Deliverable Report

Deliverable Title:

Specifications required by the low CRM aluminium alloys

Considering peculiarities of foundry, extrusion and stamping processes

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Summary

The strategy for developing low CRM Aluminium alloys for automotive components has been defined, based on

- Give priority to the concept of minimising the use of CRM, which means checking, for each composition, the above-defined Criticality Index
- Consider a starting alloy system, having the right potential to reach the mechanical performance targets individuated for SALEMA Demonstrators
- Check, by means of simplified models, the key processability issues (e.g. fluidity and low tendency for die soldering phenomena for HPDC): they must be at least similar to those of conventional starting systems
- Check, by means of thermo-dynamical models, the potential of proper microstructural characteristics of the alloys

The development of such low CRM Aluminium alloys for automotive components will be focussed on the following reference systems:

- AlSi10MnMg, AlMg(2-3) and AlMg4Fe systems for HPDC demonstrators
- 5000 and 6000 series for Wrought (Extrusion, Stamping) Demonstrators.

Minimisation of CRM content will be performed by acting on Mg and Si amounts, and considering compensating effects on mechanical performance offered both by

- elements such as Mn, Cu, Zn (solid solution strengthening) and Ti (grain refinement) for HPDC alloys
- optimisation of work hardening and heat treatment conditions for wrought alloys

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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
YS or ReH	Yield Strength
UTS or Rm	Ultimate Tensile Strength
A	Elongation at break
CRM	Critical Raw Materials
EI	Economic Importance
SR	Supply Risk
EN	European Normative
CI	Criticality Index

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1. Aluminium alloys and Critical Raw Materials

1.1. Individuation of Critical Raw Materials

The European Commission periodically investigates which raw material are to be considered critical for the EU economy 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 (Fig. 1).

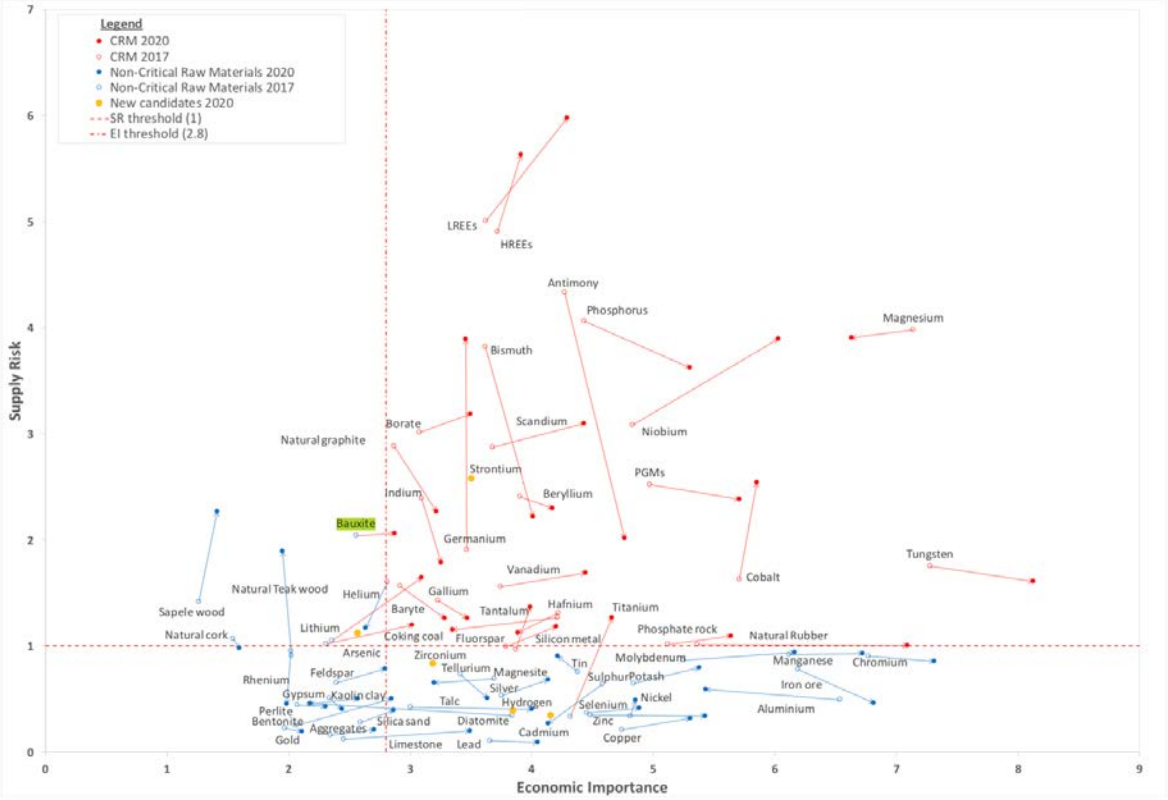


Fig. 1 – European Raw Materials classification according to EI and SR: 2017 list versus 2020 list [1]

It is worth mentioning that the criticality assessment of raw materials is not an easy task and that there is not a recognized method to reach that goal in literature [2-3]. In a recent paper, Hofmann et al. [4] showed that material scientists seem frequently not concerned with the criticality of raw materials in their work so that they suggested to advance the implementation of the concept of materials criticality in materials research and development. In this scenario, Ferro et al. [5-6], in the frame of Ashby's material selection method, developed a procedure to assess the material's index containing information about criticality.

Finally, it is worth mentioning that the criticality concept is very relative since it depends on the Country where it is formulated. In fact, the supply risk, for instance, is a geopolitical factor, based on the natural resources of a country; the technology to process, and to recycle, a raw material also varies from country to country, and it affects both the SR and the EI; and last, but not least, the strategic technologies and the strategic sectors, also vary through the globe. It is noted, in fact, that, since defence, drones and robots are today considered strategic sectors for Europe, the updated CRM list contains titanium as well as bauxite, among the others, as new critical raw materials.

1.2. Critical Raw Materials in Aluminium alloys

Aluminium alloys are the result of a continuous evolution process, which along the years identified the key-effects of alloying elements and led to the definition, for each of them, of the optimal amount in view of expected properties and performance. Fig. 2 offers an example of some of the alloying elements typically employed and of the role they are playing on properties of foundry alloys.

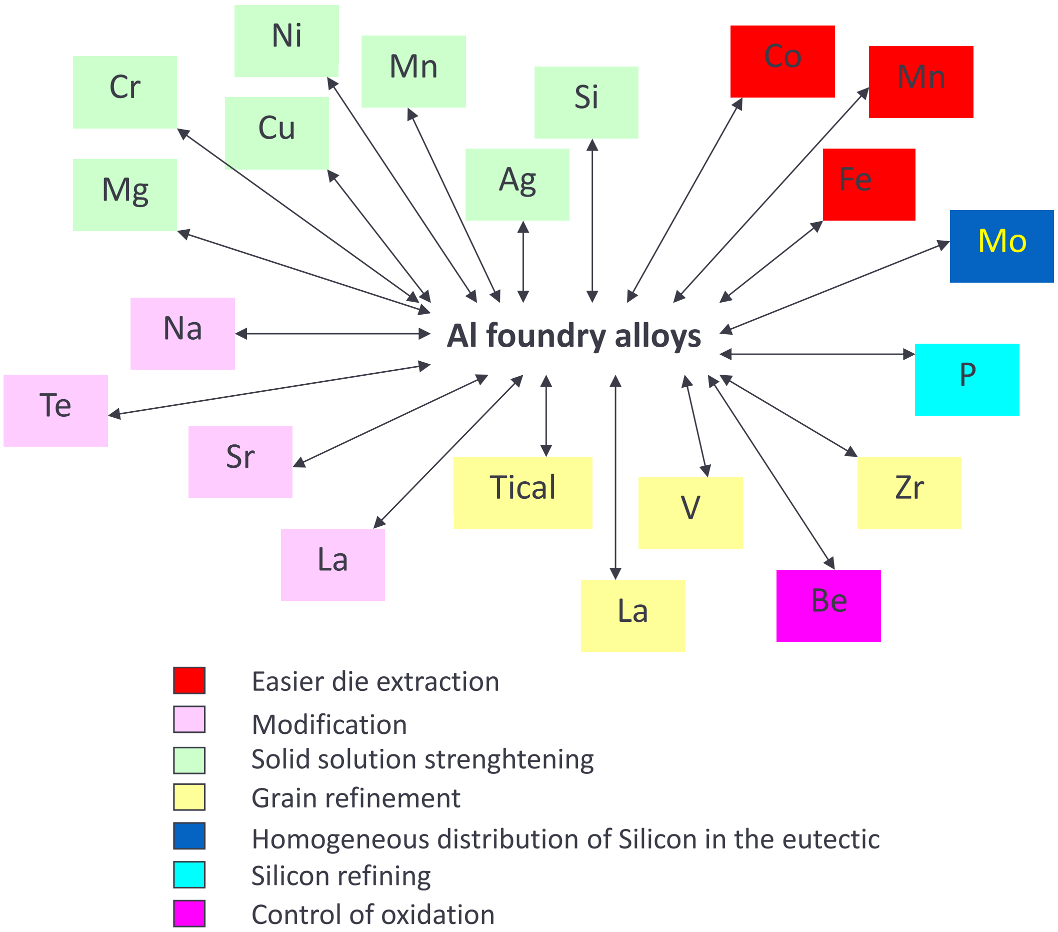


Fig. 2 – Alloying elements and their effect on properties of Aluminium foundry alloys

Thus, it is fundamental to recall that

- Aluminium alloys are highly tailored
- Balancing all alloying elements is crucial to achieve expected/improved properties.

This situation is well represented by the Classification systems for Aluminium alloys, based on 2 main Groups (Fig. 3)

- Wrought Alloys (see EN 573 Standard)
- Casting Alloys (see EN 1676 and EN 1706 Standards),

and leading to wide set of alloys and properties.

Aluminium alloy components are a strategic asset for production of electric cars, as it is widely documented in **Annex 1** to this Deliverable.

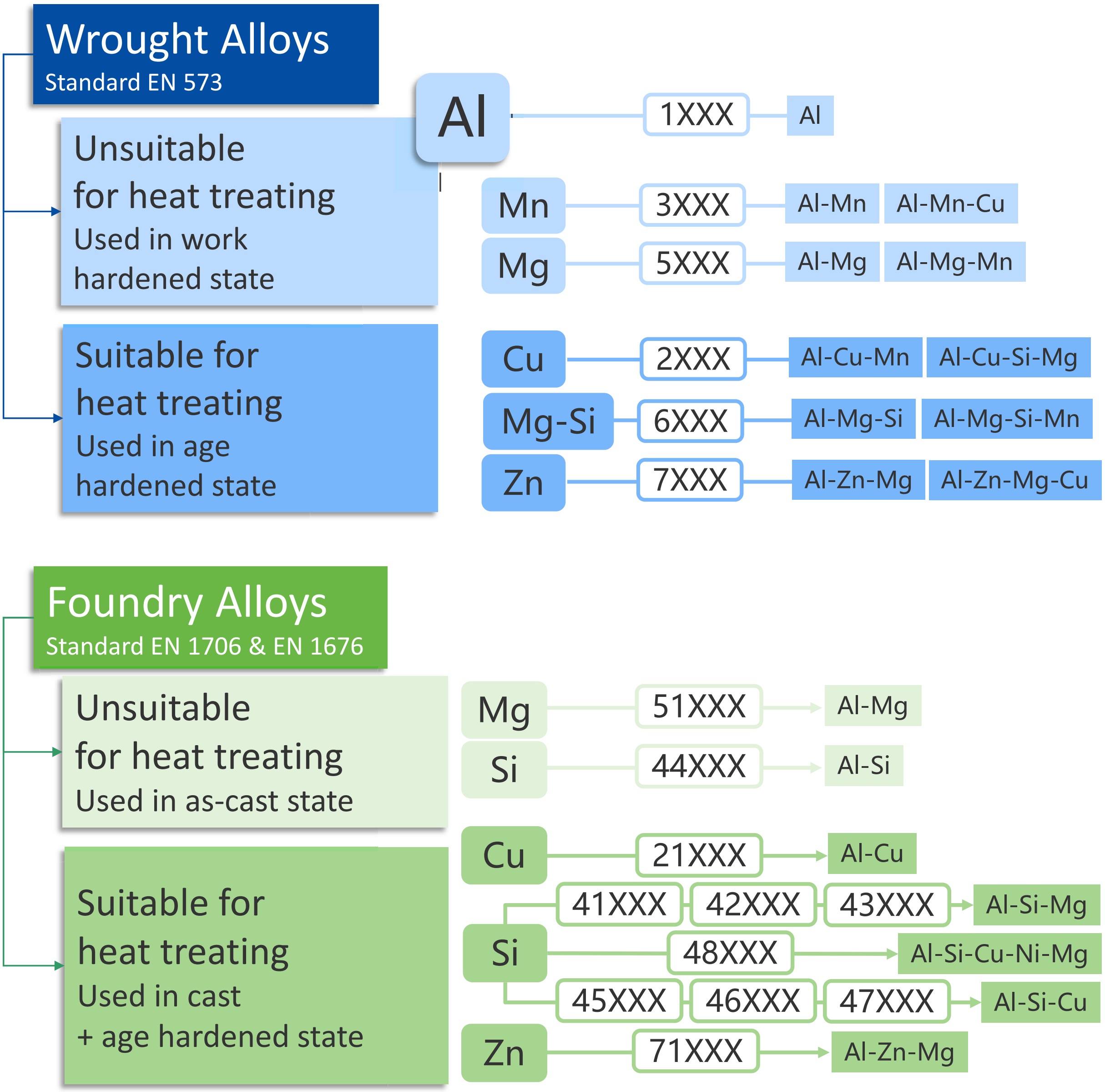


Fig. 3 – Classification of Aluminium alloys

Aluminium is not a CRM yet, but

- Bauxite, i.e. the starting point for primary aluminium production and for fabrication of high performances aluminium alloy components
- Magnesium and Silicon, which are two of the most common alloying elements in Aluminium alloys,

are present in the previous EU list of Critical Raw Materials.

WP2 of SALEMA is aimed at individuating competitive Aluminium alloys with a low content of CRM. It is clear that the raw materials criticality concept must be included in the design of alloys. Materials that minimize the component weight don't necessary reduce the criticality issues related to their CRMs content; thus, a multi-objective strategy taking advantage from trade-off diagrams is necessary (Fig. 4). In this Deliverable (and more generally in SALEMA Project), Aluminium alloys design and selection will be performed taking into account the criticality index.

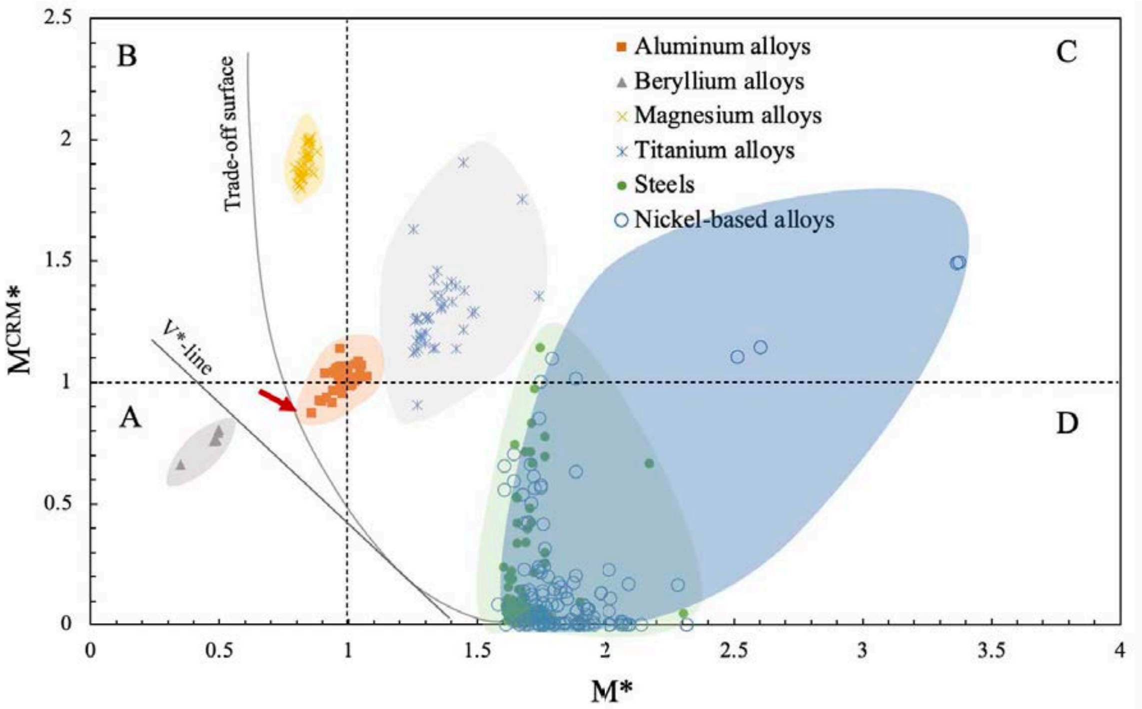


Fig. 4 – Trade-off plot

1.3. Definition of a Criticality Index

Individuation and quantification of Raw Materials criticalities is a quite complex issue. What is defined "critical" now, may be abundant in a few years, depending on mining output, geo-political changing scenarios, recycling rate or new technical developments. Ferro & al [5-6] have very recently developed a comprehensive index for a CRM 'i' (CI_{CRMi}) obtained by averaging the different normalized criticalities indexes as follows:

$$CI_{CRM_i} = (k_{ARL} ARL_i + k_{SGR} SGR_i + k_{ECR} ECR_i + k_{NSR} NSR_i + k_{NEI} NEI_i + k_{RDI} RDI_i)/6 \qquad (1)$$

where *k* is a non-dimensional coefficient which value is in between 0 and 1, according to the seriousness of the corresponding criticality aspect, ARL_i is the normalized value of the Abundance Risk Level of the CRM 'i', SGR_i is the normalized value of the Sourcing and Geopolitical Risk of the CRM 'i', ECR_i is the normalized value of the Environmental Country Risk of the CRM 'i', NSRi is the normalized Supply Risk of the CRM 'i', NEI_i the normalized value of the Economic Importance index of the CRM 'i' and finnaly RDI_i is the normalized value of the Recycling Drawback Index of the CRM 'i'. Detelied description of each of the aboved mentioned normalized criticality indicators can be found in references [11]. It is observed how the highest CI values are reached by rare earth elements and palladium metals group (Fig. 5).

