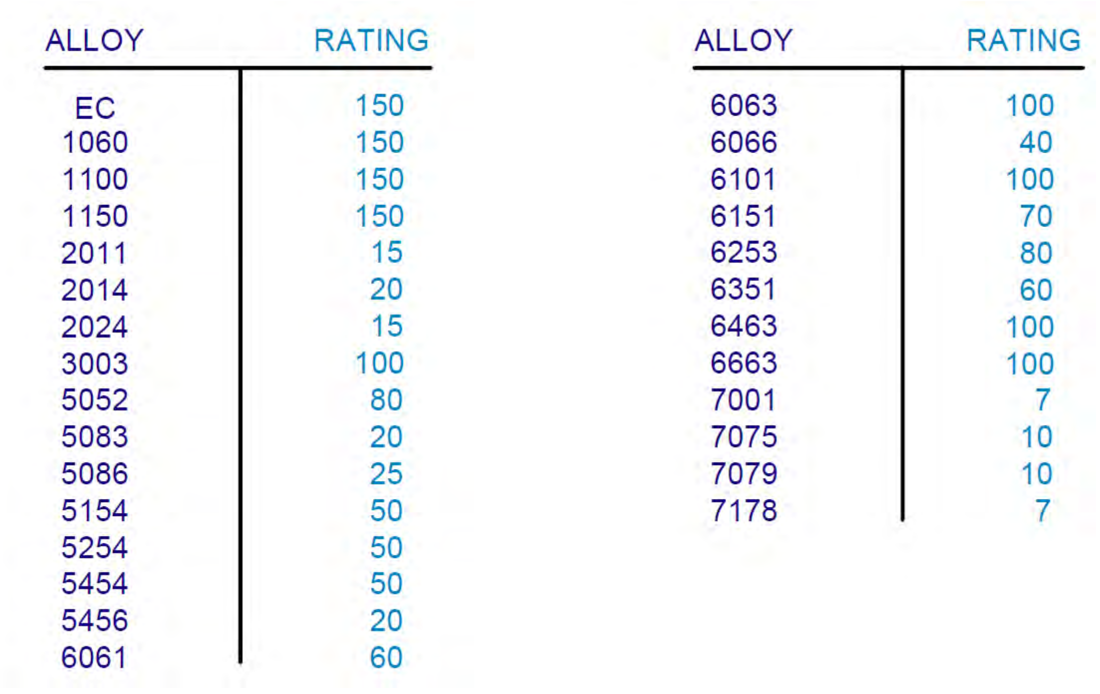
Heat treatement designation	Description
O	annealed
T1	cooled and naturally aged
T4	solution heat treatment and naturally aged
T5	cooled and artificially aged
T6	solution heat treatment and artificially aged
T8	solution heat treatment, cold worked and artificially aged

Table 6 – Typical heat treatments for Aluminium alloys

2.2. Attitude to hot working (extrusion, rolling)

Attitude to hot working, and particularly to extrusion, is evaluated by an empirical extrudability index, which can be related to extrusion speed, complexity of extruded shapes achievable and, obviously, resistance offered by the alloy to the hot deformation processes. Some examples of extrudability index attribution to various alloys are collected in Fig. 30 [12].

However, it has to be considered that extrudability (and thus attitude to hat deformation) can be related to the flow stress of the alloys, as shown in Fig. 31. When the alloy is hot deformed, the main contribution to its resistance (i.e. to its flow stress) is constituted by solid solution strengthening [13-14].



ALLOY	RATING	ALLOY	RATING
EC	150	6063	100
1060	150	6066	40
1100	150	6101	100
1150	150	6151	70
2011	15	6253	80
2014	20	6351	60
2024	15	6463	100
3003	100	6663	100
5052	80	7001	7
5083	20	7075	10
5086	25	7079	10
5154	50	7178	7
5254	50		
5454	50		
5456	20		
6061	60		

