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RESEARCH PAPER

LOW CARBON FOOTPRINT ALUMINIUM COMPONENTS FOR E-MOBILITY

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ABSTRACT

In the fast-evolving E-mobility transformation, the circular economy is one of the key factors to make Europe carbon neutral by 2050, together with sustainability, achievable only with a synergic approach, from raw material choice to recycling, through product design for re-purposing. Secondary aluminium alloys have a twenty times lower carbon footprint than primary metals, leading to significant CO_2 savings. Their properties can satisfy engineering targets through optimized product design. Adopting a smart system layout, in which functions are assigned to assemblies, some of the low-end mechanical properties of secondary alloys can be offset. Design for easy disassembling can then guarantee a selective re-purposing and, finally, an environmentally friendly recycling of components. Innovative products in this field have been developed and successfully produced by means of an optimized high-pressure die casting (HPDC) technology, adopting low carbon footprint raw materials supplied in alternative to ingot format. In this study, a housing component for an e-mobility module battery was manufactured using EN AC 46000 alloy (AlSi9Cu3(Fe)), sourced from automotive industry scraps. The selected scraps were melted and cast to form the battery housing. Consequently, both the initial scraps and the resulting components underwent comprehensive analysis to evaluate the alloy's quality. Chemical analyses, hardness tests, and microstructural observations were performed. The findings confirm a refined and high-quality microstructure in the casting, affirming the viability of producing battery housing through High-Pressure Die Casting (HPDC) using exclusively recycled alloy.

Keywords: Aluminium; High Pressure Die Casting; Aluminium Scrap; AlSi9Cu3(Fe); E-mobility; Recycling

INTRODUCTION

Today, the automotive market is moving towards E-mobility, and aluminium and its alloys certainly guide the fast, clean and sustainable way to make the electric transition. In fact, aluminium is renowned as a recyclable material, having excellent specific properties, and, last but not least, is already highly used in the automotive industries [1].

As a matter of fact, aluminium recycling is not an innovation: almost the whole amount of Al in the cast market comes from the recycling of scraps and end-of-life components. Aluminium production from primary sources requires very high energy consumption and a remarkable environmental impact. The production of 1 ton of primary aluminium requires 4 tons of Bauxite and 14.000 kWh of energy consumption [2]; on the other hand, remelting recycled alloys saves up to 95% of energy [3]. Considering this information, the aluminium scraps can only gain more and more consideration.

In an era where sustainability and environmental concerns are at the forefront of industrial practices, evaluating the environmental impact of various materials and manufacturing processes has become increasingly important. One area of particular interest is the production of aluminium alloy components in foundries [4]. Moreover, researchers have proven the importance of Aluminium recycling through LCA (Life Cycle Assessment) [5, 6].

Below the vast Al-alloys panorama, the alloy EN AC 46000 (also known as AlSi9Cu3(Fe)) finds extensive application in the automotive sector to cast thin-walled components through HPDC (High-Pressure Die Casting). Profound studies have already been conducted on such alloy, mainly in studying its microstructures and mechanical properties. Particularly, Puga et al. [7] focused on the alloy microstructures, highlighting the presence of certain phases: dendritic α-Aluminium, the eutectic Si plates, the intermetallic phase called Chinese script α-$Al_{15}(Mn,Fe)_3Si_2$ (α-Fe), the θ-Al_2Cu (θ phase), the acicular shaped Al_5FeSi phases (β-Fe) and π-$Al_8FeMg_3Si_6$ (π-Fe). Furthermore, intermetallic phases such as Al_5FeSi may negatively affect the mechanical behaviour since their shape acts as stress concentration phases, causing a premature failure of components. In this case, the addition of Co, Cr, Mn, Mo and Ni elements to convert β-Fe platelets into α-Fe Chinese script form may be considered [8].

Despite HPDC representing the primary production process used to obtain automotive Al components, Piekło et al. [9] recently proposed the usage of selective laser melting as a replacement for such technology. The authors highlighted that this kind of replacement may be considered only for a short series of manufactured parts. In this sense, HPDC is still competitive and represents the primary production process for casting AlSi9Cu3(Fe) powertrain components. Using secondary alloys represents the key to a suitable and environmentally friendly production. Kasińska et al. [10] and Matejka et al. [11] conducted experiments to evaluate the influence of Fe content on the remelting of

