A comparative cradle-to gate impact assessment: primary and secondary aluminum automotive components case

a cura di: **S. Cecchel, M. Collotta, G. Cornacchia, A. Panvini, G. Tomasoni**

Road transports release a significant percentage of global CO_2. In this field, one of the most effective solution is the reduction of vehicles' mass, which can be obtained through the substitution of heavy metals with light alloys (i.e. aluminum). In addition, in order to maximize the environmental benefits a current trend is to use secondary material (from scrap) in substitution to primary one (from ore). For this purpose, the present case study compared the environmental burden related to the same light-weighted automotive component (suspension cross beam) made in primary aluminum (from ore) or in secondary one (from scrap). In particular, a cradle to grave Life Cycle Assessment has been analyzed through the software SimaPro 7.3 with the Recipe impact method. The study highlighted and confirmed the relevance of the environmental benefits related to recycling and secondary material use.

KEYWORDS: LIFE CYCLE ASSESSMENT (LCA); ALUMINUM PROCESS; AUTOMOTIVE COMPONENTS; PRIMARY ALUMINUM; SECONDARY ALUMINUM; RECYCLING

S. Cecchel, M. Collotta, G. Cornacchia, A. Panvini, G. Tomasoni
DIMI, Department of Industrial and Mechanical Engineering, University of Brescia

INTRODUCTION

Automotive components weight reduction is a matter of great importance and emerging interest, in order to reach a better world sustainability. In fact, as is well known, the lightweighting has a direct influence on the improvement of vehicle's performances and is strictly connected to the reduction of fuel consumption and emissions [1-4].

Present EU legislation sets mandatory emissions reduction targets for new vehicles by 2020 [5], highlighting that this is a topic of primary interest. At this aim, the use of low density materials (i.e. aluminum alloys) in substitution of "heavy" metals (i.e. steel and cast iron) has exponentially increased during the last few years [6, 7].

In particular, High Pressure Die Casting is the most used by metalworking industry for high-volume of aluminum alloy components, thanks to the cost advantages derived from its high productivity rates [8].

Currently, for the manufacturing of structural components is mainly used primary aluminum (made from ore). It is clear that a major use of secondary materials would give several environmental and economic advantages such as: a reduction of the energy consumption (-95% than the production from mineral) [9, 10], a decrease of non-renewable resource consumption and a lower socio-economic impact related to the bauxite mining [11]. Anyway, the application of secondary aluminum in this class of components is limited by the difficulty in the removal of some impurities (iron and copper) during the recycling that can lead to a decrease of the mechanical properties [12]. The most common solution used in industry today is dilution with primary [12]. In addition, recently some new technologies (i.e. accurate separation scrap process) have been developed to obtain aluminum scrap with

higher chemical purity that would allow the extension of recycled material use to heavier missions [12].
Taking into account the environmental benefits arising from automotive components weight reduction, many studies have been published, almost all based on the life cycle assessment methodology. The advantages of substituting iron and steel with lighter materials, including aluminum have been confirmed [13, 14]. In particular, some of these studies focus on the entire automotive sector, discussing the benefits of vehicles light weighting at a global level [2, 15-18] or at regional [18]. Anyway, the lightening of vehicles may have other environmental effects than the reduction of emissions; such impacts are not necessarily positive and thus should be carefully taken into account. Moreover, it is important to highlight that very few works which investigate in detail the foundry production step by step have been found [8, 19, 20].
In this context, a previous work [21] presented the application of a model for the environmental analysis of HPDC at the production of a safety relevant primary aluminum component (cross beam suspension) [22], that confirmed the high benefit of aluminum recycling at the end of life. In the present research, the model has been extended and implemented in order to analyze the real environmental benefit given by the use of components made of secondary alloys. In particular, a cross beam suspension produced in primary aluminum (scenario 1), in secondary aluminum (scenario 2) and in a mix of 50% primary aluminum and 50% secondary one (scenario 3) has been analyzed and compared through a Life Cycle Assessment (LCA) and a sensitivity analysis. In particular, these aspects have been investigated through a LCA software SimaPro 7.3 using the Recipe impact method that calculates the environmental burdens for different impact categories.

MATERIALS AND METHODS

Life cycle assessment

The LCA analysis is an innovative technique for assessing the environmental aspects and potential impacts associated with a product or process throughout its life cycle. The main reference for the LCA methodology is the ISO 14040 standard [23], which describes the principles and framework for LCA, including: the definition of the goal and scope, the Life Cycle Inventory analysis (LCI) phase, the Life Cycle Impact Assessment (LCIA) phase, and the life cycle interpretation phase. In the following section, each phase is discussed and the results are presented. Since the environmental evaluation of a product is characterized by a very large number of data and complex analyses, particularly during LCI and LCIA phases, a "LCA software" (in this case SimaPro 7.1 was used) can be a very useful tool to support the calculations and to present the results obtained. Moreover, the software may access directly specific databases containing secondary inventory data, i.e. inventory data coming from literature (in this case Ecoinvent database [24]). Finally, a software allows to apply several impact assessment methods (in this case, the Recipe method was adopted) that calculate the environmental severity for different impact categories through the transformation of the long list of LCI results, into a limited number of indicator scores.

Goal and scope definition

The aim of this LCA is to identify the potential environmental benefits arising from the production with secondary vs primary aluminum of an HPDC component for light commercial vehicles, using real data. In particular, a comparison of three different scenarios in which the component is made of (1) 100% primary aluminum, (2) 100% secondary aluminum and (3) 50% primary and 50% secondary aluminum is investigated.
In detail, with reference to scenario 1, the first life cycle stage for primary aluminum components production consists in the extraction of the ore and its transformation into a primary aluminum ingot, through the following operations: bauxite mining, alumina production, electrolysis and cast house. It's worthwhile to note that the electrical energy required for the primary smelting process constitutes the major part of energy consumption in primary aluminum production [9, 10]. In particular, the total consumption has to take into account different elements: rectifying loss, DC power usage, pollution control equipment, auxiliary power (general plant use), electric transmission losses from power stations to primary smelters. Specific consumption data collected from smelters and the related true weighted average have been elaborated from European Aluminum Association and are available in literature [7].
With reference to scenario 2, secondary aluminum ingot production involves in an accurate physically separating solid scrap stream to prevent co-mingling and elements [12, 13], melting and alloying in order to reach the required composition. It's important to underline that this allow to completely avoid the highly energy transformation process needed for ore reduction above introduced. Finally, in scenario 3 a dilution of secondary aluminum with 50% primary aluminum is investigated.
The subsequent phases are the same either from primary or

secondary ingot production.

In detail, the component is realized through HPDC with the following main important foundry phases: aluminum ingot melting, molten metal holding, and casting. Then, the foundry system (i.e. sprue, air venting, and heat flow), that has to be trimmed off and recycled by remelting [25, 26].

Subsequently, the castings are subjected to machining in order to obtain the final design required by the component features.

Finally, components are recycled at their end of life.

Life cycle inventory

The functional unit adopted for all the scenarios analyzed is a typical production batch of 250 aluminum components for light commercial vehicles. The component weight is about 15 kg. The use phase of the component is not reported; in fact, having the components the same geometry and the same weight, input and output of mass and energy for the use phase does not differ among scenarios.

Whenever possible data taken from the field were used. In particular, foundry and machining phases have been evaluated through the use of the model already mentioned and with the most relevant assumption reported in the authors' previous work [21]. In this context, it is important to highlight that most of the parameters related to the foundry operation reported in this section are related to primary data achieved thank to the cooperation of some automotive Italian foundries. For the shake of clarity, the aluminum scraps due to the feeder system are reported as "yielding ratio". Secondary data regards the remaining phases and has been gathered from literature [9, 10] and Ecoinvent database [24].

In the current case study the following parameters are considered:

- Components weight 15 kg,
- Foundry time cycle 3 min,
- Foundry yielding ratio 40%,
- Foundry melting loss 5%,
- HPDC cold chamber machine with a clamping force of 3,000 t (about 30,000 kN).
- 5 axis-machining,
- Machining scrap ratio 1%
- Machining time cycle 8 min,
- Lost (not recycled) 6%
- Shredder loss 5%
- Re-melting loss 5%

The detail of input/output flows for each scenario are shown and in Fig. 1 and Tab. 1- Tab. 3.

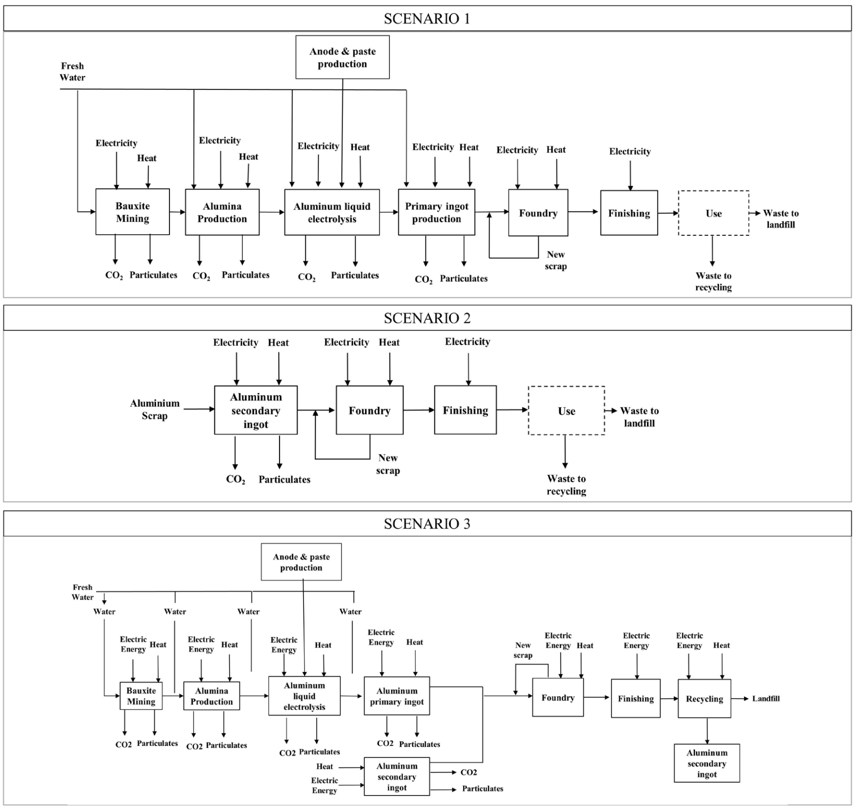

Fig. 1 - Flow charts for scenario 1 (S1), scenario 2 (S2) and scenario 3 (S3)

Tab. 1 - Input/output flows and process unit for scenario 1 (S1)

	Bauxite Mining (13,24 ton)	Alumina Production (5,89 ton)	Aluminum liquid electrolysis (3,07 ton)	Primary ingot production (4,09 ton)	Foundry (263 pcs)	Finishing (250 pcs)
INPUT						
Fresh Water (m3)	5,96	2,95	4,30	-1,63		
Heavy fuel oil (kg)	2,65					
Diesel (l)	4,67					
Electricity (kWh)	11,92	1066,63	45,67	400,53	1458	800
Sodium hydroxide (kg)		312,33				
Lime (kg)		247,51				
Heat, natural gas (MJ)		25334,01		5529,71	37907	
Heat, heavy fuel (MJ)		34314,94		760,18		
Heat, light fuel (MJ)				188,00		
Steam (MJ)		1467,36				
Anode & paste production (kg)			1350,51			
Aluminum fluoride (kg)			48,50			
Cathode (kg)			21,18			
Steel (kg)			11,66			
Cryolite (kg)			4,91			
Refractory material (kg)			24,55			
Transport by ship (tkm)			11672,26			
Transport by barge (tkm)			705,73			
Transport by lorry (tkm)			99,91			
Transport by rail (tkm)			4992,22			
Chlorine (kg)				0,20		
Argon (kg)				8,62		
Nitrogen (kg)				0,90		
Aluminum scrap (kg)				997,23		
Silicon (kg)				98,09		
OUTPUT						
Carbon Dioxide (kg)	26,48	4914,76	4831,14	461,83		
Particulates (kg)	2,25	0,83	2,58	0,16		
Sulfur dioxide (kg)		15,79	22,71	0,61		

	Bauxite Mining (13,24 ton)	Alumina Production (5,89 ton)	Aluminum liquid electrolysis (3,07 ton)	Primary ingot production (4,09 ton)	Foundry (263 pcs)	Finishing (250 pcs)
Nitrogen oxides (kg)		6,54	1,35	0,86		
Mercury (kg)		0,35				
Suspended solids (kg)		1,36		1,39		
Oils (kg)		0,59				
Waste (kg)		282,86		11,85		
Flouride (kg)			2,67			
PAH (kg)			0,04			
Benzo(a)pyrene (kg)			0,80			
Methane (kg)			0,12			
Ethane (kg)			0,01			
PFC (kg)			0,12			
Disposal (kg)			31,00	8,99	271	
Hydrogen Chlo-ride (kg)				0,08		
Dross (kg)				72,75		
Dust (kg)				3,68		
Refractory mate-rial (kg)				2,86		
New scrap (ton)					1526	
Chlorine (kg)						
TOC (kg)						
COD (kg)						

Tab. 2 - Input/output flows and process unit for scenario 2 (S2)

	Secondary ingot production (4,09 ton)	Foundry (263 pcs)	Finishing (250 pcs)
INPUT			
Fresh Water (m3)	23,70		
Electricity (kWh)	506,79	1458	800
Heat, natural gas (MJ)	15052,42	37907	
Heat, heavy fuel (MJ)	314,70		
Heat, light fuel (MJ)	273,83		
Chlorine (kg)	1,23		
Argon (kg)	6,95		
Nitrogen (kg)	2,04		
Aluminum scrap (kg)	4254,57		
			2,67
Gas (m3)	3,27		0,04
			0,80
OUTPUT			
Carbon Dioxide (kg)	1083,06		0,01
			0,12
Sulfur dioxide (kg)	264,43		
Nitrogen oxides (kg)	1443,94		
Waste (kg)	22,07		
Disposal (kg)	53,95	271	
Hydrogen Chloride (kg)	63,76		
Dross (kg)	204,35		
Dust (kg)	214,57		
New scrap (ton)		1526	
Chlorine (kg)	5,31		

Life Cycle Impact Assessment

The LCIA phase consists in the quantification of the impacts on the environment caused by the consumption of the natural resources and by the releases to the pollutant identified and quantified during the LCI. For this analysis, the Recipe model has been employed, which adopt a damage oriented approach and leads to the evaluation of environmental impacts with respect to several categories that declines the impacts affecting the human health, the ecosystem quality and resources availability. It is an "endpoint" method, i.e. it allows to perform characterization, normalization, grouping and weighting, [27] and it allows to choose among three "cultural perspectives" for the calculation of the environmental impact; in this case, the egalitarian perspective was adopted, which is based on precautionary principle thinking.

Table 4 summarizes the main results obtained through the analysis, in particular, the environmental impacts after normalization and the single score. The graph in Figure 2 reports the single score impacts.

The normalization is obtained by dividing the impacts in each category by the shares of an average person's emission and resource use in the world during one year. In practice, normalisation converts complicated units into fractions of the average person's scores per impact category and allows to identify the categories where the impact is more relevant. The calculation of the single score allows to obtain a unique a-dimensional indicator measured in Points (Pt).

Tab. 4 - Comparison between the impact values of the Recipe method related to the different scenarios: after normalization (a) and single score (b)

	S1		S2		S3	
	Normalization	Single Score	Normalization	Single Score	Normalization	Single Score
Climate change Human Health	90,24	27072,80	14,79	4436,54	55,80	16738,54
Ozone depletion	0,00	1,30	0,00	0,37	0,00	0,89
Human toxicity	280,75	84224,45	22,01	6603,91	160,76	48228,14
Photochemical oxidant formation	0,00	0,61	0,00	0,08	0,00	0,37
Particulate matter formation	11,66	3498,33	0,73	218,37	6,58	1973,75
Ionising radiation	0,10	28,73	0,01	1,76	0,05	16,20
Climate change Ecosystems	4,95	2474,43	0,81	405,41	3,06	1529,84
Terrestrial acidification	0,02	8,46	0,00	0,67	0,01	4,85
Freshwater eutrophication	0,00	2,23	0,00	0,16	0,00	1,27
Terrestrial ecotoxicity	0,04	21,03	0,00	1,16	0,02	11,76
Freshwater ecotoxicity	0,00	0,33	0,00	0,02	0,00	0,19
Marine ecotoxicity	0,00	1,64	0,00	0,09	0,00	0,92
Agricultural land occupation	0,03	15,34	0,01	3,01	0,02	9,73
Urban land occupation	0,02	8,36	0,00	1,76	0,01	5,36
Natural land transformation	0,73	367,30	0,21	106,86	0,50	250,60
Metal depletion	0,07	14,79	0,01	2,77	0,05	9,30
Fossil depletion	117,81	23561,53	24,74	4948,95	75,72	15144,39

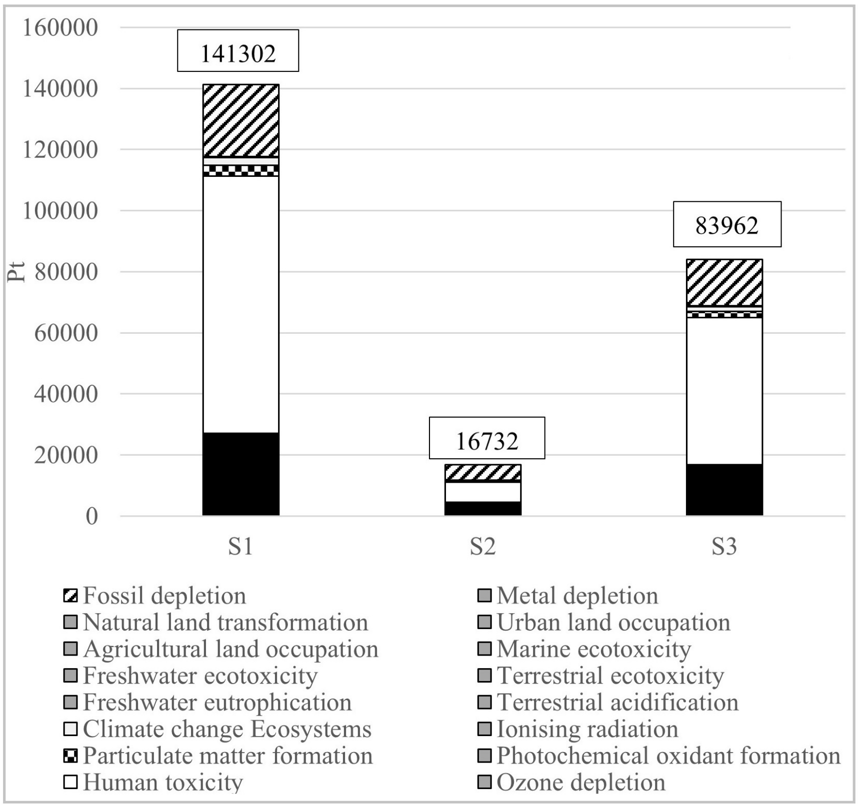

Fig. 2 - Comparison between the impact values of the Recipe method related to the different scenarios single score

It can be noted that scenario 1 has the highest impact with 141’302 points, followed by scenario 3 with 83’962 points, while the lowest environmental impact is obtained by scenario 2, which has a total score of 16’723 points. The most relevant impact categories are human toxicity, fossil depletion and climate change human health for all the scenarios. These parameters are mainly related respectively to the air emissions during the electrolysis (for scenarios with primary aluminum) and during the aluminum melting in the foundry operations (for all the scenarios), with a strongly higher impact for the former phase. In particular, taking as baseline S1, human toxicity is respectively 92% and 43% lower for S2 and S3, fossil depletion is respectively 79% and 36% lower for S2 and S3 and climate change human health is respectively 84% and 38% lower for S2 and S3. Therefore, these elevate difference between the environment indicators among different scenarios highlight the relevance of secondary aluminum use in order to reduce the transports pollution.

In order to further investigate the sensitivity of the results to the uncertainty in the inventory data, a Monte Carlo analysis has been developed. In particular, through the Monte Carlo analysis the inventory parameters are transformed into stochastic variables with a log-normal distribution. The log normal distribution was adopted as it is widely used in literature [28] for Monte Carlo analysis in the context of LCA case studies. The average value of each distribution coincides with the value of the correspondent deterministic inventory parameter, while the standard deviation has been taken from the Ecoinvent database. The values of the inventory parameters are then randomly sampled and the impact assessment method is applied for a high number of combinations of such values.

Figure 3 shows, for each environmental impact category of the Recipe method, the probability for scenario 1 to have a lower environmental impact with respect to scenario 3 (and viceversa). As can be seen, the probability for scenario 3 to have a lower environmental impact than scenario 1 is very high for all the impact categories. The same result was obtained with the comparisons between scenario 1 and scenario 2 and between scenario 2 and scenario 3. These evidences confirm the robustness of the results obtained.

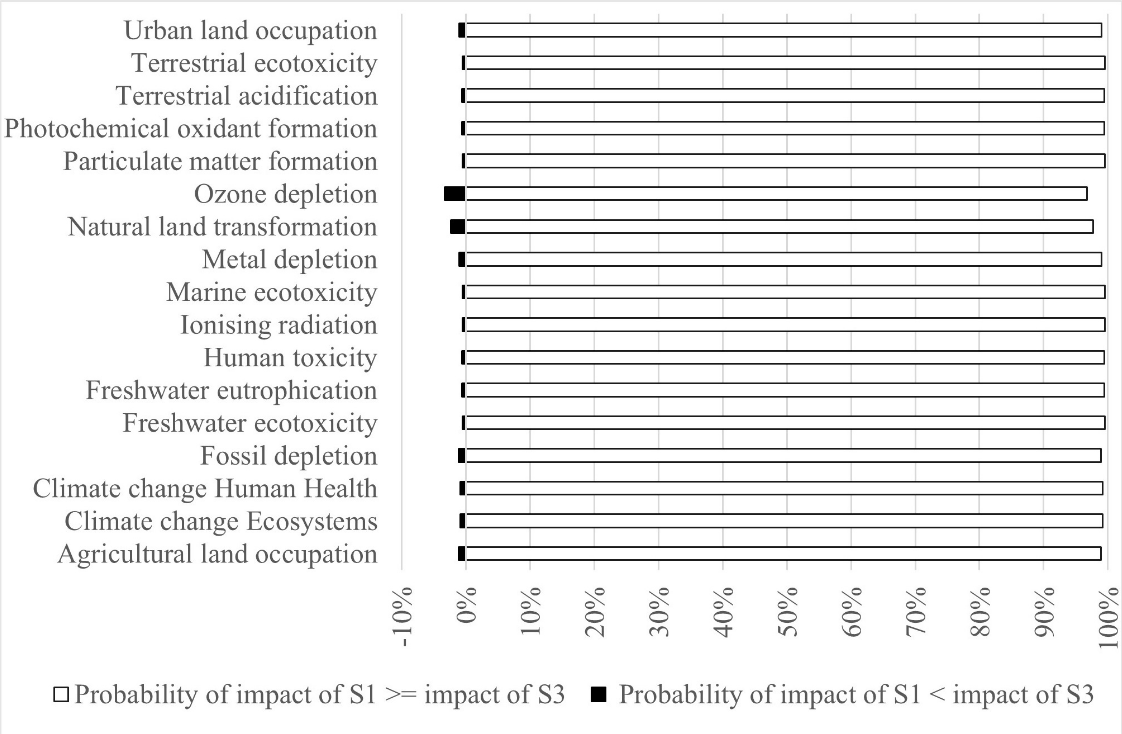

Fig. 3 - Results of the Monte Carlo analysis applied to the comparison of scenario S1 with scenario S3

CONCLUSION

The present study analyzed the environmental benefits connected with the production of lightweight commercial vehicles components. In particular, a suspension cross beam for LCVs made in primary aluminum (from ore) or in secondary one (from scrap) was studied through a cradle to grave LCA filled with real field data. The impact of each phase to the overall life cycle has been evaluated. In particular, it was confirmed that the higher impact assessment derives from electricity and heat demands in the liquid aluminum electrolysis phase included in primary aluminum's scenario (scenario 1 and 3). Regarding secondary aluminum's scenario (scenario 2 and 3) the greater impact was related to the production of ingot from scrap, although it naturally appeared clearly lower than that from ore. It is a common point for all scenario that energy demand for the production of aluminum ingot became the primary factor responsible for the corresponding environmental impact, directly followed by the significant impact related to energy and heat demand for the component's casting. This last contribution demonstrates the importance of the new approach of a deep and detailed foundry phase investigation to avoid underestimated results. Furthermore, it is worthwhile to note that in all three different scenarios recycling of aluminum provides a positive benefit in terms of energy savings.

This result confirmed the relevance of the present trend in the development of new technologies to obtain aluminum scrap with higher chemical purity that would minimizes the current difference of mechanical properties between primary and secondary aluminum alloys. Finally, it was emphasized that the well-known environmental benefit given by automotive lightweighting can be improved and maximized by the substitution of aluminum primary alloys with secondary one.

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