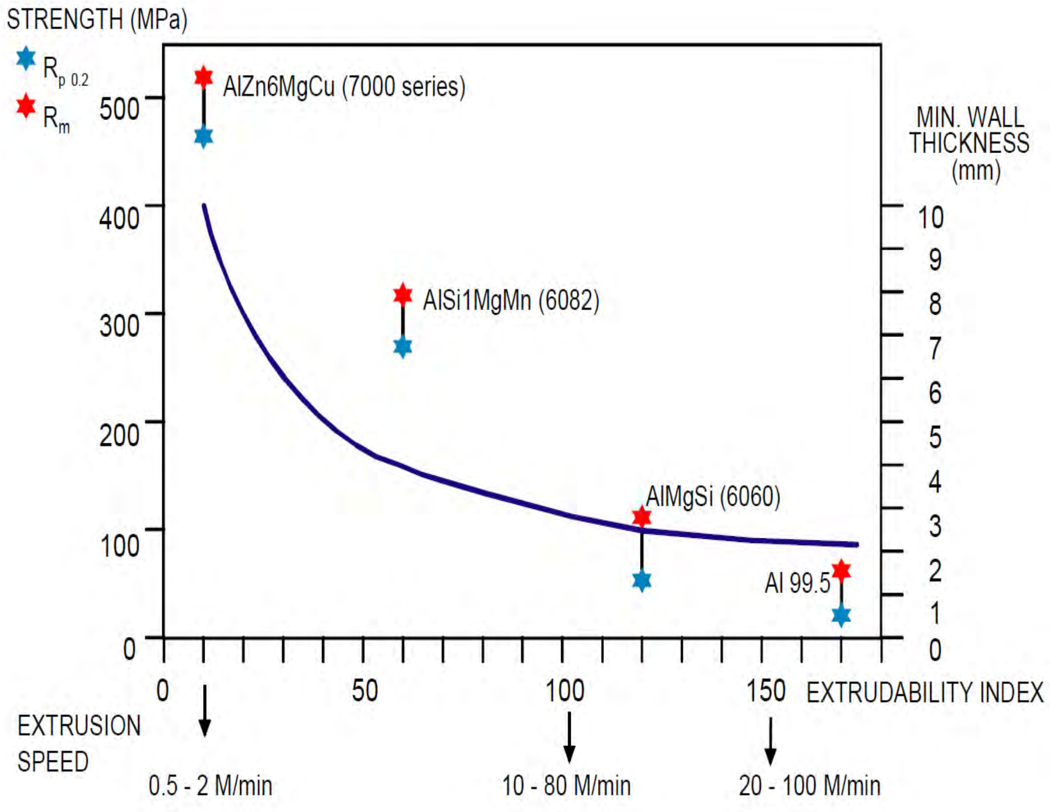


Fig. 30 – Extrudability index for various alloys

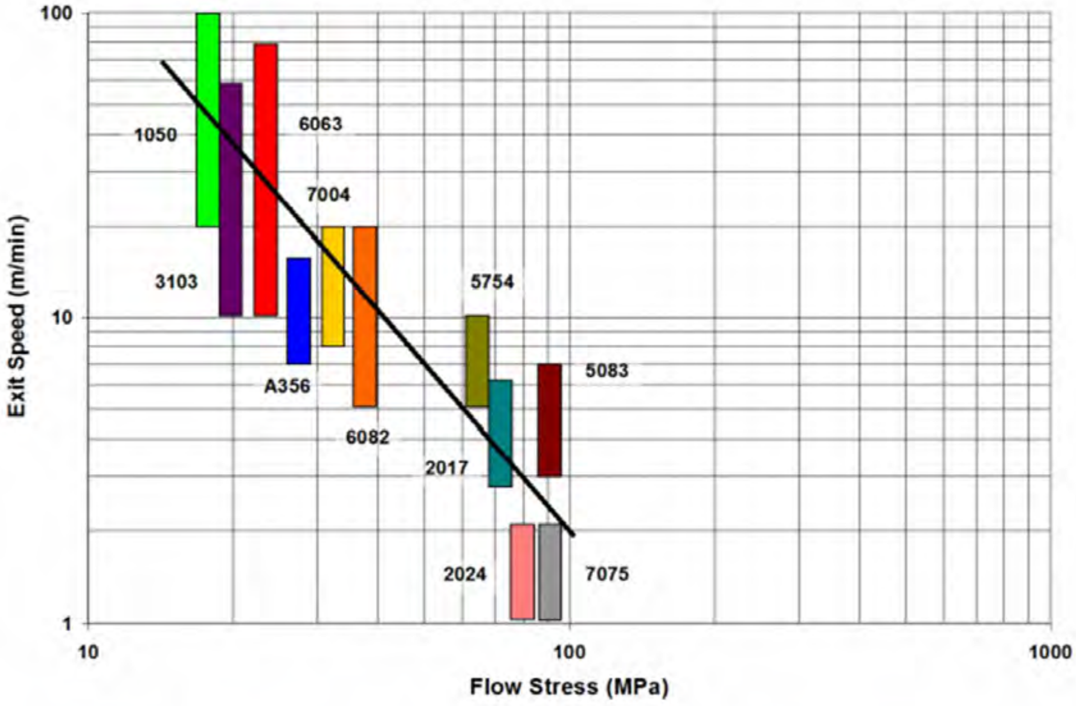


Fig. 31 – Correlation between extrusion performance and flow stress for various alloys

3. Final considerations

This document and the key-concepts presented describe how SALEMA is developing a fully innovative approach for defining requirements for sustainable Aluminium alloys for electric automotive applications:

- Mechanical properties requirements, especially for diecastings, have to be defined considering the complex interactions between defects and microstructure in controlling mechanical behaviour; microstructural variability typically results in mechanical properties distribution in diecastings, which means that mechanical properties requirements must be fixed in terms of range of variations
- Metallurgical state, both in terms of hot/cold deformation history and of heat treatment, is a key-condition for tuning of mechanical properties, with a relevance which can be considered equivalent to that of composition.
- Sustainability, in terms of usage of Raw Materials, has become a design parameter: this means that set up of innovative alloys must be performed together with the evaluation of Raw Materials Criticality index associated to the solutions individuated
- Processability performance are strategic for the real application of innovative alloys; considerations about castability (in terms of viscosity and fluidity), tendency of generating detrimental die-alloy interactions (die soldering phenomena, thermal fatigue, die wear), attitude to hot deformation processing (well represented by the extrudability index) are crucial for alloys development and selections; models, based also on empirical information, are needed, to be coupled to thermo-dynamical evaluations

These concepts will be the basis for the innovative alloy development which will be the target of WP1 and WP2.