AlSi9Cu3 alloy in terms of microstructures and mechanical properties. The authors observed severe changes in mechanical properties and microstructural features after the fourth remelting, causing the structural component's degradation. The β-Fe phases and eutectic Si evolve into thicker and brittle structures, worsening the tensile strength and the ductility. Moreover, a further study suggests that the melting temperature of scraps must be below 750°C to avoid the formation of toxic dross [12].
Recently, [13] Djurdjevic et al. proposed an analysis of the Al-Si alloys suitable for the e-mobility market, analyzing their mechanical and thermophysical properties, dimensional stability, corrosion resistance and electromagnetic compatibility. Authors analyze various compositions and propose the use of EN AC 47000 (AlSi12(Cu1)), EN AC 44300 (AlSi12(Fe)), EN AC 43500 (AlSi10MnMg) and EN AC-42100 (AlSi7Mg).
In the present work, belonging to EU-financed projects [14], the remelting of scraps represented the way to produce HPDC E-mobility motorcycle components. AlSi9Cu3(Fe) scraps have been obtained from selected defective cast and end-of-life components and re-entered into the HPDC process without adding fresh ingot alloy. Challenging thin wall-thickness components (< 1,5mm) with limited draft angles (< 0,2°) have been designed to satisfy engineering requirements and compete with alternative technologies (i.e. extrusion). Thanks also to a fast-cooling process, the component analysis highlights the very good microstructure without thick Fe-based intermetallic phases.

MATERIAL AND METHODS

Materials

The alloy AlSi9Cu3(Fe), EN AC 46000, was provided by RMB SpA from a wide range of automotive scraps in small pieces carefully selected to guarantee the chemical composition aspects. The raw material format (hereinafter called RESAL) is shown in **Fig. 1**.
Before producing components through HPDC, the RESAL-alloy quality was assessed through different preliminary analyses. Such analyses involved the chemical analyses optical emission spectrometer, the hardness measure and the Differential Scanning Calorimetry (DSC) analyses. Results were compared with the ingot alloy. To obtain an average compositional response, a total of 10kg of RESAL and 10kg of certified ingots alloys were separately melted in an electric furnace at 700°C, without adding dross fluxes, and cast into a mould, obtaining five tablet specimens of 50mm in diameter and 20mm in thickness (**Fig. 2**). Chemical analyses, DCS analyses and Brinell measurements were performed on such specimens.

Fig. 1 RESAL supply format [15].

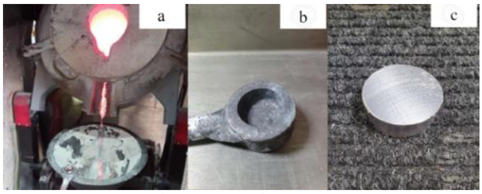


Fig. 2 Production of specimens for alloy characterization. a) casting; b) mould; c) obtained specimen [15].

RESAL composition was analyzed through an optical emission spectrometer (Spectrolab, Ametek) and compared with the certified ingot composition [15], and results are shown in **Table 1**. Overall, five chemical analyses for each alloy were carried out.

Table 1 Average alloy compositions w.t.% (RESAL and ingots).

Elements	*Si*	*Fe*	*Cu*	*Mn*	*Mg*	*Zn*	*Ti*	*Al*
RESAL	8.13	0.64	1.91	0.19	0.24	0.87	0.043	bal.
Ingot	8.16	1.03	2.02	0.29	0.17	0.95	0.066	bal.

Regardless of the results of the chemical analyses shown in **Table 1**, it is evident that slight compositional variations are always possible due to the diverse nature of the scrap component selection.

Methods

The RESAL alloy was loaded into a 5 tons gas-fired melting furnace, degassed and transferred to the HPDC cell to produce an innovative battery module housing concept (BM-Basic Module) by Endurance Spa. The HPDC of the BM-Basic Module battery housing was performed on a 1350-ton machine using the following working parameters: metal temperature set at 710 °C, injection speed at 2,67 m/s and max pressure at 220 bar. The obtained component is shown in **Fig. 3**.
RESAL and ingot alloys in tablet form, as in **Fig. 2-c**, were studied in terms of Differential Scanning Calorimetry (DSC parameters: temperature up to 650°C and a heating rate of 10 K/min) [15]. Even the Module battery housing produced in Endurance [14] was evaluated through DSC analysis (temperature up to 650°C and a heating rate of 10 K/min) using a Setaram Typ. TGA 92 16.18 DSC.

Fig. 3 BM- Basic Module battery housing.

Brinell hardness measurements were performed following the ASTM E10-23 standard (load 62.5kg, indenter diameter 2.5mm, 5 indentations) on the RESAL and ingot tablets [15] and through a universal macro-durometer tester Emcotest Typ M4U 025 on the cast component of **Fig. 3**.
Optical microscope analyses were conducted to observe and compare the microstructures of the RESAL section and the cast

battery housing obtained. Samples were ground through SiC papers up to 2400 grit and then polished using diamond pastes of 6μm, 3μm, and 1μm; finally, the mirror polishing was obtained by colloidal silica 0.04μm.
Scanning Electron Microscope SEM Zeiss EVO15 equipped through EDX probe Oxford Ultim Max 40 was used to evaluate the intermetallic phases composition in the final cast obtained.

RESULTS AND DISCUSSION

DSC analyses

DSC analyses on ingot and RESAL alloys were performed. Results obtained for the ingot alloy and RESAL alloy tabs of **Fig. 2-c** during the heating step showed slight differences in peak temperatures (**Fig. 4**).
In RESAL alloy, peaks of eutectic melting appear at slightly lower temperatures. Particularly, peaks at 506.9°C (ingot) and at 498.4°C (RESAL - tablets) indicate Cu-based intermetallic compounds, while peaks at 571°C (ingot) and 569°C (RESAL) indicate the eutectic silicon melting. The additional peaks after the eutectic melting at almost 584°C and 587°C refer to the alloy melting [15].

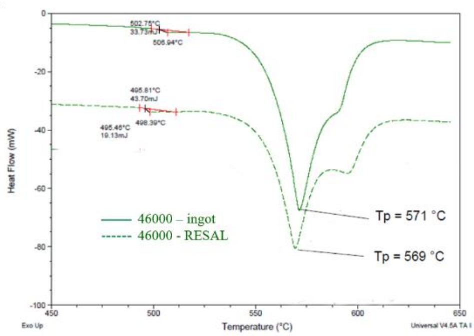


Fig. 4 DSC analyses - RESAL and Ingot tabs.

DSC analyses were further performed on the module battery housing. **Fig. 5** reports the DSC in both cooling and heating scanning. During the heating ramp-up, only the alloy melt was detected, at about 591°C, while in the cooling step, different phases were detected such as the eutectic silicon formation (539.7°C) and the Cu-based intermetallic compounds nucleation (494.1 °C).

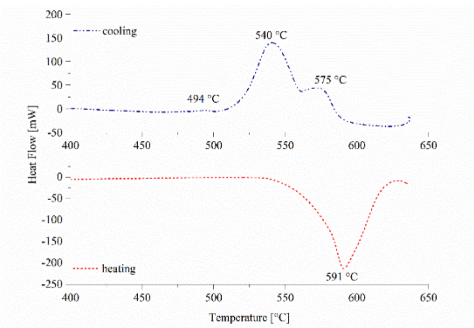


Fig. 5 DSC analyses in the heating and cooling conditions for the Module battery housing alloy.

Brinell hardness

After the surface polishing, Brinell hardness was measured for each type of alloy (certified ingot, RESAL and casting). Results highlight similar average values for both ingot and RESAL tablets and a slightly higher standard deviation in the RESAL tablets specimen, with an HB value of 77.4±6 HB compared to the ingot value of 78.1±1.8 HB [15].
Brinell hardness measures were further performed on the module battery housing component and on a single casual section of RESAL in the as-supplied form, (form previously shown in **Fig. 1**). Results highlight a slightly lower hardness in the casted part, 72 ±1.5 HB, similar to the hardness measured in the RESAL section (73 ±1.6 HB). The complete results are shown in **Fig. 6**.

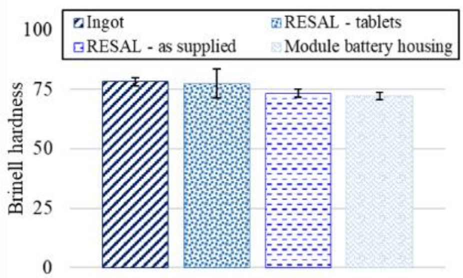


Fig. 6 Brinell hardness results.

The RESAL sample (RESAL tablets sample) is characterized by greater variability, with respect to the RESAL as-supplied piece of alloy, due to different compositions and processes that define the selected scraps, likely exerting a more significant influence on the final hardness.

Microstructures

From the perspective of Brinell hardness measurements, the alloys appear to exhibit similar behaviour. Consequently, additional microstructural evaluations are necessary to observe the shape and type of intermetallic phases.
Fig. 7 reports the microstructures at magnifications 20x and 50x observed in the RESAL and ingot tablets.
Fig. 8 and Fig. **9** show the microstructures at magnification 20x and 50x for both the RESAL section alloy and the battery housing. The RESAL alloy microstructure presents a large plate-like shape silicon (**Fig. 8**). In contrast, a very fine and refined eutectic structure in cast alloy is noticeable (**Fig. 9**).
Intermetallic Fe and Cu-containing phases were noticed in both alloys [16], along with π-$Al_8FeMg_3Si_6$, α-$Al_{15}(Mn,Fe)_3Si_2$ and β-Al_5FeSi phases. Intermetallic phases Zn-containing were not clearly noticed.
In **Fig. 7**, **Fig. 8** and **Fig. 9**, numbers indicated the phases detected and, particularly:
1: α-Al. It represents the matrix. Other elements may be present in this phase, thanks to their high solubility in the matrix.
2: Eutectic Silicon. The eutectic silicon typically appears as very fine and acicular (**Fig. 7-a,c**) or large and polygonal (for instance in the ingot **Fig. 7-b,d**). The heat treatment, the production process or the modification treatment causes its spheroidization, as in **Fig. 9** [17].
3: Script-like π-Fe. Known as π-Fe, this intermetallic phase, π-$Al_8FeMg_3Si_6$ was in particular noticed in RESAL alloy, mainly because the battery housing microstructure is too fine to clearly observe intermetallic phases at the optical microscope [18].
4: α-$Al_{15}(Mn, Fe)_3Si_2$. Known as α-Fe, this polygonal Fe-based phase was noticed in all the specimens, mainly thanks to the Mn

amount that modifies the shape of the acicular Fe-based phase [18].

5: β-Al_5FeSi. Known as β-Fe, this acicular phase is detrimental to the microstructure because it acts as a stress concentrator, decreasing the alloy's toughness. It is a typical intermetallic phase in Al alloys, particularly in the HPDC components; in fact, it was noticed in RESAL Fig**. 7** and in the cast component **Fig. 9**. Notably, in the cast component it appears very thin and shorter than in RESAL microstructures **Fig. 7** [18].

6: Cu intermetallic phases. These phases were mainly noticed in RESAL and ingot alloys. In fact, the cast microstructure appears too fine to distinguish such phases, which are typically very small [19, 20].

7: Q-phase $Al_5Cu_2Mg_8Si_6$. This phase was noticed only in the ingot alloy (**Fig. 10**) and was observed in combination with θ-Al_2Cu, as reported by Toschi [19].

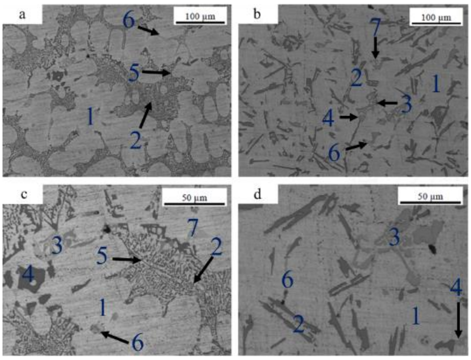


Fig. 7 Optical Microscope images. RESAL tablets microstructures (a, c) and ingot microstructures (b, d).

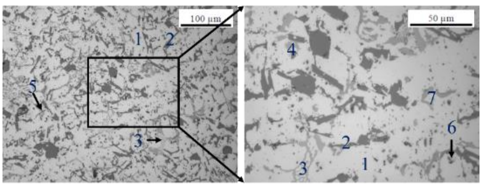


Fig. 8 Optical Microscope images. RESAL section microstructures. Magnification 20X (left) and 50X (right).

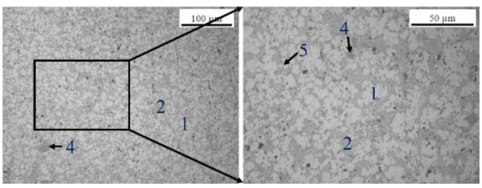


Fig. 9 Optical Microscope images. Cast microstructures. Magnification 20X (left) and 50X (right).

Even the SEM micrographs in the casted part highlight the presence of complex intermetallic phases such as the iron-based phases and Cu-based phases (**Fig. 11**). A certain amount of Cr was detected in the plate-like intermetallics, despite Cr results in very low amount (0.036 w.t.%) in the optical emission spectroscopy, and it was not reported in **Table 1**. This behaviour further highlights the variability of the alloy composition.

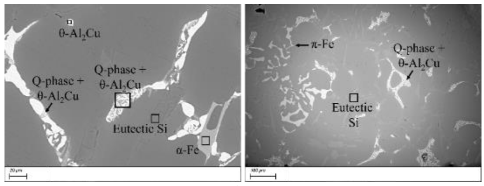
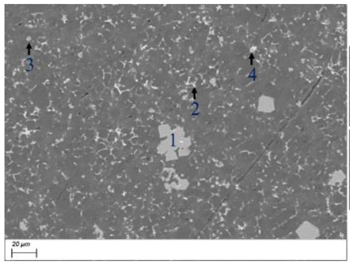


Fig. 10 SEM images. Ingot (left) and RESAL (right).



1	
Element	Wt%
Al	61,5
Fe	17,6
Si	10,3
Mn	7,2
Cr	3,4

2	
Element	Wt%
Al	70,6
Cu	16,6
Si	7,6
Fe	4,1
Mg	1,1

3	
Element	Wt%
Al	66,8
Fe	14,5
Si	10,9
Mn	4,6
Cu	1,9
Cr	1,3

4	
Element	Wt%
Al	84,5
Cu	11,6
Si	3,8

Fig. 11 SEM image and EDX analysis in cast component (Fig. 3).

DISCUSSION

The RESAL alloy, which is an alloy obtained after the remelting of AlSi9Cu3(Fe) scraps, presents a microstructure strongly dependent on the production process. These scraps, which are automotive components at the end-of-life or production scraps, are characterized by variable compositions depending on the origin of the starting ingots; for instance, Fe and Zn amounts may change, or Cu may be in higher or lower amounts. At the same time, their microstructure may change as a function of the production process (pressure, temperatures, casting additives). The chemical composition could be altered due to incorrect casting parameters or dross formation, with subsequent oxidative processes or loss of Mg.

In particular, when a certain amount of alloy is melted to realize tablets, as shown in **Fig. 2**, the average chemical composition appears to suffer from a copper depletion with respect to the ingot composition. The microstructure appears dendritic (**Fig. 7**-a), and β-Al5FeSi phases could be noticed at higher magnifications (Fig 7-c). On the other hand, a single scrap section microstructure may appear having different microstructures (**Fig. 8**) characterized by large intermetallics having a plates-like shape and a coarser eutectic silicon, as a function of the production process and the melt treatments.

The specific HPDC production process here adopted leads to a very fine microstructure characterized by a very small and refined eutectic Si (**Fig. 9**). The Brinell hardness measurements appear slightly different in both the RESAL alloy, the tablets obtained after the melting of 10kg of scraps and the single scrap section analyzed. In particular, a very small difference was noticed, probably due to the natural aging processing that may be take place. In each case, the same intermetallic phases were noticed. The comparison with the ingot hardness and microstructures lead to highlight that the re-melting of such alloy does not lead to a depletion of the alloy properties or to a coarsening of the Iron-based intermetallics. The DSC analyses highlight that the remelt in the industrial furnace and the subsequent cast in the Module battery housing shape lead to a very fine microstructure without peaks of Cu-based intermetallic phases (Fig 5- heating ramp). This may be due to the very fast cooling of the casting caused by the very small wall thickness. In fact, during the DSC cooling ramp, Cu-based intermetallic precipitation was noticed along to the Si eutectic peak. On the other hand, SEM analysis

noticed Cu-based intermetallic phases **Fig. 11**, even though not in large quantities.
Other intermetallic phases were noticed from the microstructure analyses: intermetallic iron-based phases such as π-Al8FeMg3Si6, α-Al15(Mn,Fe)3Si2 and β-Al5FeSi phases, while intermetallic phases Zn-containing were not noticed: this was probably due to the high solubility of Zn in the Al matrix.

CONCLUSIONS

In this work, the progress in the European project that involves Endurance Overseas (named IPCEI – BATTERIE 1) has been presented. The work involves the use of end-of-life alloy 46000 castings to produce new castings for use in the e-mobility sector without further treatment of the alloys.
From the hardness and microstructural analyses, it is evident that the quality of the alloy appears to be preserved despite the additional re-casting steps, even without the use of casting additives such as modifiers or grain refiners.
Furthermore, the microstructure, following the casting process, does not appear to be thickened; on the contrary, an extremely fine and uniformly distributed eutectic silicon phase is observed within the α-aluminium matrix in the casted component.
In conclusion, at this state of the project, it was clearly demonstrated the feasibility of recycling Al scraps to realize new components at very low costs and only using scrap alloy. Further characterization improvement will regard the mechanical tests on the Basic Module battery housing to assess the whole quality of such components.

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