Interestingly, this approach has been implemented to alloys. Since in a general alloy different elements are present including CRMs, it is reasonable to assess the alloy criticality issue by using the following defined index:

$$CI_A = \sum_{i=1}^{n} CI_{CRMi} \cdot P_{CRMi} \qquad (2)$$

where n is the number of CRMs in the alloy chemical composition and P_{CRMi} is the weight amount of CRM 'i' in the alloy. It is observed that the alloy criticality index (CI_A) represents an overall criticality value per unit of mass of the alloy.

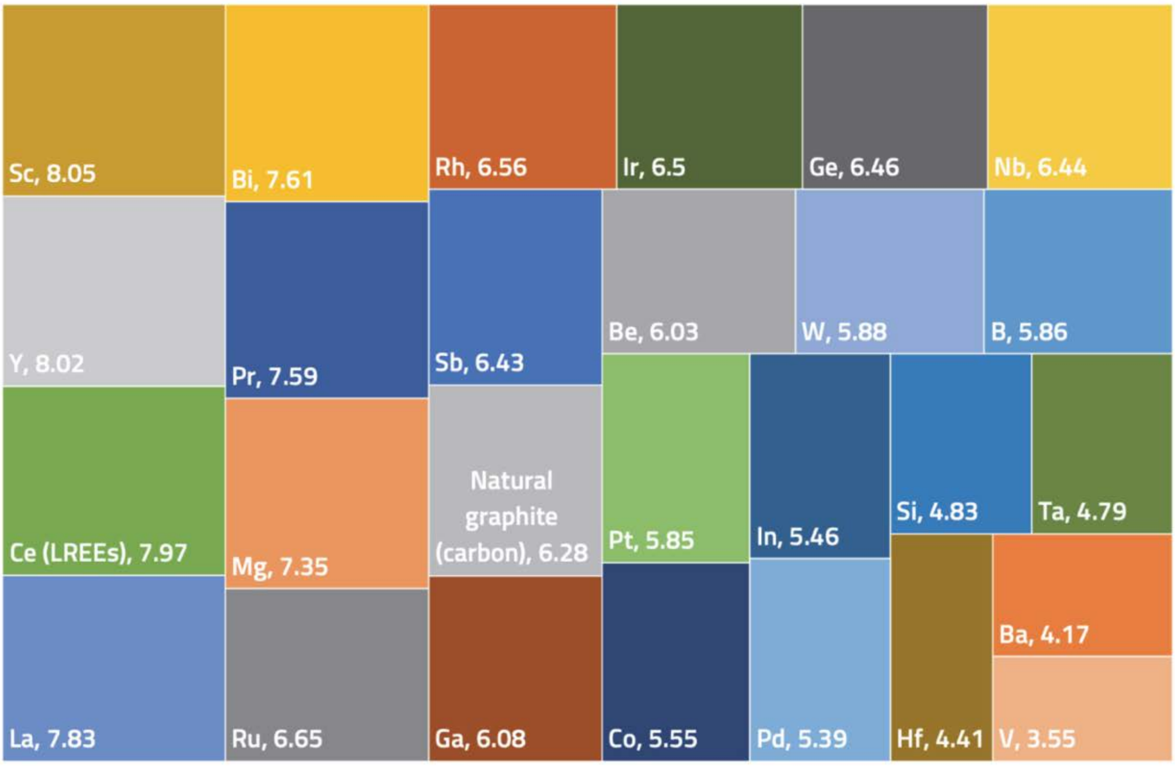


Fig. 5 – Criticality grade of different CRMs measured by the RM Criticality Indicator (Areas are proportional to the elements' criticality indexes, whose numerical values are also reported) [5-6]

2. Requirements for SALEMA Demonstrators

Definition of requirements for SALEMA Demonstrators have been reported with full details in Deliverable 1.1, and thus they will be shortly summarised in this section.

2.1. HPDC Demonstrators

2.1.1. Requirements of demonstrator 1 (Shock Tower)

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 %

As specified in **Annex 1**, due to properties distribution in HPDC castings, such values are intended as expected values in relevant regions of the Demonstrator.

Further requirements have to be verified by means of specific testing procedures for what concerns (see Deliverable 1.1):

- **Bending**
- **Crash performance**
- **Corrosion properties**
- **Riveting**

2.1.2. Requirements of demonstrator 2 (Frontal Frame)

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 specified in **Annex 1**, due to properties distribution in HPDC castings, such values are intended as expected values in relevant regions of the Demonstrator.

Further requirements have to be verified by means of specific testing procedures for what concerns (see Deliverable 1.1):

- **Fatigue behaviour**
- **Corrosion properties**
- **Weldability**

2.2. Stamping Demonstrators

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

2.2.1. Cold stamping demonstrator: car door

This demonstrator 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. 5000 and 6000 series are considered for this application.

2.2.2. 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.

2.2.3. 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 *1*.

	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

Table 1 – Relevant properties for each of the demonstrator cases

2.3. Extrusion demonstrators

2.3.1. Requirements of demonstrator 1 (Battery Tray)

The first demonstrator used to validate SALEMA extrusion alloys is going to be achieved by means of the dies designed and fabricated in MARBEL project (where are also involved ASAS, EURECAT and CRF). 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.

2.3.2. Requirements of demonstrator 2 (Frontal Frame)

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 %

Further requirements have to be verified by means of specific testing procedures for what concerns (see Deliverable 1.1):

- **Fatigue behaviour**
- **Corrosion properties**
- **Weldability**

3. SALEMA approach to develop low CRM HPDC alloys

3.1. Strategy for the development of low CRM Aluminium alloys for HPDC demonstrators

As reported in SALEMA Deliverable 1.1, among foundry processes, High Pressure Die-Casting (HPDC) has been considered as a simple but effective method for the fabrication of Aluminium alloy components. Due to its advantages of high efficiency and short production cycle, HPDC has been widely employed by automotive industries, even if some challenges are still open, in view of the best compromise between high productivity and reliable and relevant performance. Today's cast components 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 [7].

Classic composition specifications for Aluminium casting alloys are referred to Al-Si family in the range of 7 to 11% Silicon, with varying amounts of Mg (for Mg_2Si hardening), low contents of Fe and Mn for die soldering resistance are added as well. Other alloying elements (e.g. Zn, Ti, Sr, etc.) may be used to improve specific properties, as displayed in Fig. 2.

The strategy for the development of low CRM Aluminium alloys for HPDC demonstrators, in the frame of SALEMA Project, can be identified as follows:

- Give priority to the concept of **minimising the use of CRM**, which means checking, for each composition, the above-defined Criticality Index
- Consider a starting alloy system, having the right potential to reach the **mechanical performance targets** individuated for HPDC Demonstrators #1 and #2
- Check, by means of simplified models, the key **processability issues**, such as fluidity and low tendency for die soldering phenomena: they must be at least similar to those of conventional starting systems
- Check, by means of thermo-dynamical models, the potential of proper **microstructural characteristics** of the alloys

3.2. Selection of starting systems

3.2.1. Alloy system #1: AlSi10MnMg

As reported in Deliverable 1.1, AlSi10MnMg alloy has been selected as reference for further development in SALEMA project, as the base for developing the addition of high scrap ratios and the potentially required micro-additions to compensate the high impurity level. 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, on the basis of the contacts and agreement among Raffmetal, the end-users (CRF and FORD) and the demonstrator producers (Fagor and Endurance), it can be adopted also as the starting system for developing a low CRM 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 reduce the amount of CRM used for its production.

According to Raffmetal alloy datasheet [8], 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 [8] it also stated that this alloy has GOOD general resistance to corrosion and EXCELLENT castability.

3.2.2. Alloy system #2: AlMg(2-3)

An interesting alternative to Alloy system #1 can be constituted by an alloy belonging to the Al-Mg system, on which previous research activities have been performed, with good results.

A reference composition reported in literature [9], referred to the **system Al-Mg(2-3)** is shown in Table 2.

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Co	Ca	Na
min.	0.2			0.8	2.4			0.3		
max.	0.3	0.15	0.05	1.1	3.0	0.080	0.20	0.4	0.001	0.001

Table 2 – Reference composition of AlMg(2-3) alloy [9]

It was designed some years ago, but not subsequently investigated, due to other alternatives, which used CRM such as Silicon. Now, with a completely changed scenario in terms of sustainability, it appears relevant to investigate more on this alloy system.

The mechanical properties, in the as-cast state, are shown in Fig. 6. It can be seen that the best results of elongation were achieved from the samples with a wall thickness of 2mm and 3mm. Every tested sample had an elongation of more than 15%, and in one case a maximum elongation of 27% was measured. It could be assumed that in these cases the casting parameters were adjusted in optimum condition. In case of yield strength there is an influence of the wall thickness. With heavier wall thickness, or lower cooling condition, the yield strength decreases from 150MPa to 125MPa. The ultimate tensile strength seems to be independent from the wall thickness.

Attention must be paid to some issues related to this alloy system:

- The feeding behaviour may be limited by the absence of an eutectic phase
- Shrinkage is higher with respect to Aluminium-Silicon alloys
- Some tendency to hot tearing may be developed

These issues, as explained in Annex 1 to this Deliverable, can be faced by an integrated view of the die design process, and by adopting proper strategies in terms of grain refinement, to support castability, fluidity and feeding behaviour.

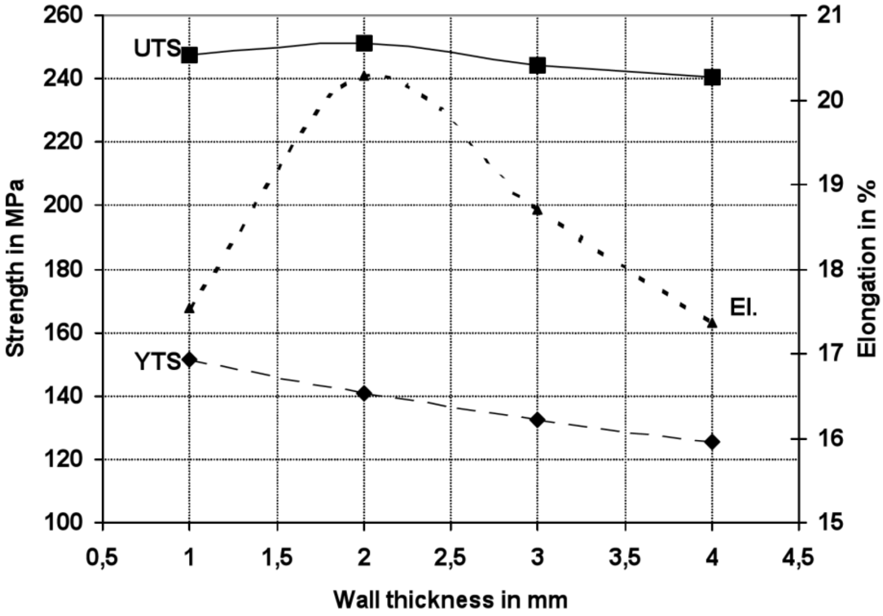


Fig. 6 – Summary of mechanical properties of AlMg(2-3) alloy [9]

3.2.3. Alloy system #3: AlMg4Fe

Another interesting **system is constituted by AlMg4Fe** alloys, for which good elongation in the as-cast and non-heat treated condition, along with a yield strength similar to AlSi10MnMg cast alloys with a T7 two-stage heat treatment are reported, as well as good castability and an easy handling in the die-casting process. A reduced sticking tendency (about 50% reduction in the chemical erosion of the die steel) and thus an improved die life are reported [10]. Typical composition is given in Table 3a. Possible criticalities are related to a higher shrinkage tendency with respect to conventional Al-Si HTDC alloys (Linear shrinkage ranging from 0,6 to 1,1%, compared to 0,4-0,6%). The typical oxidation tendency of Al-Mg alloys is counterbalanced by the use of a very limited amount of Berillium. Table 3b reports the typical performance achievable by this alloy system (specimens taken from HPDC castings). A good behaviour in joining (riveting, MIG welding) has been also mentioned [10].

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr	others
min		**1,5**			**4,1**				
max	**0,2**	**1,7**	0,2	0,15	**4,5**	0,3	0,2	0,1	**Be**

Table 3a – Reference composition of AlMg4Fe alloy [10]

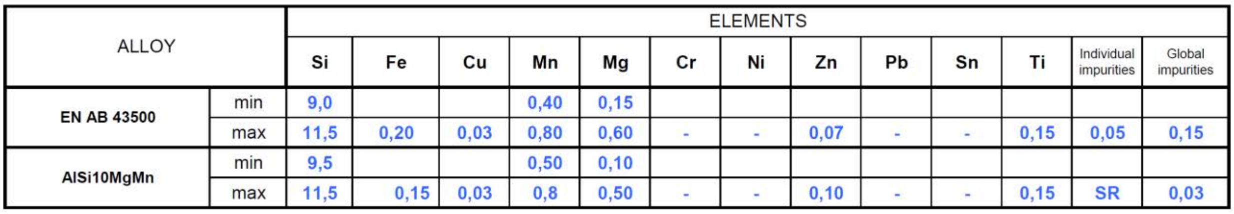
Ultimate Tensile Strength [MPa]	**240 - 280**	**277**
Yield Strength [MPa]	**120 - 150**	**148**
Elongation [%]	**10 - 22**	**22,2**

Table 3b – Reference mechanical properties of AlMg4Fe alloy [10]

3.3. Implementation of alloy development strategies

Stage 1: Minimisation of use of CRM
As mentioned in previous sections, among the typical alloying elements for Aluminium alloys, those included in the CRM list are Silicon and Magnesium.
In case of the **Alloy system #1**, this means that actions have to be performed to check the real potential of this system with Silicon and Magnesium contents located around the lower limits (see Table 3):

- **From 9.0% to 10.0% for Silicon**
- **From 0.10% to 0.30% for Magnesium**



ALLOY		ELEMENTS												
		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Individual impurities	Global impurities
EN AB 43500	min	9,0			0,40	0,15								
	max	11,5	0,20	0,03	0,80	0,60	-	-	0,07	-	-	0,15	0,05	0,15
AlSi10MgMn	min	9,5			0,50	0,10								
	max	11,5	0,15	0,03	0,8	0,50	-	-	0,10	-	-	0,15	SR	0,03

Table 4: Composition of AlSi10MgMn alloy [8]

In the case of the **Alloy system #2** the key-action must be focussed on Magnesium, whose content, again, should be located around the lower limits (see Table 2): **from 2.4% to 2.7%**.
For **Alloy system #3**, attention should be paid to Mg minimisation (**close to the lower limit, i.e. 4%**).

Alloy Systems #1, #2 and #3 represent, in terms of CRM content, a **reduction**, with a related benefit which will be quantified by means of the Criticality Index defined above.

Stage 2: Keeping a proper level of mechanical performance
As discussed in Annex 1 to this Deliverable, mechanical behaviour of HPDC castings is the result of a high number of variables and effects.
In "standard" AlSi10MgMn alloys, under the hypothesis that a sound casting is produced, key effect on mechanical behaviour are given by

- Cooling rate, producing fine grains, with positive influence on mechanical properties (Hall-Petch' Law)
- Strengthening offered by the solid solution mechanism (for all the alloying elements, in a way related to their content)
- Strengthening offered by the precipitation mechanism, associate to the formation, during an ageing stage, of Mg_2Si precipitates; according to the specific heat treatment parameters, a relevant variation range can be observed (Fig. 7) [11].

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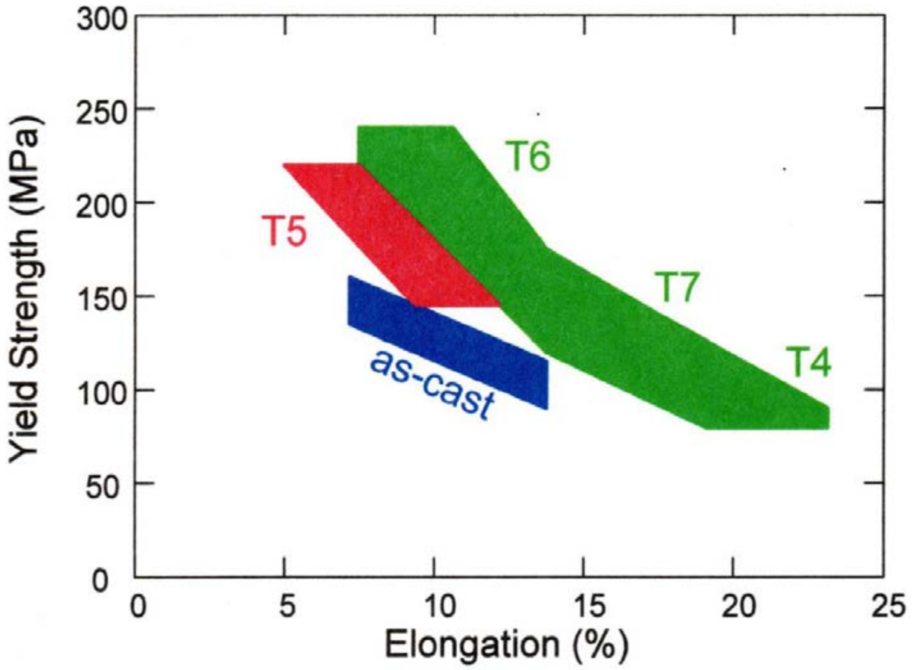


Fig. 7 – Range of properties available in structural diecastings, as a function of heat treatment [11]

Thus, for **Alloy system #1**, the reduced amount of Si and Mg (to achieve a low Criticality Index) must be associated to an **optimisation of the heat treatment stage**.

In case of **Alloy systems #2 and #3**, only grain refinement and solid solution strengthening are affecting the mechanical behaviour. Thus, to compensate the minimised amount of Magnesium, actions must be performed on use of alternative, non-critical, alloying elements, such as Manganese, Zinc and Copper.

Stage 3: Processability

As shown in Annex 1, HPDC processability, first of all, is related to fluidity of alloys and to minimisation of die soldering phenomena (one of the most frequent causes of defects in HPDC).

Fluidity is one of the alloy dependent phenomena that determine castability. Other are 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 [12-14]. 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.

In the preliminary stage of SALEMA alloy development, the proper approach is that related to modelling viscosity (and, thus, its inverse, which is fluidity), while experimental test can be used in a further stage, to specifically check the alloys produced.

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.
From experimental data and theoretical analyses, an Arrhenius-type equation has been proposed for evaluating the effect of temperature on viscosity [13-14]:

$$\eta(T) = \eta_0 * \exp(E/RT) \tag{3}$$

Where η (T) is the viscosity as a function of temperature,
η_0 is the pre-exponential constant for viscosity,
E is the activation energy for viscosity,
R is the gas constant (8,3144 J K^{-1} mol $^{-1}$),
T is the temperature (K).

Table 4, taken from Ref. [15-16] collects the values of E, η_0 and η (at melting point) for some pure metals and for the Aluminium-Silicon eutectic. For what concerns molten binary alloys, the equation proposed by Moelwyn-Hughes can be used:

$$\eta = (x_a\eta_A + x_b\eta_B) * (1 - 2\, x_a x_b \Omega \,/RT) \tag{4}$$

where η_a and η_b are the viscosity values of the alloying elements a and b, x_a and x_b are their molar fractions, while Ω is the interaction parameter. If Ω is unknown (i.e. in the most part of cases), equation (2) has to be simplified, obtaining

$$\eta = (x_a\, \eta_a + x_b\, \eta_b) \qquad (5).$$

For multi-component alloys, equation (3) can be generalised, achieving

$$\eta = \Sigma_i\, x_i\, \eta_i \qquad (6).$$

where i is the i-th alloying element.

Metal or alloy	T_{melt} [°C]	η (T_{melt}) [mPa·s]	η_0 [mPa·s]	E [kJmol^{-1}]
Al	660	1,30	0,1492	16,50
Cu	1083	4,00	0,3009	30,50
Fe	1536	5,50	0,3699	41,40
Mg	651	1,25	0,0245	30,50
Mn	1241	5,00	0,5700	33,25
Nb	1454	4,90	0,1663	50,20
Pb	327	2,65	0,4636	8,61
Si	1410	0,80	0,0900	31,50
Sn	232	1,85	0,5380	5,40
Ti	1685	2,20	0,0340	68,00
Zn	419	3,85	0,4131	12,70
Al-Si (eutectic)	577	1.31	0.2330	14,00

Table 5 – Parameters for evaluating the viscosity of some liquid metals and of the Al-Si eutectic [15]

Die soldering phenomena are associated to 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 literature [9], with the calculation, starting from experimental test, of a die soldering index (DSI). The variation of this index with the manganese content is shown in Figure 8 (lower DSI numbers correspond to longer die life).

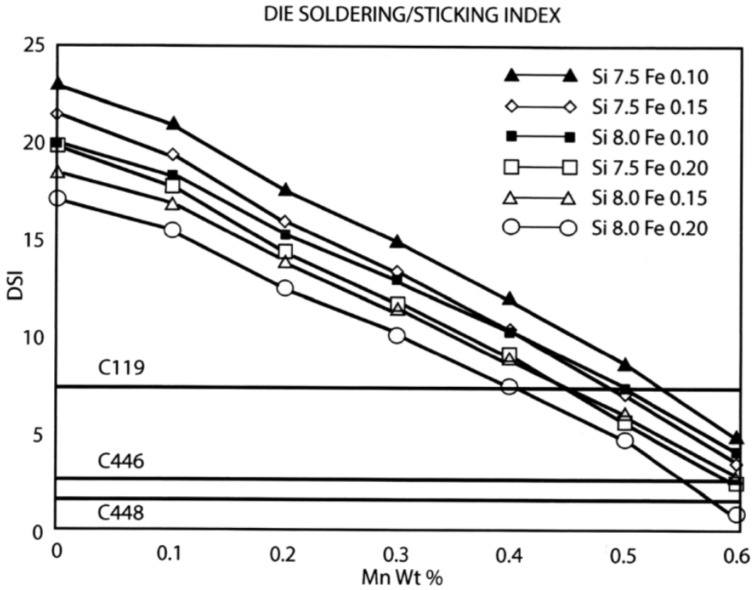


Fig. 8: Die soldering index in several die casting alloys [11]

Commercial experience tends to confirm the results shown: the Mn-containing die casting alloys 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.

Thus, for **all systems (#1, #2 and #3)**, the processability will be preliminarily evaluated by models based on fluidity and on Die Soldering Index. Such models will describe the role of composition on fluidity and on die soldering. Thus, the proposed solutions, minimising Si and Mg contents, must show a processability behaviour similar to that of the conventionally used HPDC alloys

In case of **Alloy systems #2 and #3**, processability will also be related to evaluation of proper grain refinement treatments, to minimise typical criticalities of the Al-Mg and Al-Mg-Fe systems.

Stage 4: Microstructure prediction
Thermodynamic computation codes allow the evaluation of various alloys features, such as:

- Solidification interval
- Heat (ΔH)
- Latent Heat
- Viscosity
- Shrinkage (Chance in Density)
- Microstructural features (e.g. intermetallics, sludge phases, amount of elements in solid solution, etc.)

as a function of temperature and composition.

Being a thermodynamic approach, some general information (i.e. not directly linked, for instance, to the specific cooling conditions established in the die) are offered, supporting the comparison between the solutions proposed for **Alloy systems #1, #2 and #3**.

4. SALEMA approach to develop low CRM wrought alloys

4.1. Strategy for the development of low CRM Aluminium alloys for extruded and stamped demonstrators

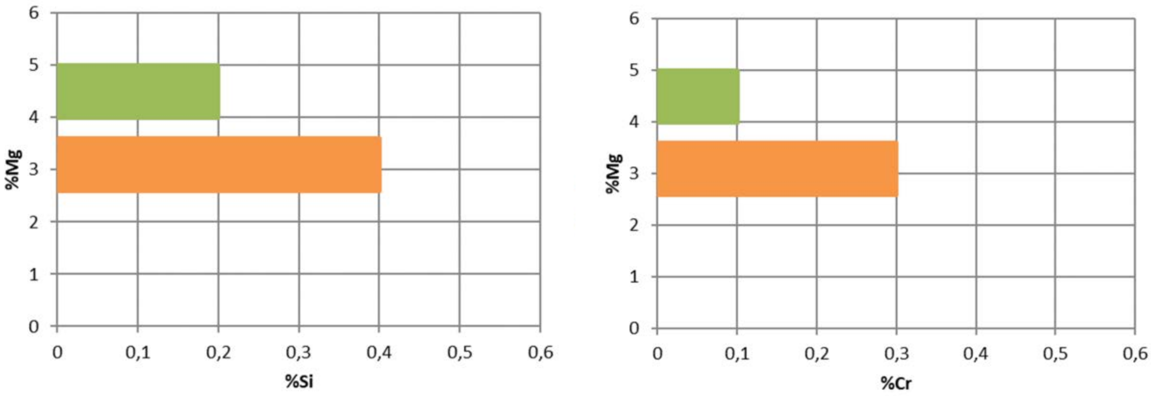
The most used Wrought Aluminium alloys for automotive belong to 5000 and 6000 families, as already evidenced in Section 2 of this Deliverable and in Annex 1.

4.1.1. Alloy system #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). Table 6 and Fig. 9 show the composition of two of the most used 5000 alloys: 5754 and 5182 [17].

Elements	**5754**	**5182**
Aluminum, Al	93.6 - 97.3 %	93.2 - 95.8 %
Chromium, Cr	≤ 0.30 %	≤ 0.10 %
Copper, Cu	≤ 0.10 %	≤ 0.15 %
Cr + Mn	0.10 - 0.60 %	
Iron, Fe	≤ 0.40 %	≤ 0.35 %
Magnesium, Mg	2.6 - 3.6 %	4.0 - 5.0 %
Manganese, Mn	≤ 0.50 %	0.20 - 0.50 %
Silicon, Si	≤ 0.40 %	≤ 0.20 %
Titanium, Ti	≤ 0.15 %	≤ 0.10 %
Zinc, Zn	≤ 0.20 %	≤ 0.25 %
Other, each	≤ 0.050 %	≤ 0.05 %
Other, total	≤ 0.15 %	≤ 0.15 %

Table 6 – Composition range for alloys 5754 and 5182 [17]



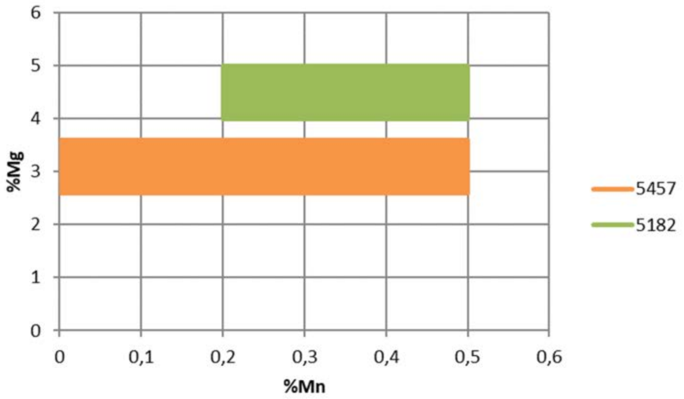


Fig. 9 – Visualisation of composition range for alloys 5754 and 5182 [16]

Table 7 and Fig. 10a-b collect the mechanical properties of these alloys, as a function of the metallurgical state [17].

heat treatement designation	description	AA 5754			AA 5182		
		UTS [MPa]	YS [MPa]	A%	UTS [MPa]	YS [MPa]	A%
O	annealed	190-240	80-135	12-20	275	130-170	12-25
H22	1/4 hard	220-270	130-180	7-15	315-317	230-245	12
H24	1/2 hard	240-280	160-215	5-10	340-338	240-285	10
H26	3/4 hard	265-305	190-245	4-6			
H28	4/4 hard	290	230-250	3-4	390	320	1-6
H19	extra hard				420-421	360-395	1-4

Table 7 – Mechanical properties of 5754 and 5182 alloys, as function of their metallurgical state [17]

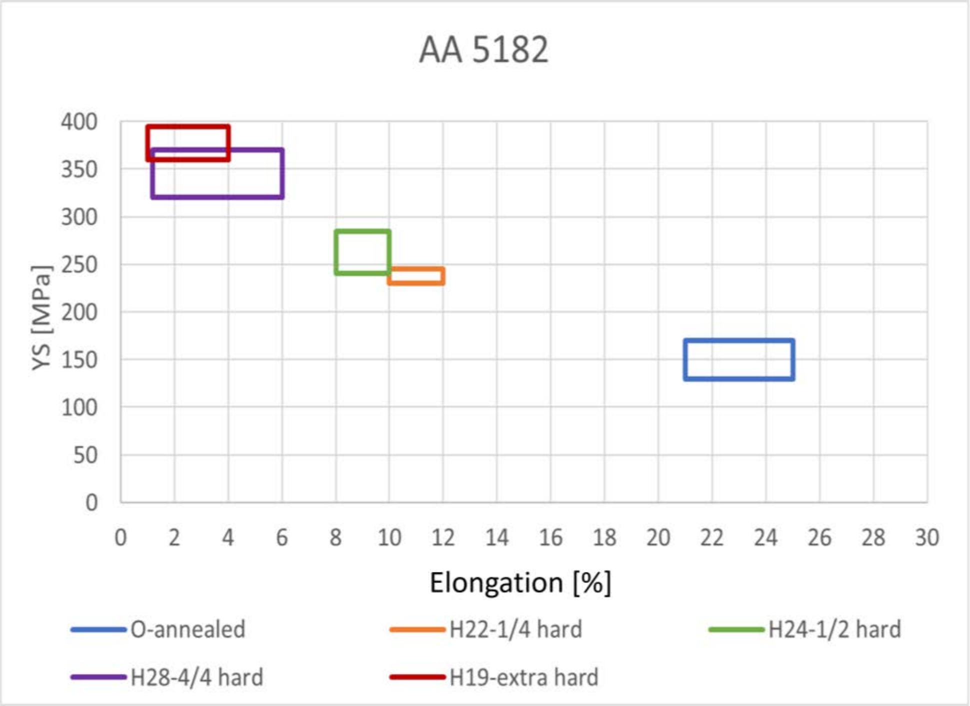


Fig. 10a – Mechanical properties of 5182 alloy, as function of its metallurgical state [17]

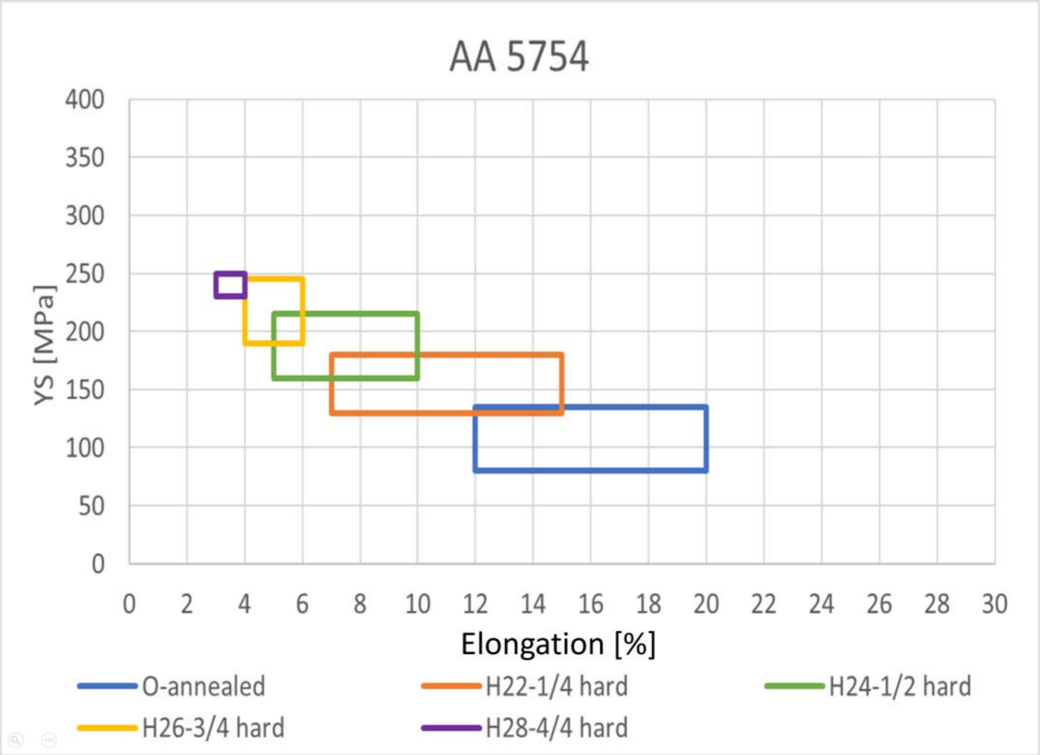


Fig. 10b – Mechanical properties of 5754 alloy, as function of its metallurgical state [17]

4.1.2. Alloy system #2: 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). Table 8 and Fig. 11 show the composition of two of the most used 6000 alloys: 6005, 6016, 6063, 6082 and 6111.

Elements	**6005**	**6016**	**6063**	**6082**	**6111**
Aluminum. Al	97.5 - 99 %	96.4 - 98.8 %	≤ 97.5 %	95.2 - 98.3 %	95.6 - 98.3 %
Chromium. Cr	≤ 0.10 %	≤ 0.10 %	≤ 0.10 %	≤ 0.25 %	≤ 0.10 %
Copper. Cu	≤ 0.10 %	≤ 0.20 %	≤ 0.10 %	≤ 0.10 %	0.50 - 0.90 %
Iron. Fe	≤ 0.35 %	≤ 0.50 %	≤ 0.35 %	≤ 0.50 %	≤ 0.40 %
Magnesium. Mg	0.40 - 0.60 %	0.25 - 0.60 %	0.45 - 0.90 %	0.60 - 1.2 %	0.50 - 1.0 %
Manganese. Mn	≤ 0.10 %	≤ 0.20 %	≤ 0.10 %	0.40 - 1.0 %	0.10 - 0.45 %
Silicon. Si	0.60 - 0.90 %	1.0 - 1.5 %	0.20 - 0.60 %	0.70 - 1.3 %	0.60 - 1.1 %
Titanium. Ti	≤ 0.10 %	≤ 0.15 %	≤ 0.10 %	≤ 0.10 %	≤ 0.10 %
Zinc. Zn	≤ 0.10 %	≤ 0.20 %	≤ 0.10 %	≤ 0.20 %	≤ 0.15 %
Other. each	≤ 0.05 %	≤ 0.05 %	≤ 0.05 %	≤ 0.05 %	≤ 0.05 %
Other. total	≤ 0.15 %	≤ 0.15 %	≤ 0.15 %	≤ 0.15 %	≤ 0.15 %

Table 8 – Composition range for the most common 6000 alloys [17]

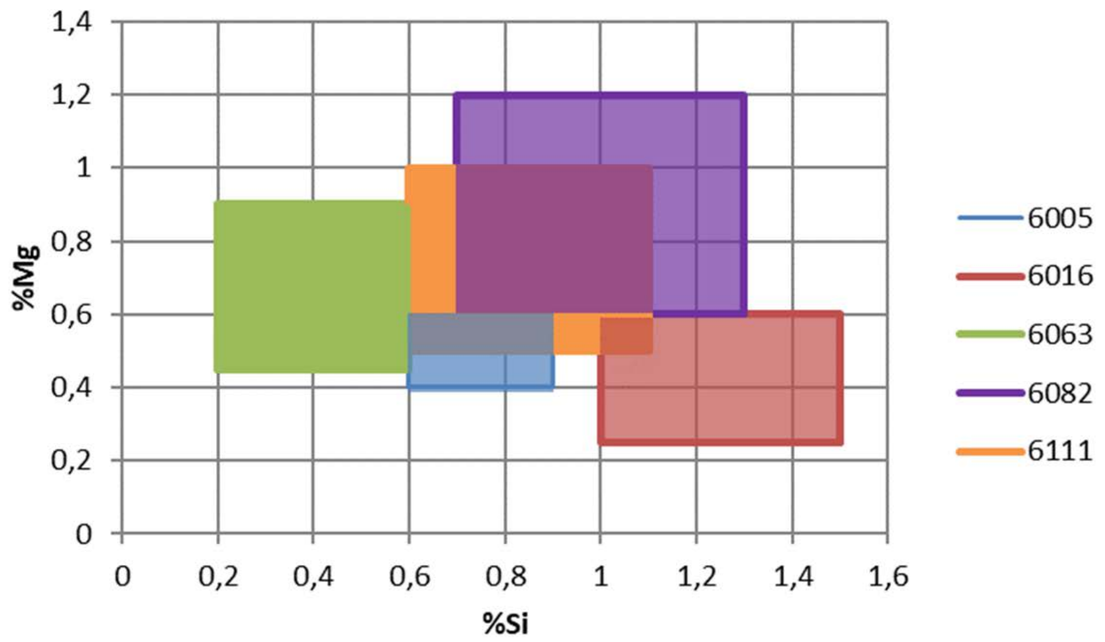


Fig. 11 – Visualisation of composition range for the most common 6000 alloys [17]

Table 9 shows the most used heat treatments adopted for 6000 alloys, while Table 10 collects the mechanical properties of these alloys, as a function of the heat treatment.
Fig.12 displays, as an example, the range of mechanical properties achievable by 6082 alloy, according to the different heat treatments used.

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 9 – Most adopted heat treatments for 6000 alloys [17]

TT	AA 6005			AA 6016			AA 6063			AA 6082			AA 6111		
	UTS [MPa]	YS [MPa]	A%	UTS [MPa]	YS [MPa]	A%	UTS [MPa]	YS [MPa]	A%	UTS [MPa]	YS [MPa]	A%	UTS [MPa]	YS [MPa]	A%
O							100-90	50-55	29	125-155	60-85	14-27			
T1	170-172	105-103	16				155-150	95-90	19 e 20						
T4	200	100	15	170-250	80-140	24-26	170-172	90-115	20 a 22	205-240	110-140	12 a 23	270-290	150-180	20-26
T5	260-270	215-240	8 a 10				185-205	145-165	12 a 22						
T6	270-280	225-250	6a8	260-300	180-260	10 a 12	230-241	190-205	12 a 18	260-375	220-310	4 a 13	360-390	250-310	8a14
T8							250-265	230	9						

Table 10 – Mechanical properties of the most common 6000 alloys, as function of their metallurgical state [17]

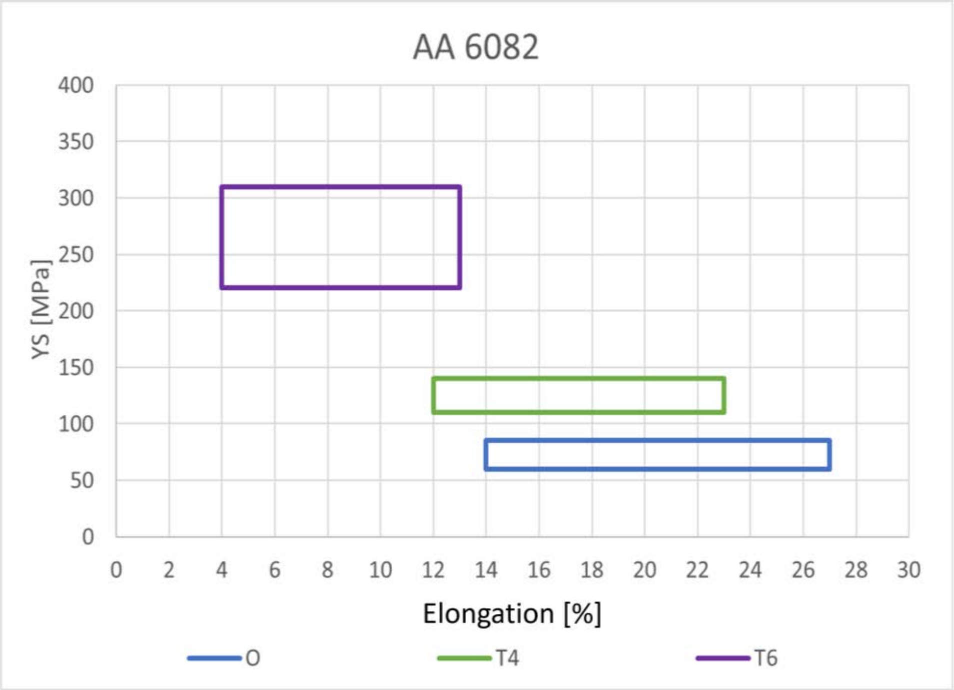


Fig. 12 – Mechanical properties of 6082 alloy, as function of its metallurgical state [16]

4.1.3. Alloy development strategy

The strategy for the development of low CRM Aluminium alloys for extruded and stamped demonstrators, in the frame of SALEMA Project, can be identified as follows:

- Give priority to the concept of minimising the use of CRM, which means checking, for each composition, the above-defined Criticality Index: **as a paradox, this basically means try to minimise Mg and Si contents in alloys based on Al-Mg and Al-Mg-Si systems**
- Consider a starting alloy system, having the right potential to reach the mechanical performance targets individuated for extruded and stamped Demonstrators: as clearly shown in Figs 9-12, this is particularly related to the **metallurgical state optimisation, with reference to the minimised amount of Si and Mg contents in the selected alloys**
- Check, by means of simplified models, the key **processability issues**, with particular reference to the attitude to hot deformation (extrusion, rolling, stamping): they must be at least similar to those of conventional starting systems
- Check, by means of thermo-dynamical models, the potential of proper **microstructural characteristics** of the alloys.

4.2. Implementation of alloy development strategy

Stage 1: Minimisation of use of CRM & Stage 2: Keeping a proper level of mechanical performance
As explained above (see Figs 9-12), there is a strong correlation among composition, metallurgical state and mechanical performance.
This means that the reduction of Mg content (in 5000 alloys) and of both Mg & Si contents (in 6000 alloys), which certainly decreases mechanical behaviour of the alloys, must be counterbalanced by

- Evaluation of possible solid solution strengthening elements (e.g. Mn, Zn, Cu),
- Optimisation of work hardening (for 5000 alloys, see Figs. 9-10) and of heat treatment parameters (for 6000 alloys, see Figs 11-12), to reach the target properties; an example of this optimisation task is given in Fig. 13, showing how composition is affecting the amount of the Mg_2Si reinforcing phase in 6000 alloys, as well as the solutioning temperatures and the final YS/UTS values.

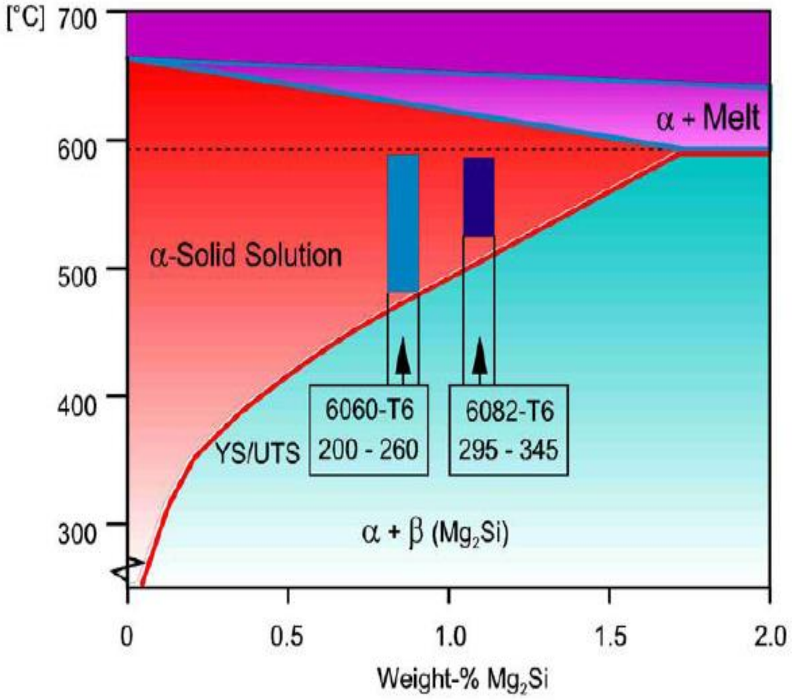
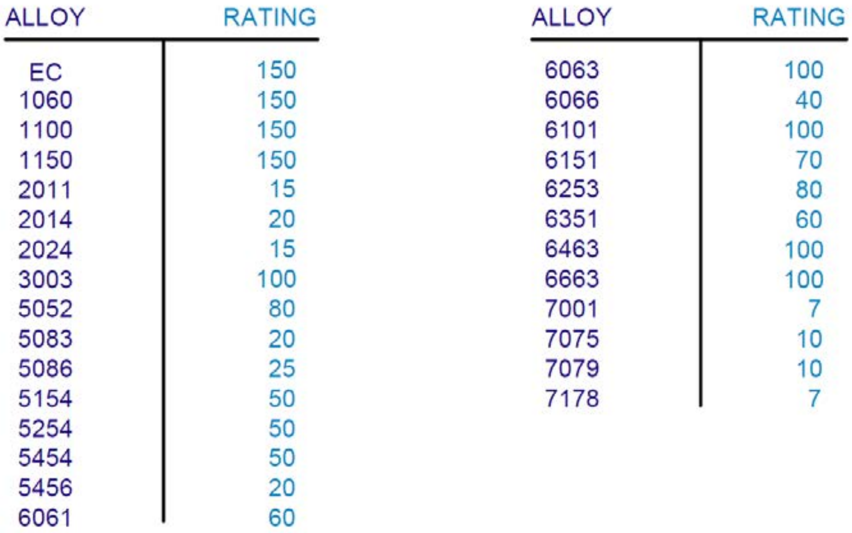


Fig. 13 – Effect of composition on solutioning parameters and properties of 6060 and 6082 alloys

Stage 3: 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 Table 11 and in Figs 14-15 [18-20].



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		

Table 11 – Extrudability Index for various wrought Aluminium alloys [18]

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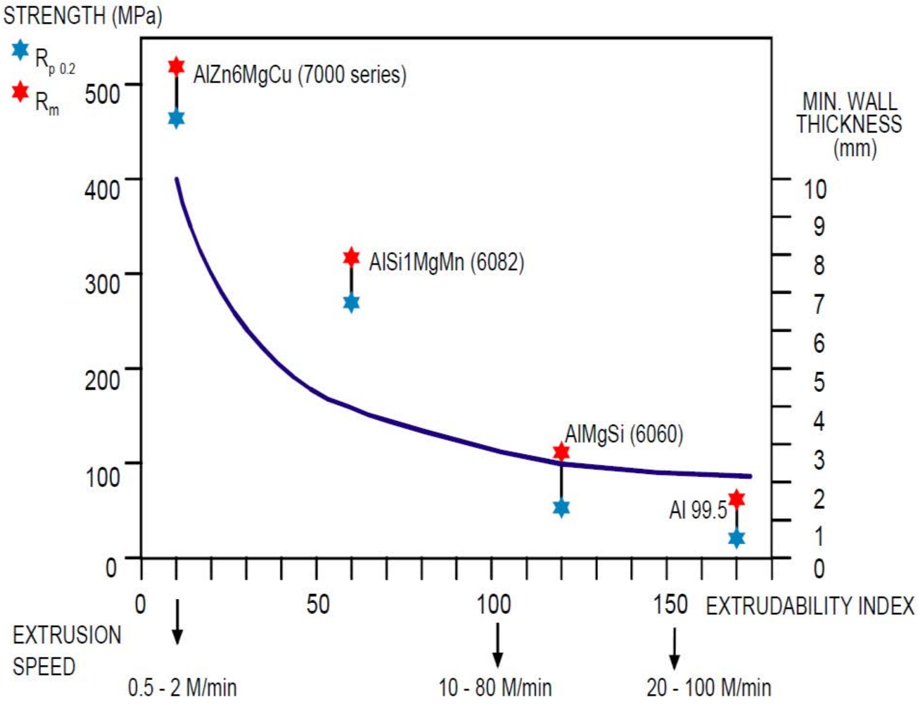

Fig. 14 – Extrudability index and related properties/performance for various alloys [18]

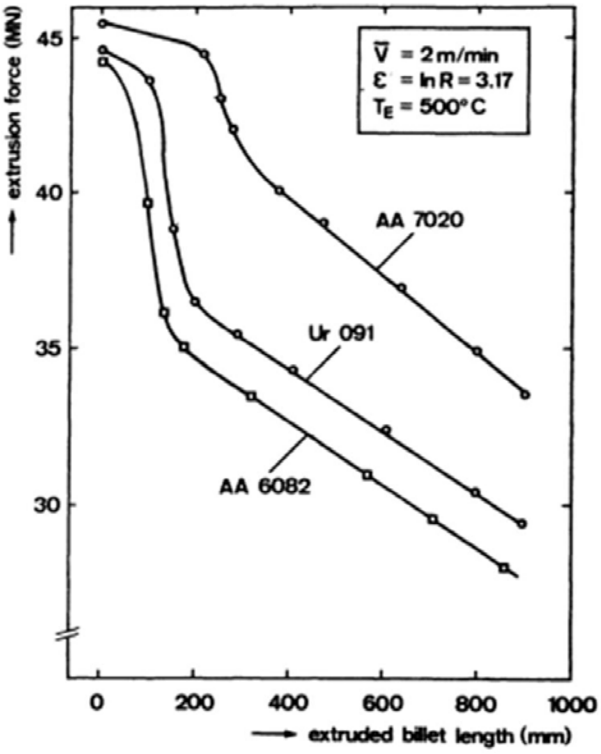

Fig. 15 – Comparison of extrudability of various Aluminium alloys [19]

However, it has to be considered that extrudability (and thus attitude to hot deformation) can be related to the flow stress of the alloys, as shown in Fig. 16. When the alloy is hot deformed, the main contribution to its resistance (i.e. to its flow stress) is constituted by solid solution strengthening.

Thus, in view of prediction of attitude to hot deformation of alloys (i.e. attitude to extrusion and rolling), a simplified approach should be that of using the amount of alloying elements (multiplied by the coefficient describing their contribution to solid solution strengthening) as the reference parameter. This approach is summarised in Fig. 17, and will be applied for low CRM alloys development.

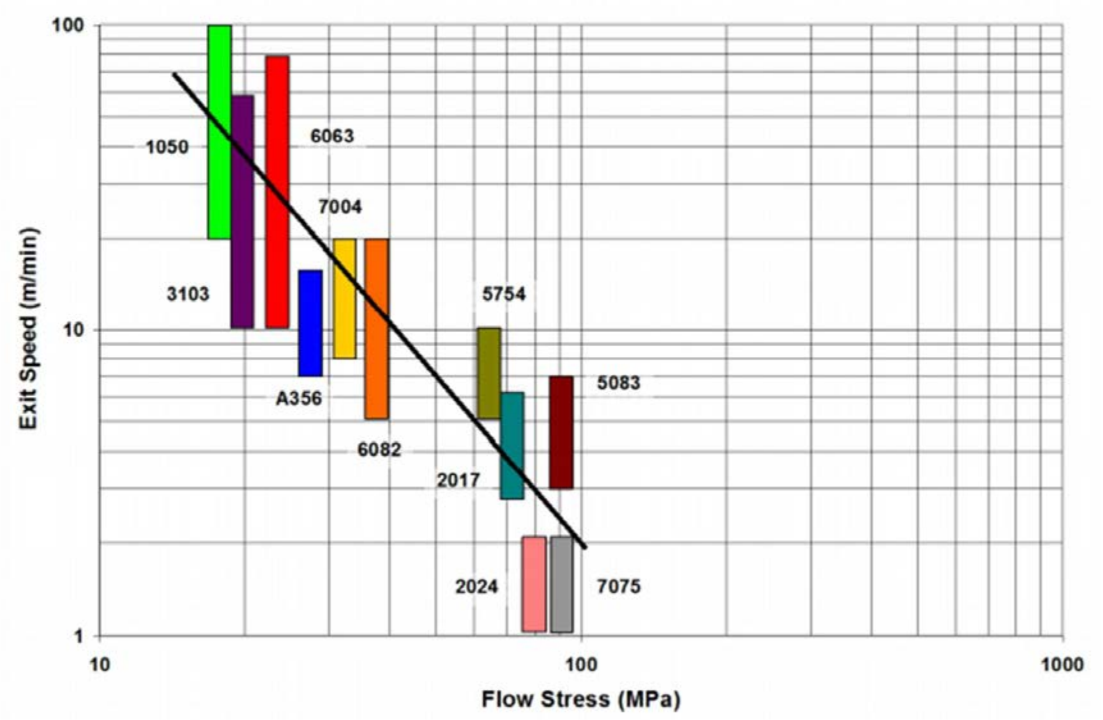

Fig. 16 – Correlation between flow stress and extrusion speed for various alloys [20]

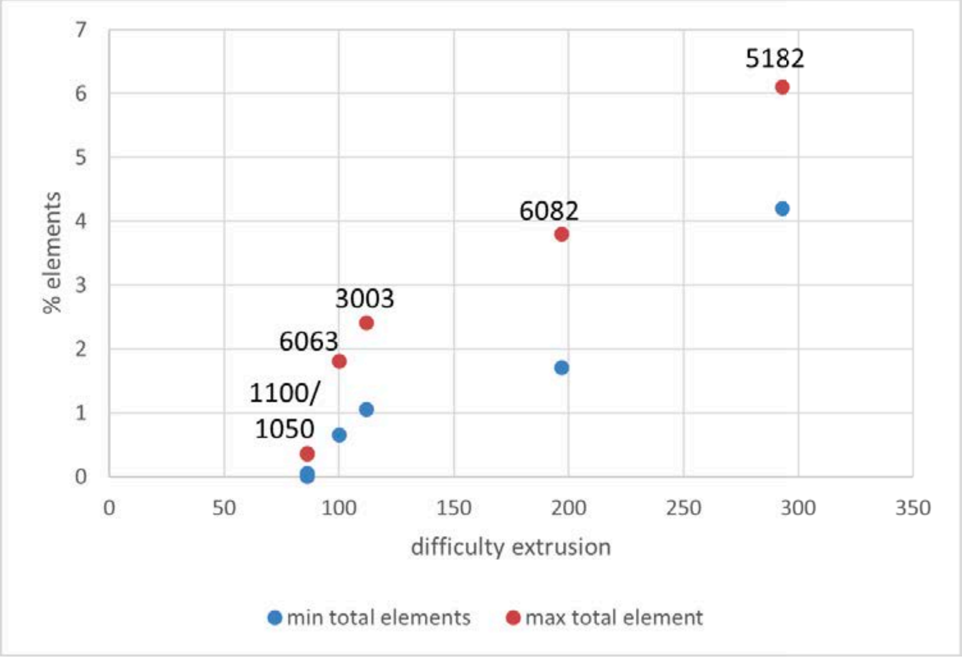

Fig. 17 – Correlation among alloying elements (Cu, Mg, Mn, Si and Zn) and extrudability

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

Stage 4: Microstructure prediction

Thermodynamic computation codes allow the evaluation of various alloys features, such as:

- Solidification interval
- Heat (ΔH)
- Latent Heat
- Viscosity
- Shrinkage (Chance in Density)
- Microstructural features (e.g. intermetallics, precipitates, amount of elements in solid solution, etc.)

as a function of temperature and composition.

For the development of low CRM 5000 and 6000 alloys, specific focus will be devoted to solubility of alloying elements (Si, Mg, Cu, Mn, Zn) and of the conditions leading to the formation of reinforcing precipitates in 6000 alloys.

5. Conclusions

Specifications required by the low CRM aluminium alloys to be developed in the next step of SALEMA activities have been defined. In particular, the following reference systems have been identified:

- **AlSi10MnMg, AlMg and Al4MgFe systems for HPDC demonstrators**
- **5000 and 6000 series for Wrought (Extrusion, Stamping) Demonstrators.**

Minimisation of CRM content will be performed by acting on Mg and Si amounts, and considering compensating effects on mechanical performance offered both by

- **elements such as Mn, Cu, Zn (solid solution strengthening) and Ti (grain refinement) for HPDC alloys**
- **optimisation of work hardening and heat treatment conditions for wrought alloys**

Peculiarities of foundry, extrusion and stamping processes will be taken into account by specific models suitable for evaluating viscosity and die soldering tendency (for HPDC alloys) and attitude to hot working (for extrusion and stamping alloys).

This approach will lead to the elaboration of Deliverable 2.2 (Report containing description of criteria and tools used for exploring alternative alloying systems, and for performing process vs microstructure optimization), and thus to the definition of candidate low CRM alloys, whose full characterisation will be performed in further WPs.

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Annex 1

Aluminium Alloys for Electric Cars: base-line concepts

Summary

The definition of the requirements for the various Aluminium-based alloys to be developed in the frame of SALEMA Project is the target of Deliverables 1.1 and 2.1. However, when elaborating these Deliverables, it appeared quite clear the need to set up a common baseline, reporting

- the current state of the art of Aluminium alloys (cast, extruded, rolled and stamped) for automotive application, with focus on electric cars,

- the key-items concerning processing and post-processing issues, accepted variations in performance, etc., which are the basis for the approach followed by SALEMA for the development of Aluminium-based alloys, with respect to current state of the art.

The baseline considerations contained in this **Annex** are the logical premises to **Deliverables 1.1 and 2.1**, and will be specifically mentioned in these documents, to motivate the approaches followed to individuate target values.

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].

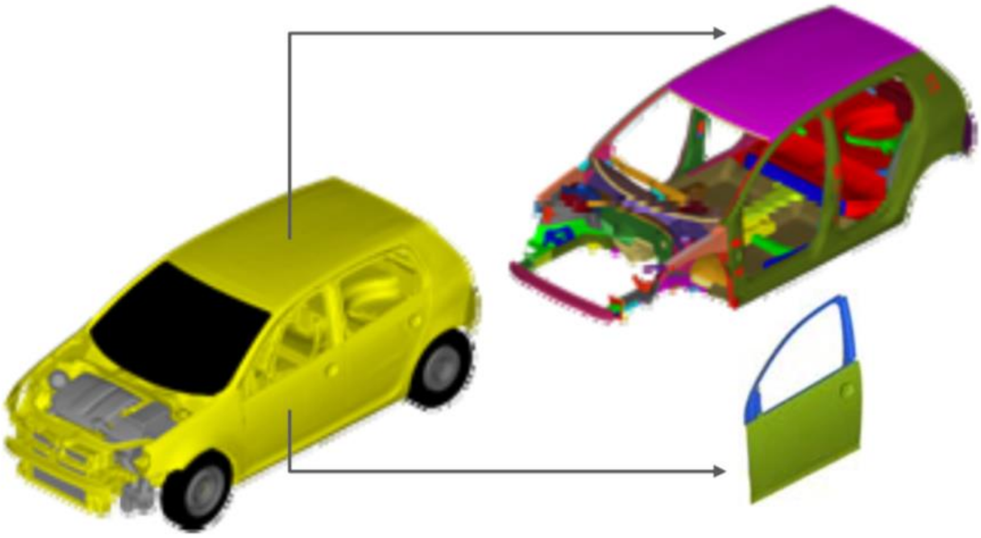

Fig. 1 – SLC-reference FE-model [1]

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.

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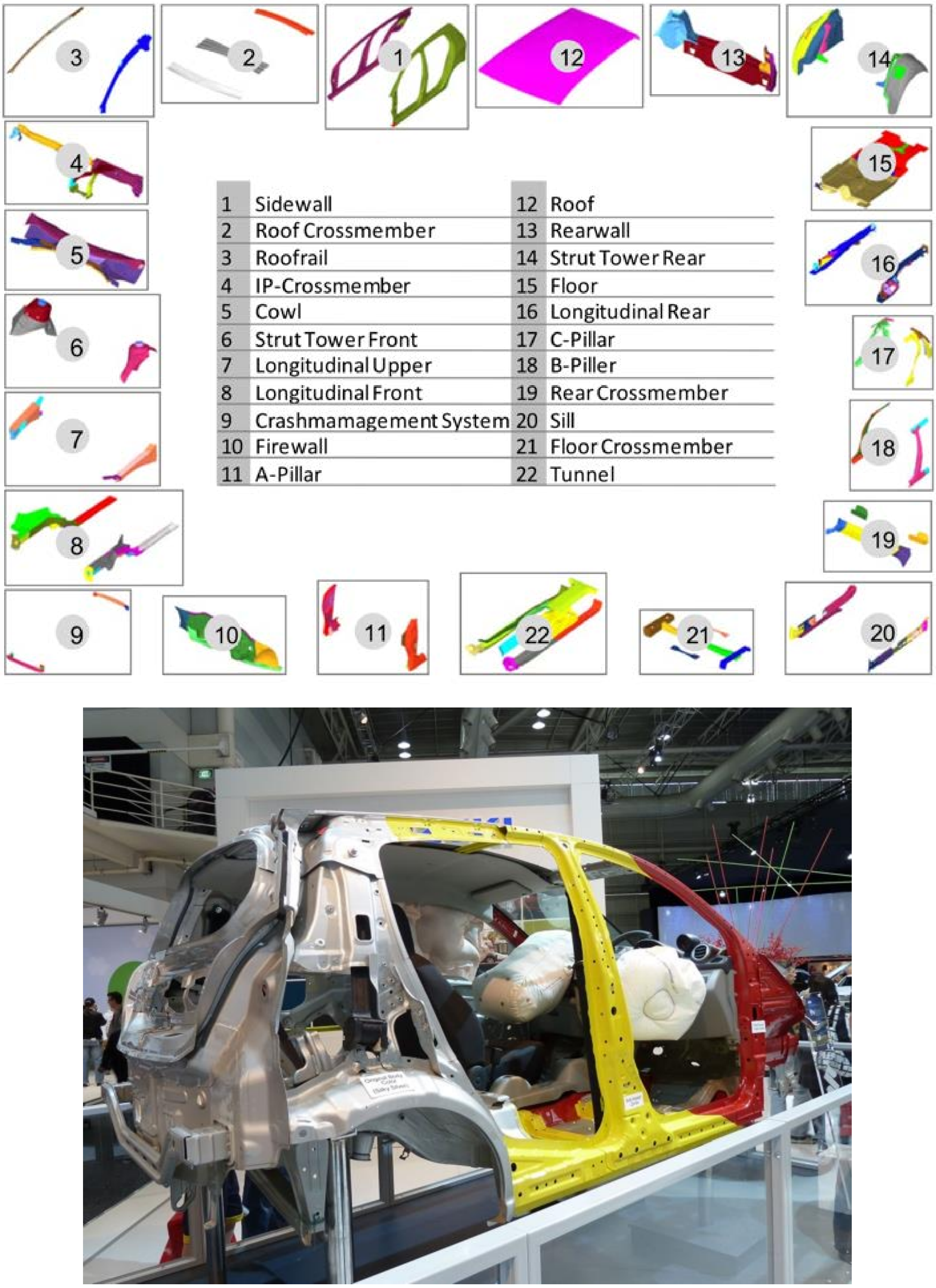

1	Sidewall	12	Roof
2	Roof Crossmember	13	Rearwall
3	Roofrail	14	Strut Tower Rear
4	IP-Crossmember	15	Floor
5	Cowl	16	Longitudinal Rear
6	Strut Tower Front	17	C-Pillar
7	Longitudinal Upper	18	B-Piller
8	Longitudinal Front	19	Rear Crossmember
9	Crashmamagement System	20	Sill
10	Firewall	21	Floor Crossmember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

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

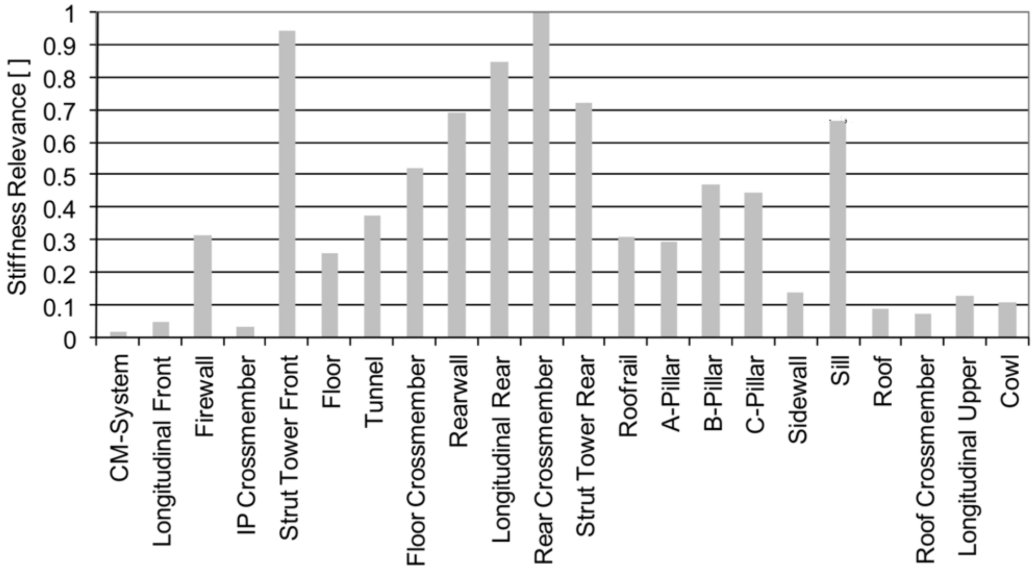

Fig. 3 – Stiffness relevance of body-in-white components for all load cases [1]

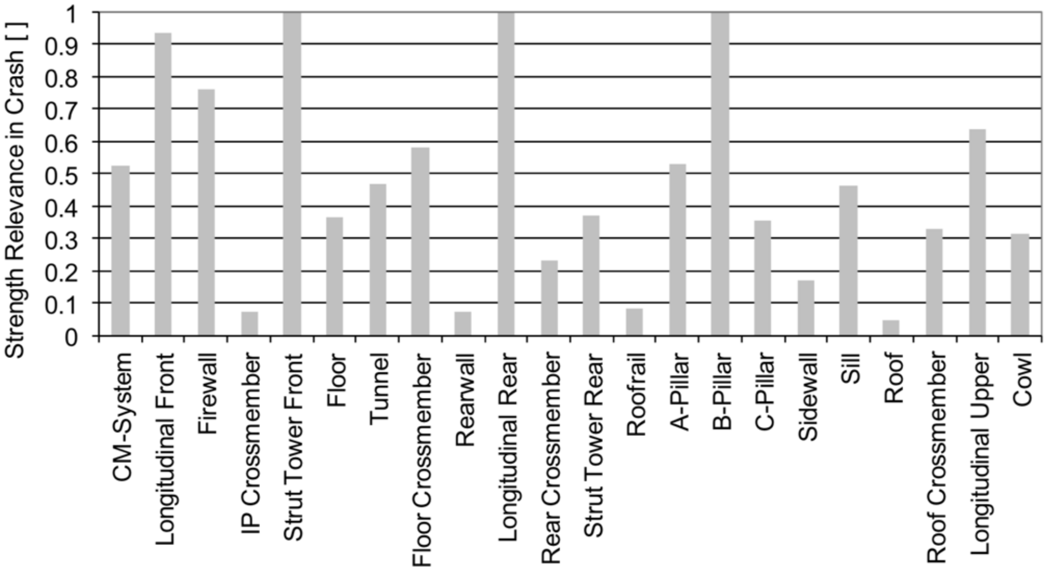

Fig. 4 – Strength relevance in crash of door components [1]

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.

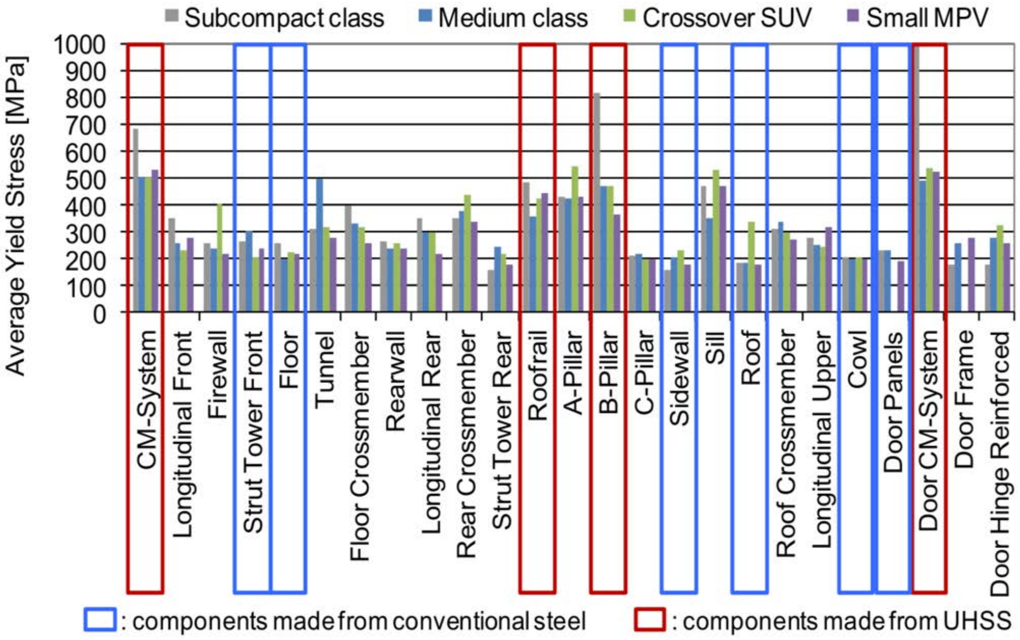

Fig. 5 – Comparison of material usage in all classes [1]

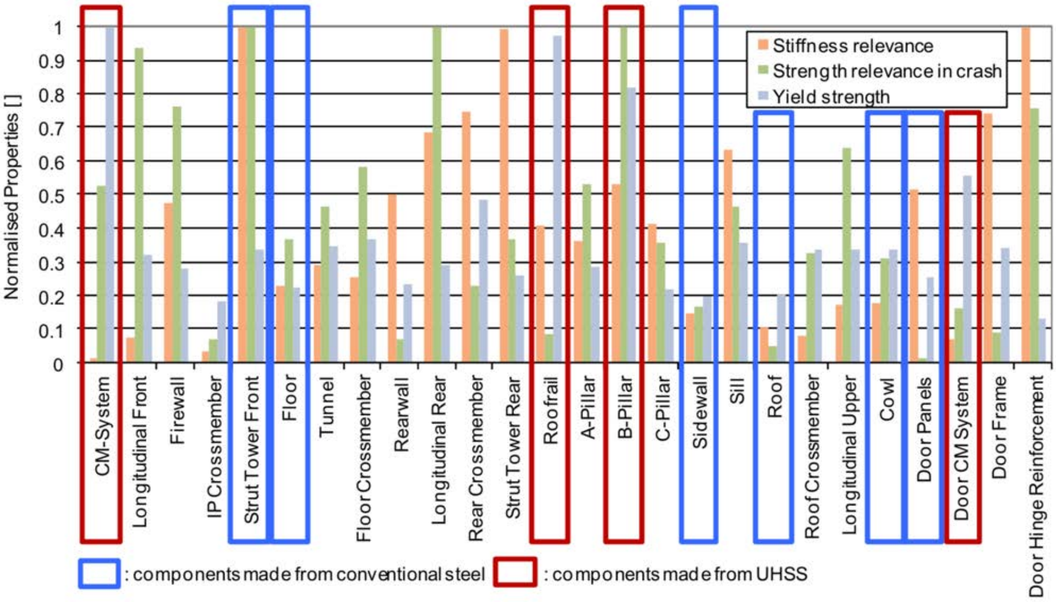

Fig. 6 – Overview of the evaluation results [1]

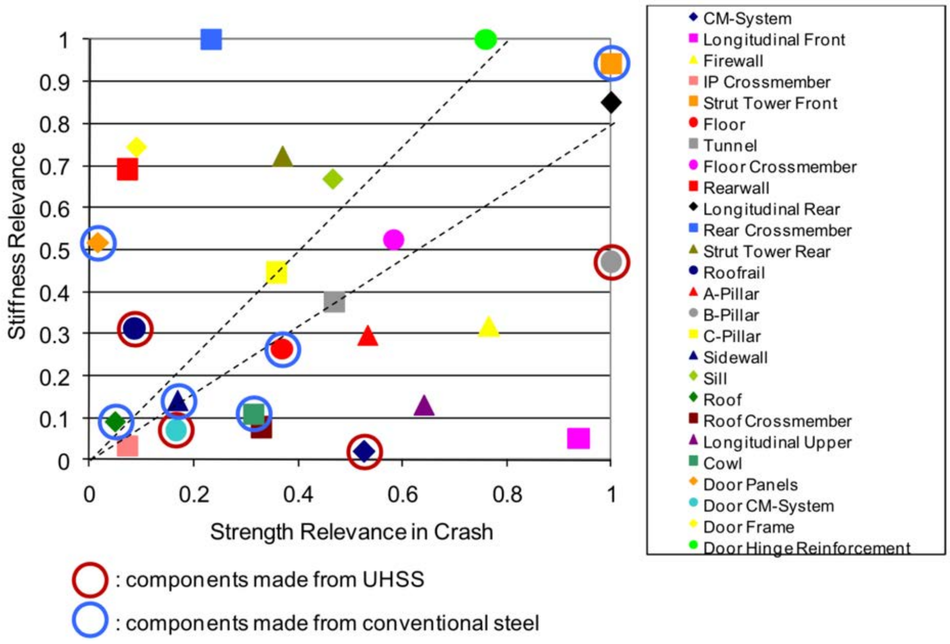

Fig. 7 – Evaluation of the UHSS body components [1]

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]

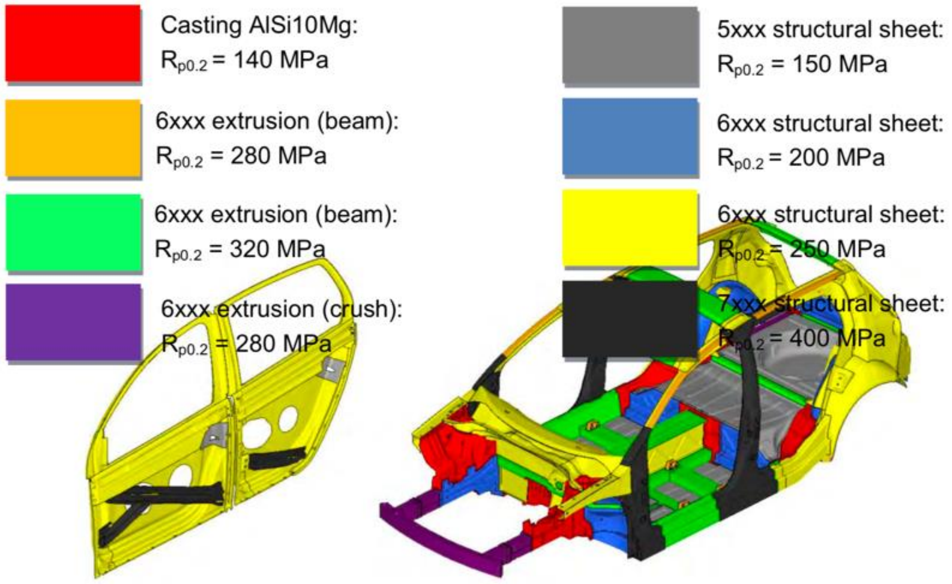

Fig. 8 – Material attribution to body-in-white, armatures and doors for target vehicle model [2]

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.

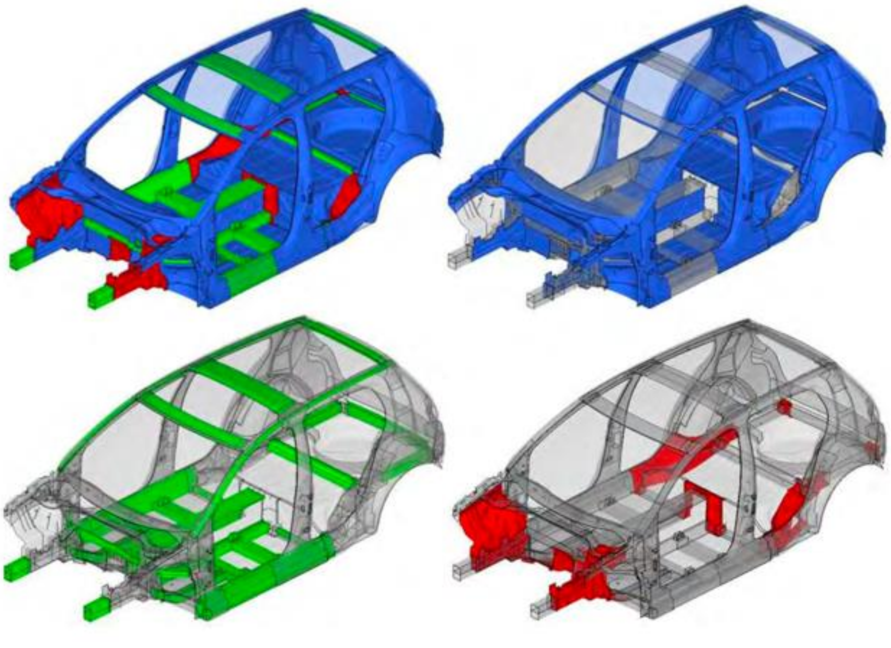

Fig. 9 – Application of aluminum manufacturing methods to the target vehicle model (blue: sheet, green: extrusion, red: casting) [2]

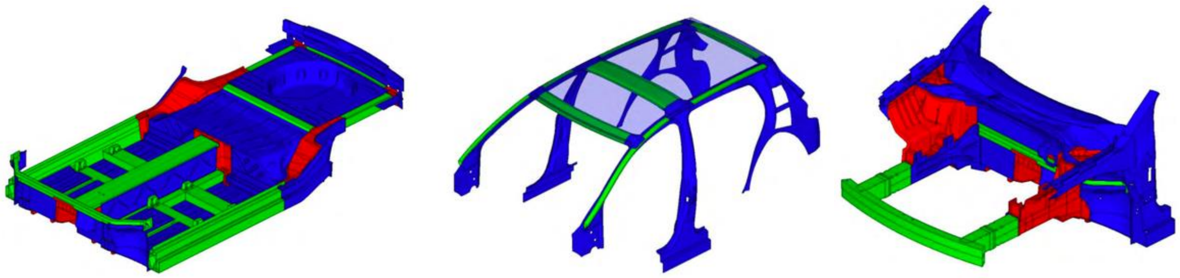

Fig. 10 – Schematic of target vehicle model floor, target vehicle model roof and target vehicle model front, respectively [2]

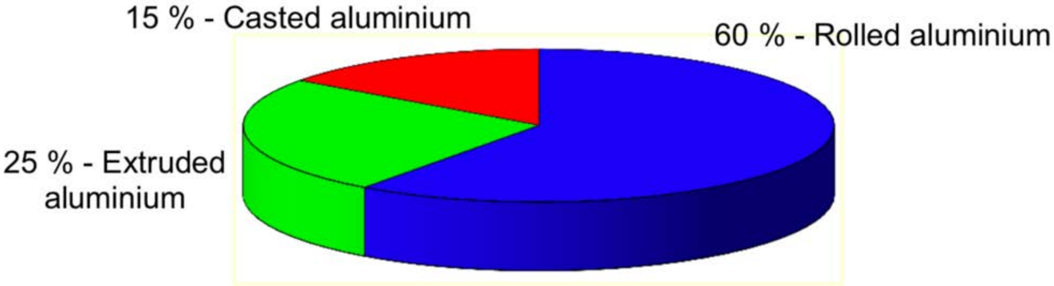

Fig. 11 – Distribution of aluminum manufacturing methods over the target vehicle body [2]

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]

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

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)

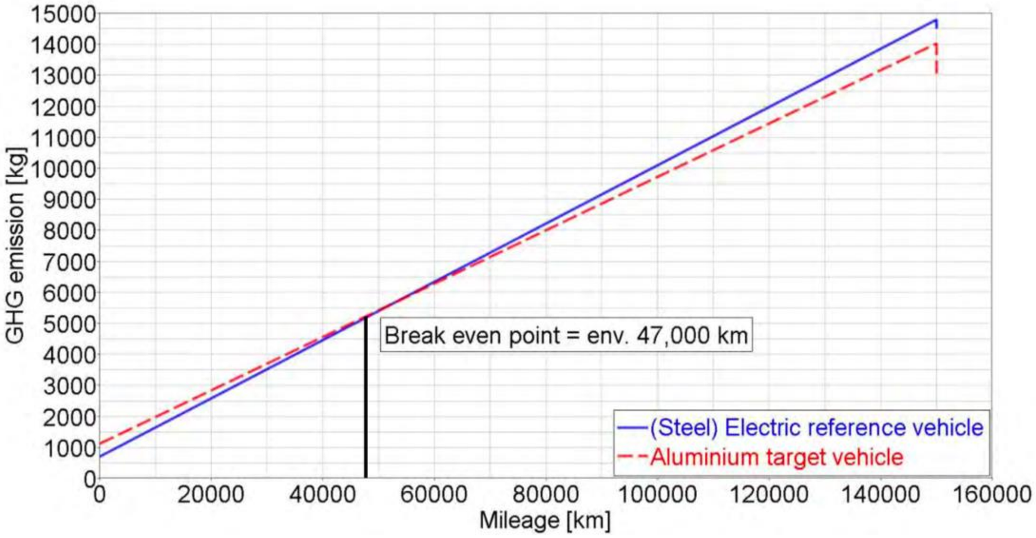

Fig. 12 – Comparison of Greenhouse Gas (GHG) emission over full life cycle for aluminum target and electric reference vehicles [2]

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).

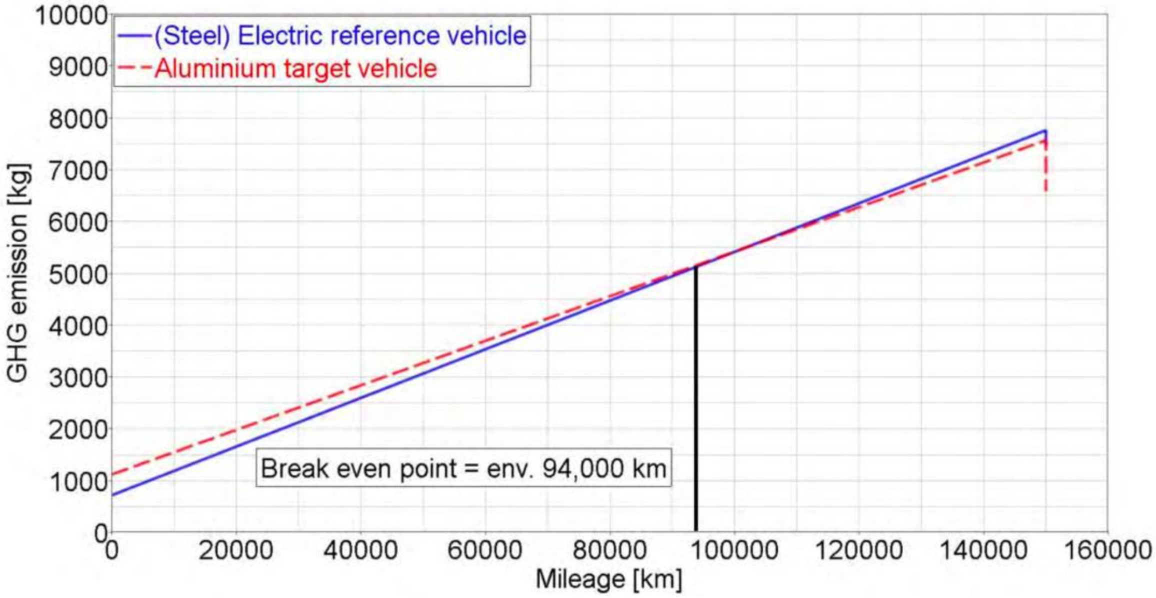

Fig. 13 – Comparison of GHG emission over full life cycle for aluminium target and electric reference vehicles with 50 % emission reduction over use phase [2]

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

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]. The European Commission periodically investigates which raw material are to be considered critical for the EU economy 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.

2. Casting Aluminium alloys: processing & properties

2.1. 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.

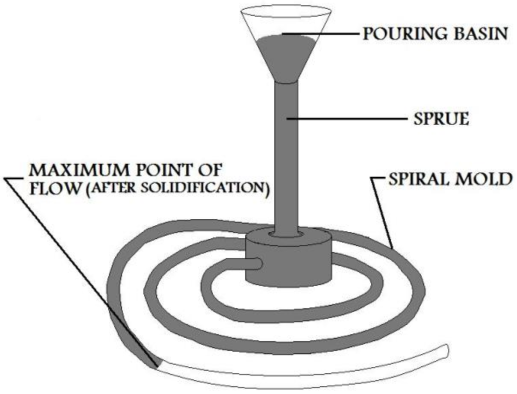

Fig. 14 — Description of the principle of Spiral Fluidity Test [7].

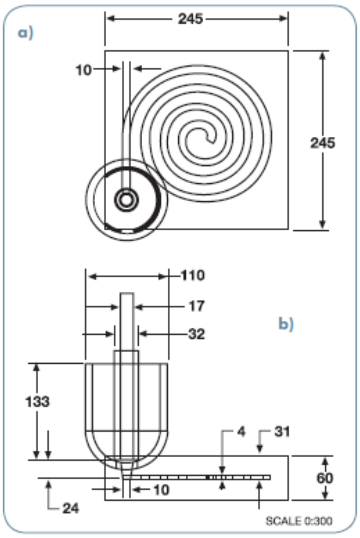

Fig. 15 — a) Top and b) side views of the spiral-shaped fluidity test [7].

<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.

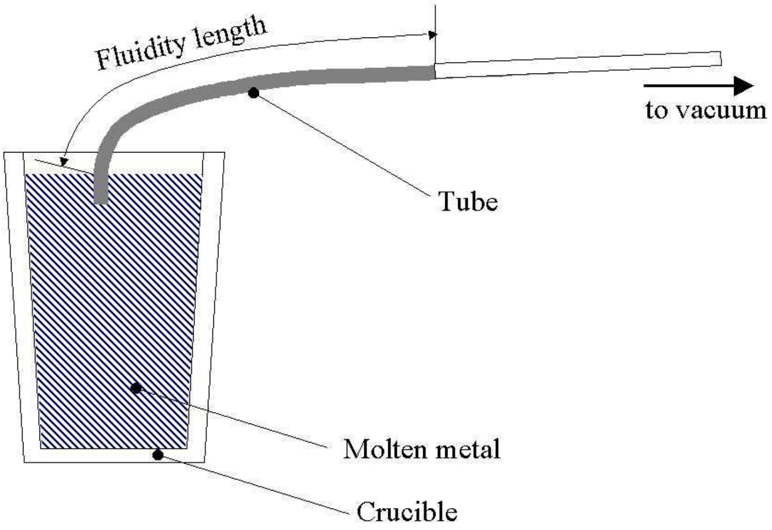

Fig. 16 — Description of the principle of Horizontal Vacuum Fluidity Test [7].

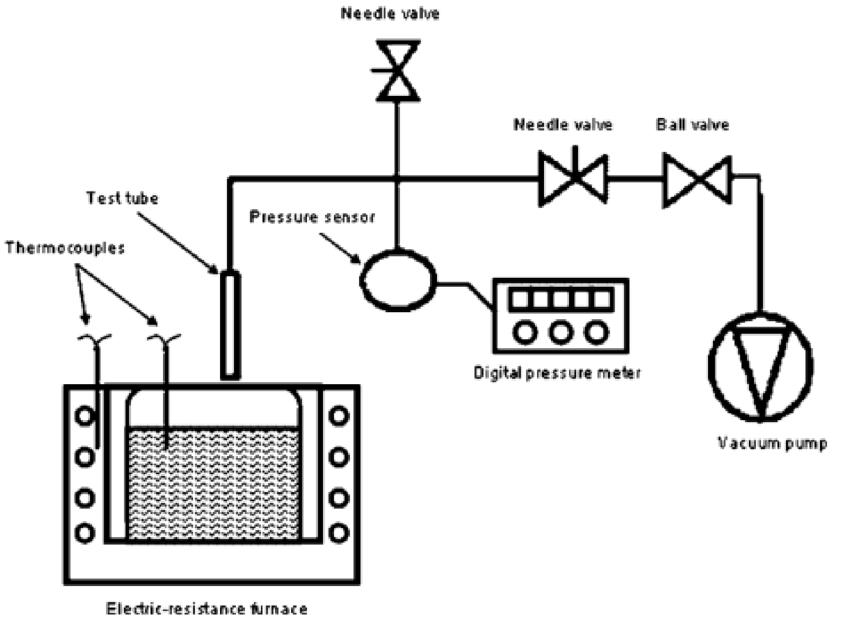

Fig. 17 — Description of the Vertical Vacuum Fluidity Test apparatus [7].

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Fluidity strip mould Test

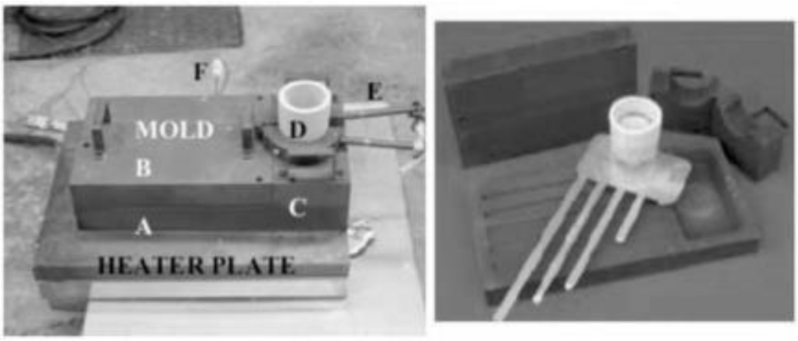
The fluidity mold (Fig. 18) consists of the following parts :

- 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].

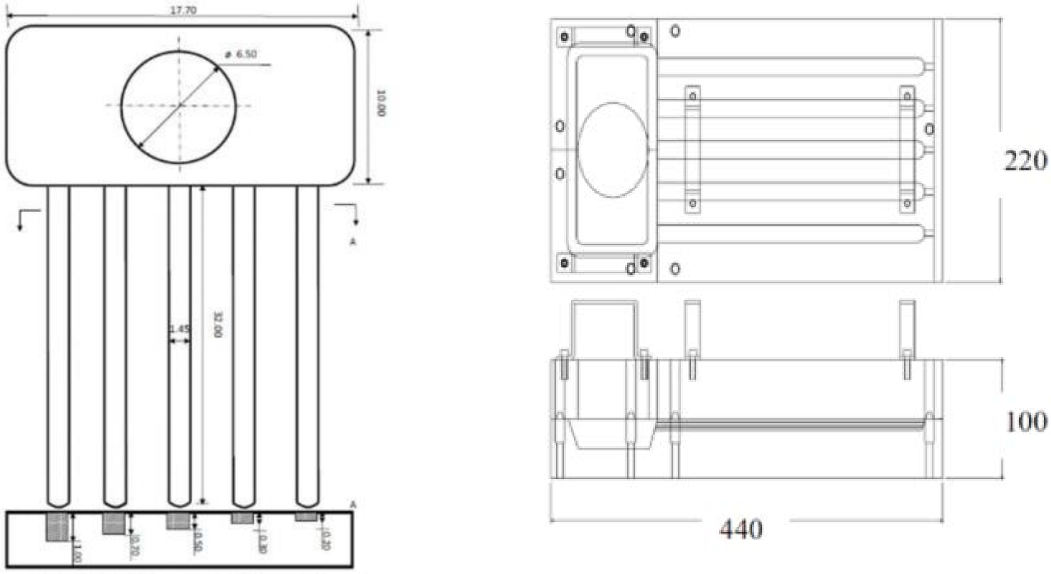


Fig. 19 — Design of Fluidity strip mould test configurations [7].

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2.2. 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.

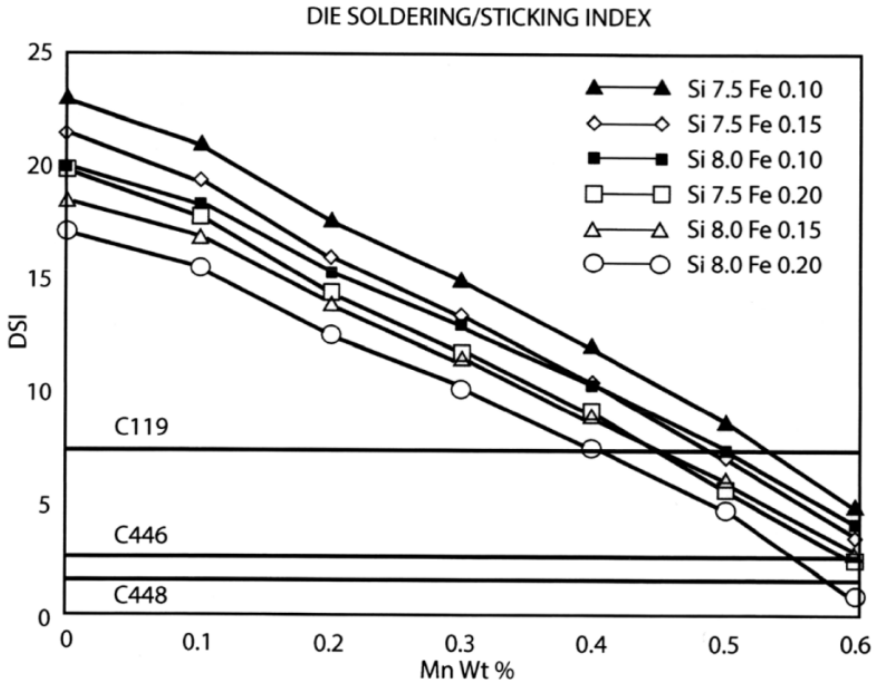

Fig. 20 – Die soldering index in several die casting alloys [8]

2.3. 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.

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).

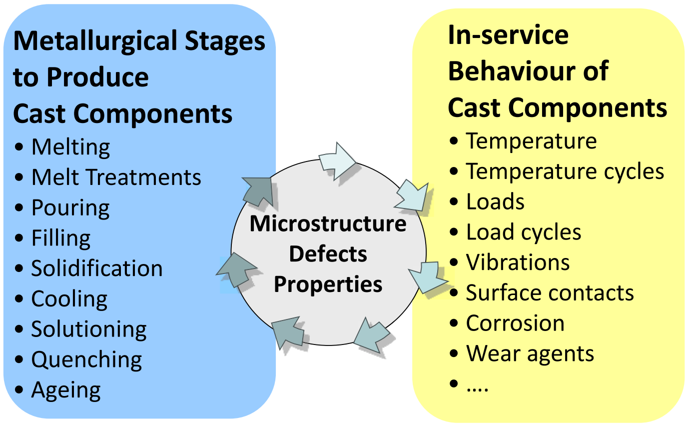

Fig. 21 – General approach to optimisation in design of Aluminium castings

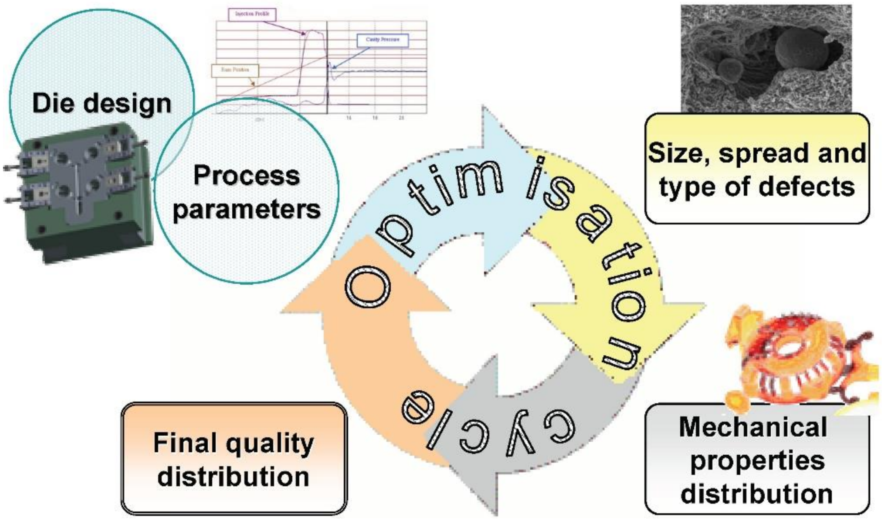

Fig. 22 – Specific optimisation cycle of a die cast component [9].

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.

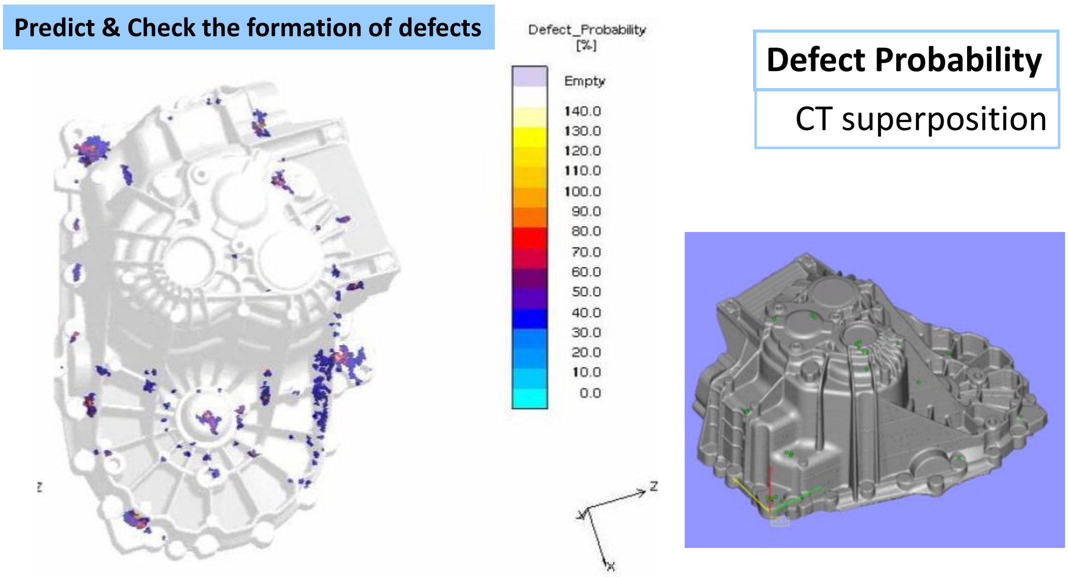

Fig. 23 – Example of defect distribution in an Al-alloy diecasting

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].

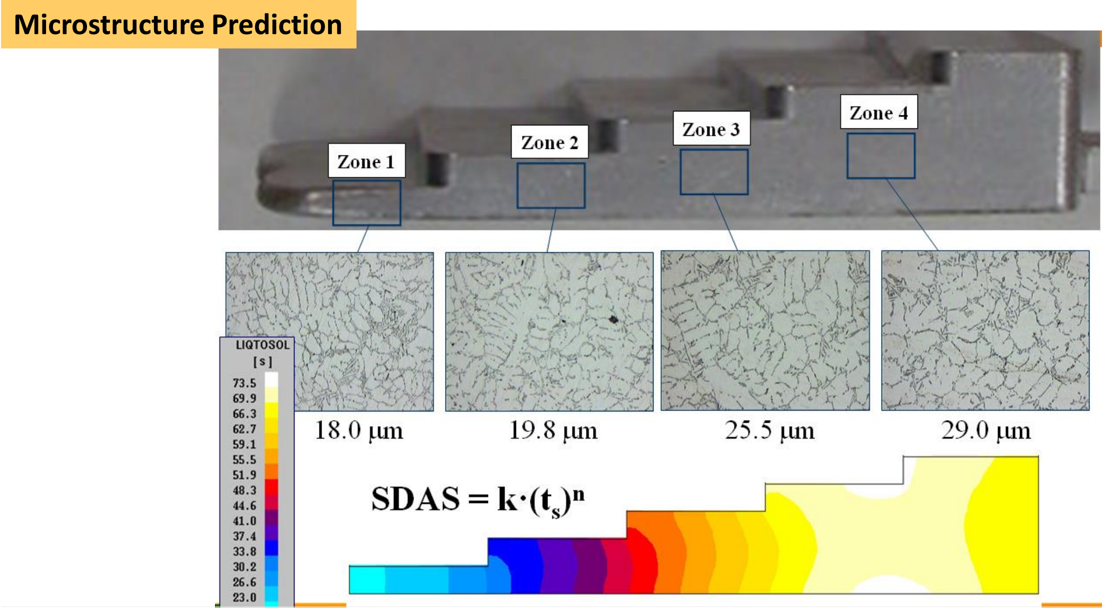

Fig. 24 – Example of correlation among casting thickness, cooling rate and microstructure (by SDAS, Secondary Dentrite Arm Spacing) [10]

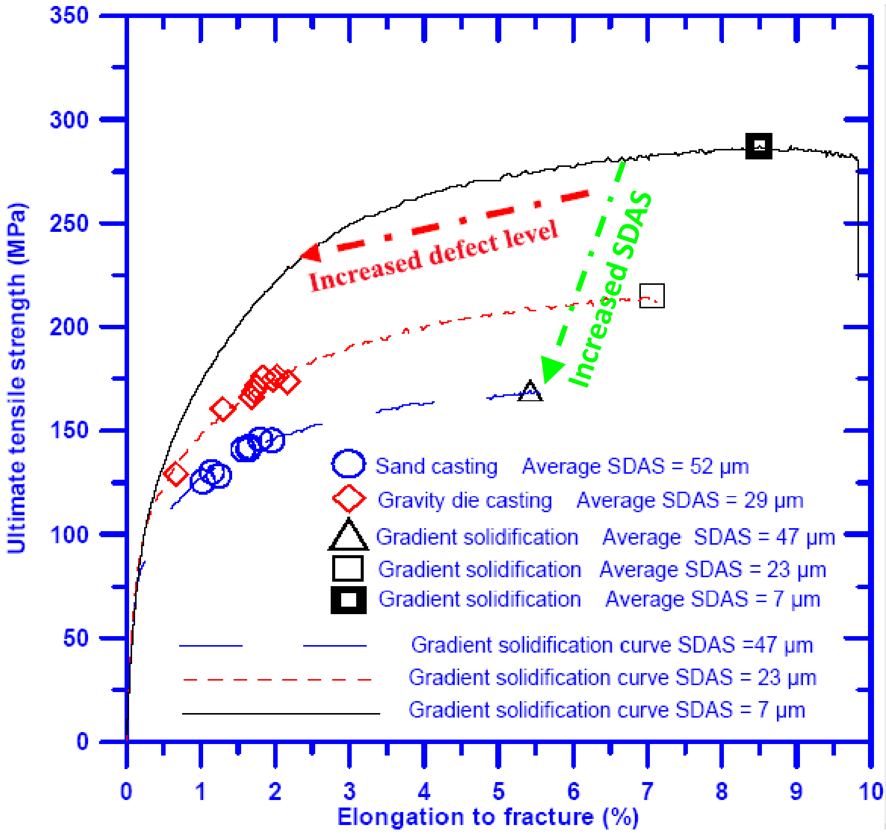

Fig. 25 – Example of correlation among casting process, cooling rate, microstructure (by SDAS) and mechanical behaviour [11]

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.

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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.

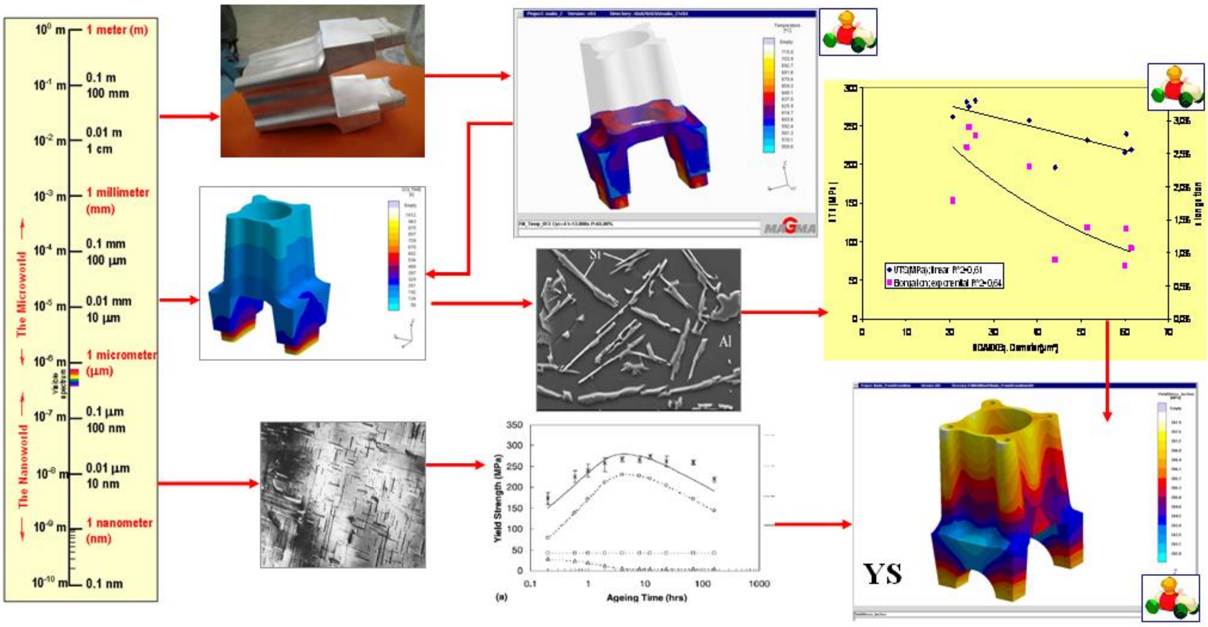


Fig. 26a – Multi-scale approach in designing Aluminium alloys castings

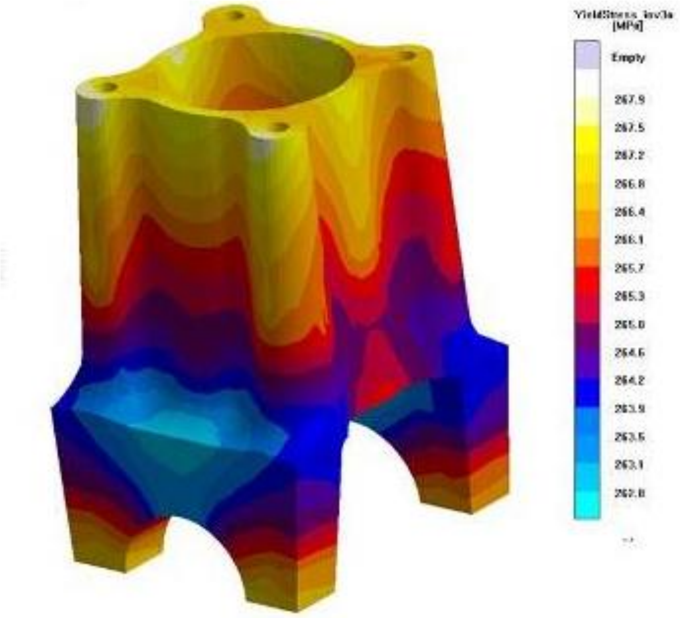
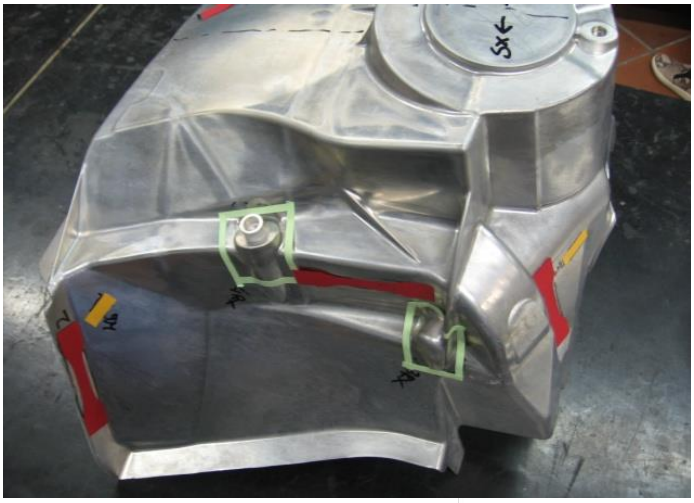


Fig. 26b – Example of YS distribution, as predicted in an Aluminium alloy casting, by means of the multi-scale design approach

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 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

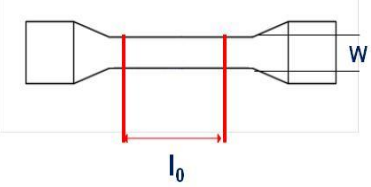


Fig. 27 – Specimens extraction form a structural HPDC casting

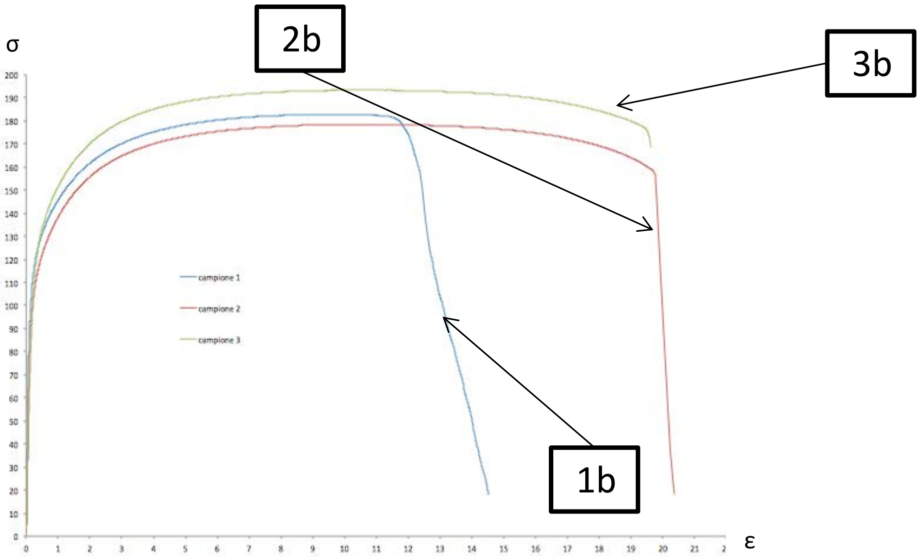


Fig. 28 – Results of tensile tests

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].

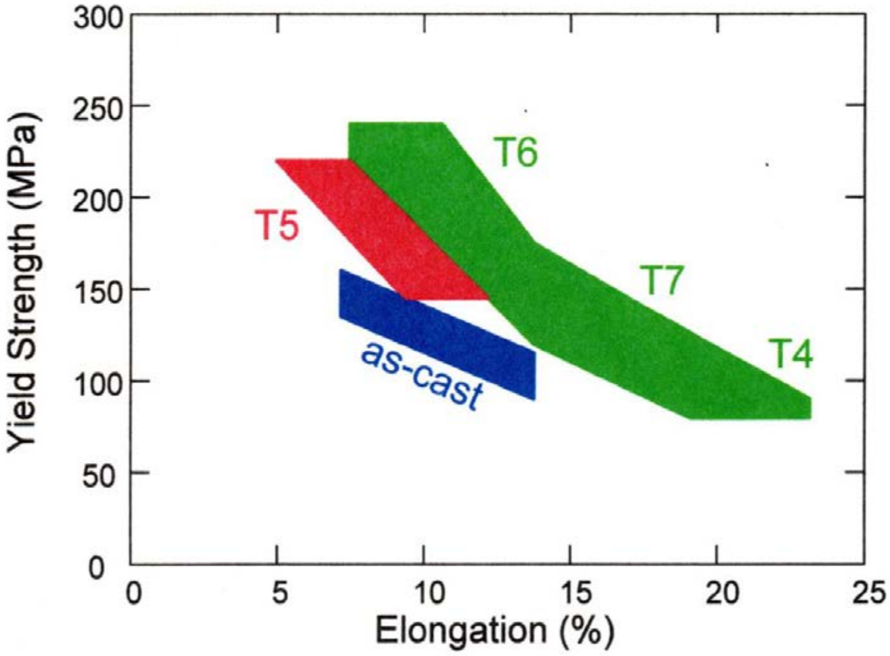


Fig. 29 – Range of properties available in structural diecastings, as a function of heat treatment

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

3.1. 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.

<u>5000 Alloys</u>

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).

<u>6000 Alloys</u>

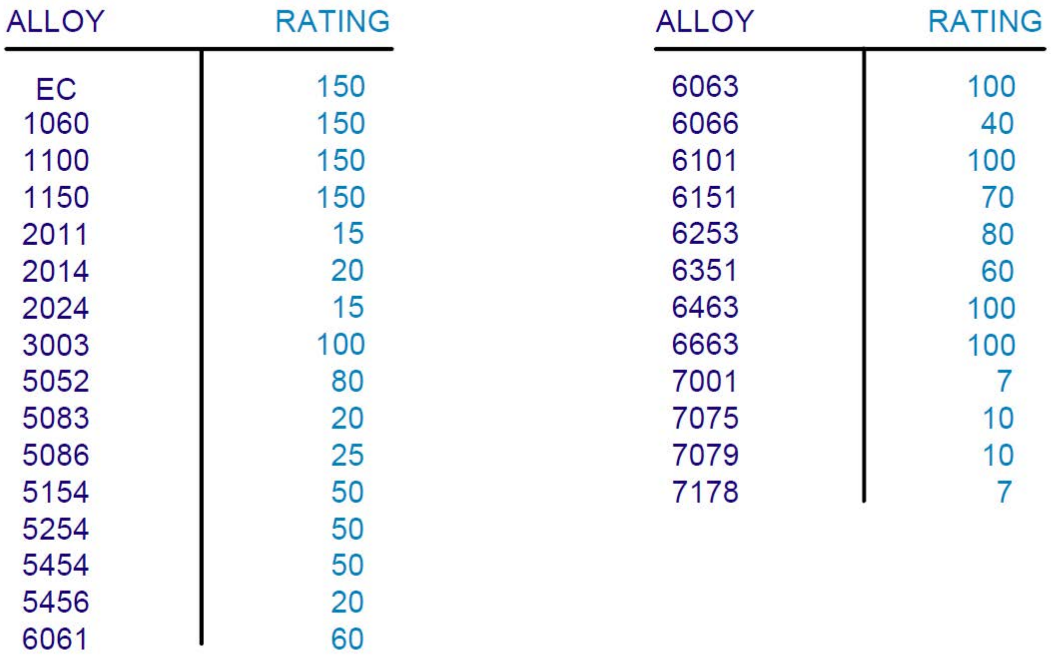
These alloys are typical Al-Si-Mg hardenable alloys, whose final mechanical behaviour is the result of precipitation hardening (performed by means of various codified treatments, e.g. T4, T5, T6 and T7, see Table 6).

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

3.2. 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		

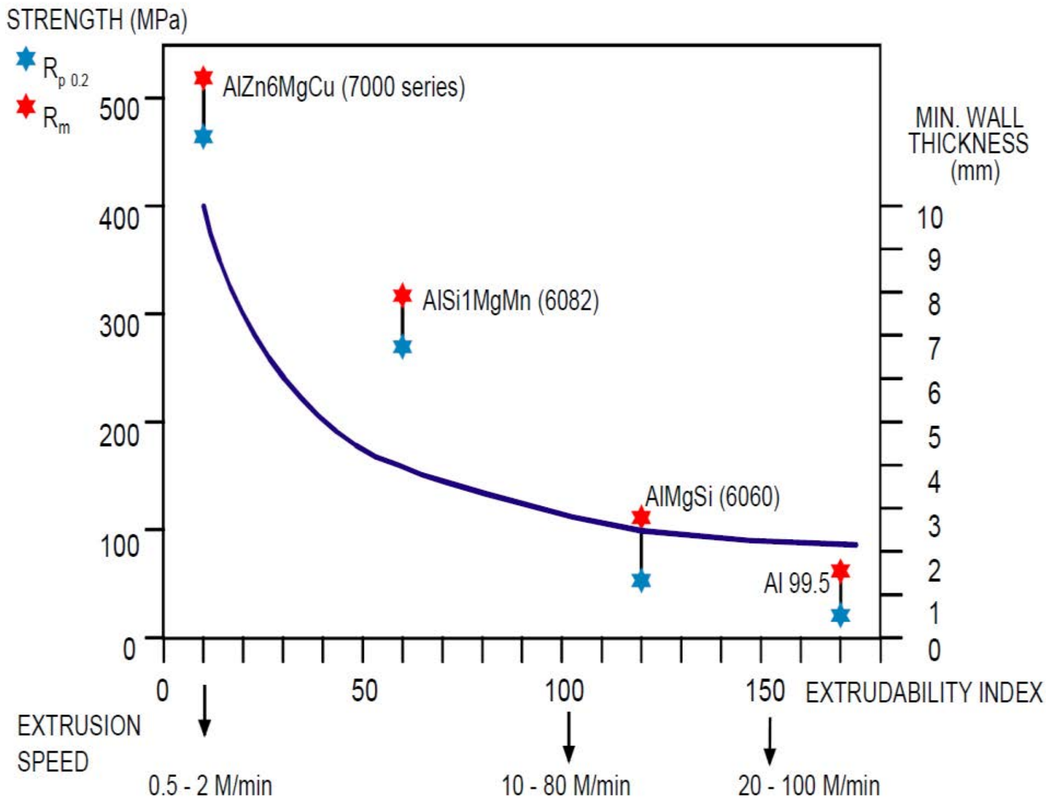


Fig. 30 – Extrudability index for various alloys

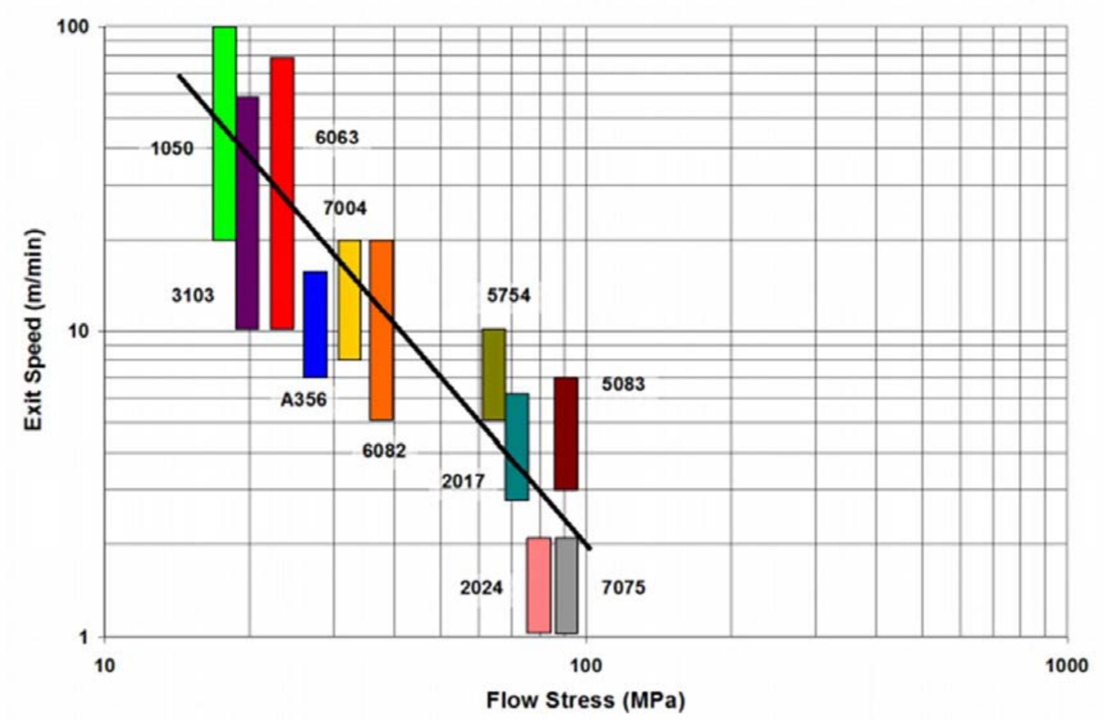


Fig. 31 – Correlation between extrusion performance and flow stress for various alloys

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4. 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.

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