



An Innovative Digital Liquid Metal Manufacturing Method for Aerospace Applications: Incorporating Life Cycle Assessment for Sustainability

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Abstract. The Ultra Clean Cast (UCC) system presents an innovative approach to aerospace manufacturing by prioritizing component quality and manufacturing repeatability. It incorporates a cradle-to-gate life cycle assessment to highlight its additional environmental benefits, with a greater focus on enhancing sustainability. This novel approach improves upon traditional shape-casting by maintaining the high cleanliness of melt metal, critical for aluminum alloys, and difficult to achieve in general for aerospace parts, under varied conditions. By providing a sustainable, cost-efficient route for fabricating complex components, UCC is adaptable across aerospace platforms and evaluates the use of recycled aluminum, supporting the sector's shift towards a circular economy. This paper outlines the UCC system's integration of technological advancements with environmental responsibility, incorporating recycled aluminium raw material, material manufacturing, and product manufacturing stages. This system provides a new benchmark for environmentally friendly aircraft manufacturing by outlining process improvements and their implications for industry sustainability and efficiency. The findings highlight UCCs potential to affect aerospace manufacturing in the future, combining high-quality output with environmental considerations.

Keywords: Life Cycle Assessment · Sustainability · Ultra Clean Casting · Recycled Aluminum

1 Introduction

The manufacturing sector is making significant steps toward achieving net-zero emissions, with the aerospace industry leading these efforts. A major challenge in aerospace manufacturing is reducing carbon emissions. Aluminium, known for its high strength-to-weight ratio, is in high demand for various applications. However, despite advancements in manufacturing methods, aluminium casting is underused in aerospace due to strict standards and unpredictable quality [1, 2].

In aluminium casting, ingots are melted and poured into molds. