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Cradle-to-Gate Impact Assessment of a High-Pressure Die-Casting Safety-Relevant Automotive Component

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The mass of automotive components has a direct influence on several aspects of vehicle performance, including both fuel consumption and tailpipe emissions, but the real environmental benefit has to be evaluated considering the entire life of the products with a proper life cycle assessment. In this context, the present paper analyzes the environmental burden connected to the production of a safety-relevant aluminum high-pressure die-casting component for commercial vehicles (a suspension cross-beam) considering all the phases connected to its manufacture. The focus on aluminum high-pressure die casting reflects the current trend of the industry and its high energy consumption. This work shows a new method that deeply analyzes every single step of the component's production through the implementation of a wide database of primary data collected thanks to collaborations of some automotive supplier companies. This energy analysis shows significant environmental benefits of aluminum recycling.

INTRODUCTION

In recent years, the lightweighting of automotive components has become important, especially for economical reasons and to address political pressures about environmental issues. Indeed, as is known from the vehicle's dynamics, a reduction of the moving mass leads to an improvement in performance as well as an emissions reduction. For instance, fuel savings are estimated to be 0.3–0.5 L per 100 km per 100 kg for passenger cars and up to 0.4 L per 100 km per 100 kg for articulated trucks.[1]

Achieving a significant mass reduction on todays' vehicles will likely require adopting low-density materials such as aluminum alloys. For this reason, there is an increasing trend to substitute conventional steel and cast iron parts with aluminum ones.[2] Accordingly, during the last decade the automotive industry has exponentially increased the volume of aluminum alloys used in vehicles and this trend is expected to continue in the next years.[3,4]

In this context, it is worthwhile to note that aluminum automotive components are overall produced in wrought or cast forms.[5,6] In particular, the most prevalent process used for the manufacturing of high-volume aluminum alloy components is high-pressure die casting (HPDC), thanks to the cost advantages derived from its high productivity rates. HPDC is a very efficient process to manufacture near-net shape lightweight aluminum parts, providing from 30% to 50% weight reduction compared with steel.[7,8]

As previously mentioned, the light weight has a direct influence on several aspects, overall on fuel consumption and emissions, but the entire life cycle of the products, from raw material extraction to its disposal, has to be considered to evaluate the actual environmental impact.

Life cycle analysis (LCA) is an instrument for the study of the environmental burden of products at all stages: from the extraction of resources, through the manufacturing of materials and the use of the component, to its discard, either for recycling or for its disposal ('from the cradle to the grave'). One of the most important roles of a LCA is to support a correct eco-design of the examined case. For instance, the reduction of a vehicle's weight obtained through the use of aluminum instead of steel involves a reduction of fuel consumption, but much more energy could be required for aluminum alloy components production. Only when all these

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matters are examined together can it be evaluated whether a car made of aluminum is really more environmental friendly than one made of steel.[9]

The main important driving standard for LCA is ISO 14040:2006.[10] These international standards describe LCA as a four-step process: goal definition and scope; inventory analysis; impact assessment; and interpretation.[10,11]

The object of the first step of a LCA is the definition of the proposed application, the reasons for carrying out the study and the intended audience. This is very important in order to define the system and its boundaries in a way that achieves the aim of the project. For this purpose, it is necessary to identify the total system of unit processes involved in the life cycle (product system) and to explain the criteria used for defining the system boundaries.[10,11]

Inventory analysis consists of data collection and calculation processes to quantify the various inputs and outputs (i.e. energy, wastes, and resources) outlined in the previous stage. This analysis should be iterative.

During the impact assessment phase, life cycle inventory (LCI) results are analyzed in order to quantify the environmental burdens of the system. In particular, the aim of the LCI phase is to identify the effects on human health, ecosystem health and natural resources.[10,11]

Finally, the interpretation phase considers in total the results of the inventory and impact analysis and should deliver results that are coherent with the goal and scope defined at the beginning of the life cycle assessment.[11]

The present work will analyze the production of a safety-relevant aluminum high-pressure die-casting component for commercial vehicles (a suspension cross-beam) considering all the phases connected to its manufacture and disposal: extraction of raw material, realization of aluminum ingot, casting of component, finishing and end of life. As already mentioned, aluminum involves a reduction of fuel consumption during vehicle use in comparison with heavier materials components.[12–15] In this context, it is important to clarify that the present work focuses on an elaborate analysis of aluminum component manufacture and on the benefit of recycling and does not involve a comparison with heavier production techniques of the same component; that will be investigated in future works.

This study has been conducted according to the ISO 14040:2006[10] standard, using a cumulative energy use assessment method.

METHODS

General Architecture of the Model and Data Collection

The present work develops a new model and applies that model to understand the real environmental impact of high-pressure die-casting aluminum automotive parts. When considered in detail, the HPDC process comprises many energy-intensive manufacturing phases that need to be evaluated step by step. Therefore, the method employed in this paper deeply analyzes every single step of the component's production through the implementation of a wide database composed of numerous data collected, thanks to collaborations with some automotive companies, and validated during the production of the component.

In this context, many scientific papers about automotive components' LCA can be retrieved, but only a few of them[16–18] study in detail the real parts' production processes. Dalquist et al.[16] made a detailed analysis based on aggregate national data and representative machines in order to give some general information about the environmental impact of this process. Since the aim of this work is to give general purpose data, it does not allow the evaluation of a specific component production with a high grade of accuracy. Singh et al.[17] developed a model to evaluate the sustainability of a die-casting part at its design stage. This research analyzed only a small part of the manufacturing phase (melting and holding), based on theoretical equations. Gunasegaram et al.'s work[18] compared aluminum and magnesium production of a small automotive component (a converter housing about 3 kg in weight) using primary data. Unfortunately, this model cannot be applied to the component object of the present study which is a safety-relevant automotive component with larger dimensions (about 15 kg) which implies different process parameters and tooling (pressure, velocity, clamping force, etc.)

The various phases that constitute the model developed in the present work are described in detail in the following sub-sections.

CASE STUDY: ALUMINUM SUSPENSION BEAM FOR COMMERCIAL VEHICLES

Goal and System Boundary Definition

In the present paper, the model is applied to the production of a high-pressure die-casting aluminum suspension beam for commercial vehicles. Due to their strength-to-weight ratio, corrosion resistance and processability qualities, aluminum alloys have been intensively used in commercial vehicles in recent years.[19] In this context, the accurate design of this component allows a lightweighting of about 50% compared to the previous steel version. Furthermore, thanks to the high-quality aluminum alloy selected during the eco-design, the casting does not need a heat treatment to reach the mechanical properties required. Finally, the high corrosion resistance of aluminum alloys permits the use of this component without any coating or surface treatment. All these initial statements are apparently related to a reduction of the environmental burden, but it is necessary to analyze all the

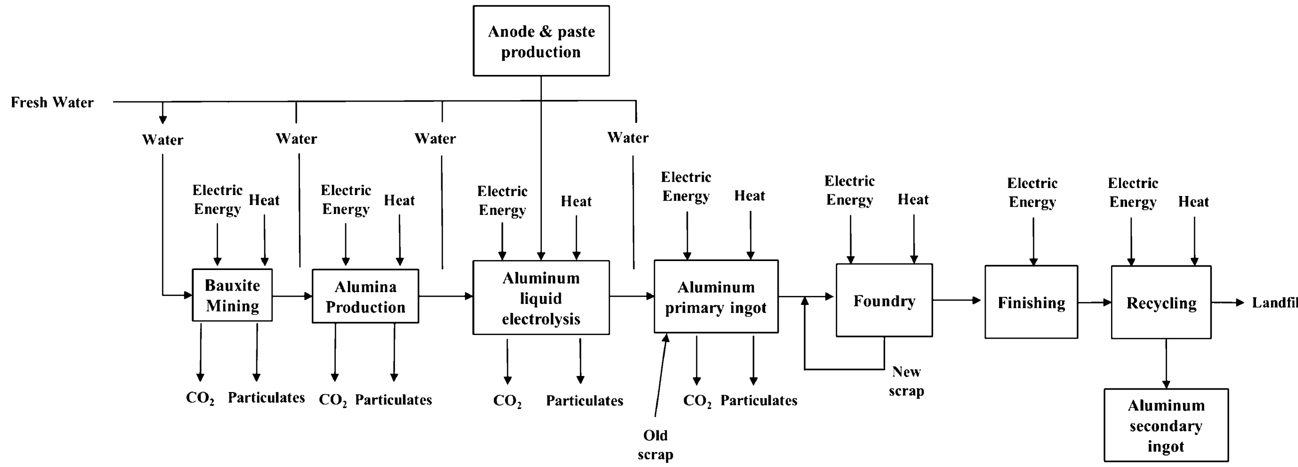

Fig. 1. Life cycle assessment flow-chart.

other life cycle steps of the component to evaluate whether a suspension beam made of aluminum alloy is truly environmentally friendly.

For this reason, the aim of the LCA described below is to assess the environmental impact of this automotive component's production in terms of the energy used.

The system boundary of the study is from cradle to grave, covering the extraction of the raw material, the realization of the aluminum primary alloy ingot, the components' casting, the finishing and the recycling (Fig. 1).

Inventory Analysis

For the present work, the functional unit selected is a typical production batch which is defined as "manufacture of 250 units of high-pressure die-casting aluminum suspension beams". All the evaluation, as well as all inputs and outputs in the inventory analysis and impact assessment phases, are related to this functional unit.

The current inventory analysis consists of data collection and calculation processes which quantify the various energy inputs and outputs defined in the previous stage.

From the Extraction of the Raw Material to the Realization of the Aluminum Primary Ingot

For the first step, "From the extraction of the raw material to the realization of the aluminum primary ingot", the data collection of EAA[20] are elaborated. The output of this stage is the production of 4 tons of aluminum primary ingots that correspond to the production of 250 units. To better understand this first stage, it is worthwhile to note the high energy cost related to the extraction of aluminum from bauxite. For this purpose, the principal steps to obtain an aluminum primary ingot (bauxite mining, alumina production, electrolysis and cast house) are detailed in the following paragraphs.

Bauxite, the common raw material for aluminum production, has to be processed into alumina through the use of the Bayer chemical process. This practice takes place in autoclaves at a temperature range between 100°C and 350°C: NaOH and CaO are the main reactants. During the cooling, aluminum hydroxide is leached from the soda solution, washed and dried. Then, the aluminum hydroxide is calcined at about 1100°C in order to obtain the final-product. Actually in Europe about 2250 kg of bauxite is necessary for producing 1000 kg of alumina.[20]

Hereafter, pure alumina is reduced into primary aluminum by the electrolysis Hall–Héroult process. About 1920 kg of alumina is needed to produce 1000 kg of aluminum. The reduction of alumina into liquid aluminum is operated at about 950°C under a high-intensity electrical current. This process takes place in electrolytic cells, in which carbon anodes are consumed during the reaction with the oxygen coming from the alumina. The electrical energy required for the primary smelting process constitutes the major part of energy consumption in the primary aluminum production.[20]

Finally, primary molten aluminum is transferred to the cast house where it is alloyed. Average data have been considered for a generic aluminum ingot for remelting.[20]

The present analysis includes a complex model of transport developed by EAA that is useful for the evaluation of the environmental impact of bauxite and alumina's import in Europe.

From Aluminum Primary Ingot to the Casting of the Component

For the implementation of this step, the analysis focuses on the main important activities which take place in an aluminum high-pressure die-casting foundry: melting, holding, and casting.

Table I. Energy by life cycle stages

	Primary aluminum	Casting	Finishing	EOL	Total	Total EOL
Energy (kWh)	68,211	15,005	800	−47,751	84,016	36,265

Two different reverberatory furnaces, widely used in aluminum die-casting foundries, are examined for the melting and holding's phases, respectively. Indeed, even if the same types of oven can be used for both purposes, foundries usually use different furnaced for melting and holding in order to enhance their efficiency.[16,21]

The main data collected about these operations are the real amount of gas (200 m^3/ton) and the total energy needed to melt and hold 4 tons of aluminum (respectively, about 7000 MJ/ton and 1500 MJ/ton), including energy losses. It is worthwhile to note that the data used have been collected by actual aluminum foundries.

The first step of the casting phase is the choice of the type of die-casting machine. In this process, the melting unit is not an integral part of the machine, but the molten material is fed from a holding furnace into the shot sleeve and then forced into the die cavity.[22] In addition, the cycle time must be calculated as the size of the machine it has to be set depending on the shape and the weight of the component. Subsequently, it is also important to calculate the aluminum scraps due to the feeder system and the melting loss. Last but not least, the energy connected with the complete high-pressure die-casting working cell has to be considered, including the energy cost of all the ancillary systems (i.e. ejector, feeder, cooler, etc.). For this purpose, different aluminum die-casting foundries have provided much energy consumption data for the high-pressure die-casting working cell being considered (average value 175 kW/h).

In compliance with these considerations and foundry experience, in the current case study the following parameters are considered:

- components weight 15 kg,
- time cycle is 3 min,
- yielding ratio 40%,
- melting loss 5%,
- cold chamber machine with a clamping force of 3000 t (about 30,000 kN).

Finishing

As is known, the molten metal solidifies in the die including runners and overflows. However, only the actual casting (formed in the cavity) will be used and all the other parts are trimmed off and recycled by onsite remelting.[23] Finally, the castings are usually subjected to machining, heat treatment and/or coating.

As said above, the present case study does not need any heat treatment and coating operations, therefore only the machining energy requirements

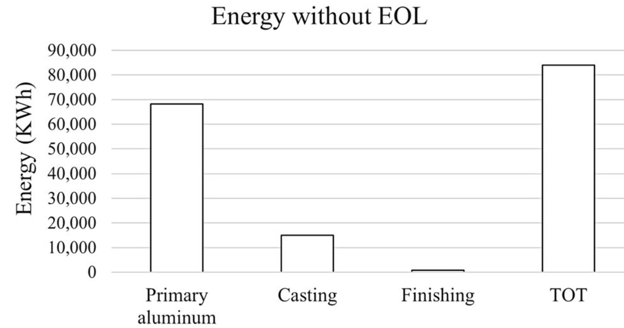

Fig. 2. Energy by life cycle stages without EOL.

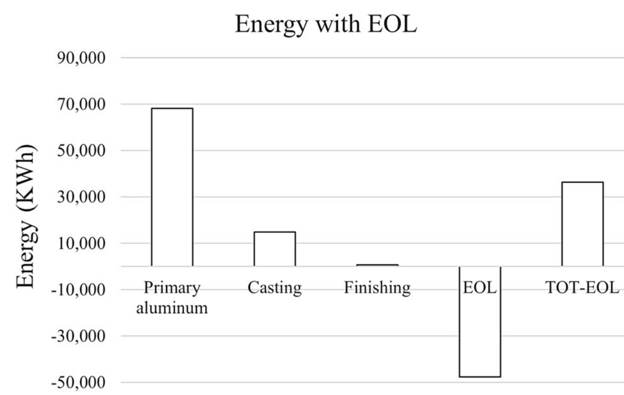

Fig. 3. Energy by life cycle stages with EOL.

will be taken into account. For this purpose, it is necessary to consider the proper device and to evaluate the machining time.

The following parameters have been selected:

- 5-axis machining,
- Scrap ratio 1%
- Machining time cycle 8 min,
- Energy consumption 40 kW/h.

Recycling

Recycling is a very important step of the life cycle, because the energy needed to remelt aluminum old scrap is only 5% compared with the production from bauxite.[20] Therefore, aluminum can be recycled almost endlessly without significant loss of properties. In conclusion, aluminum recycling thus saves raw materials and energy, and also reduces demands on landfill sites.[24]

For this step, the present work has considered the following assumptions:[25]

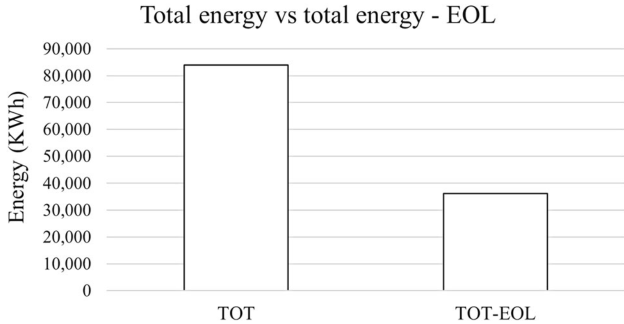

Fig. 4. Total energy comparison.

- Lost (not recycled) 6%
- Shredder loss 5%
- Melting loss 5%.

RESULTS

The energy results by life cycle stages are presented here.

As observed (Table I; Fig. 2), there is a huge amount of energy attributable to the primary aluminum production, followed by the components' casting. In contrast, the finishing operation involves a negligible contribution. These results confirm what was expected, not only for the well-known high primary energy production but also for the importance of an energetic analysis of all the foundry steps obtained by the deep investigation developed in the present research work.

Finally, it is worth noting the value of aluminum recycling (Table I; Figs. 3 and 4) underlined by the high contribution of the end of life (EOL) step. In fact, about the 42% of the total energy is recovered in this final phase of the life cycle.

CONCLUSION

The present work analyzes the environmental burden connected to the production of a safety-relevant aluminum high-pressure die-casting component for commercial vehicles (suspension cross-beam) considering all the phases connected to its manufacturing: extraction of raw material, realization of aluminum ingot, casting of component, finishing and recycling. The study has been conducted according to the ISO 14040:2006[10] standard.

The aluminum foundry process comprises many energy-intensive manufacturing phases that have been evaluated in detail step by step. In this context, the first important result was to develop a deep knowledge of the process in order to evaluate the proper technical specifications. Then, the boundary condition of the system was estimated with a realistic hypothesis. Therefore, the second step was the construction of a wide database of numerous data collected thanks to relationships with some automotive companies. In this context, a very important part of this analysis was the collaboration with industry in order to use real data and not just theoretical estimations.

Finally, a new model used to understand the real environmental impact of high-pressure die-casting aluminum automotive parts was developed and the analyses were performed.

The energy results by life cycle stages shows that there is a huge amount of energy attributable to the primary aluminum production, closely related to the liquid aluminum electrolysis. Secondary, but not least, about 18% of total energy is necessary for the components' casting. This significant energy contribution demonstrates the importance of a deep and detailed investigation of all the foundry phases to avoid underestimated results. Nevertheless, the finishing operations make a negligible contribution. Finally, it is important to emphasize that about the 42% of the total energy is recovered taking into account aluminum EOL. These results highlight the appeal of aluminum alloy recycling, strictly connected to its high intrinsic value. In conclusion, the present work confirms the relevance of increasing aluminum recycling to save raw materials and reduce energy consumption.

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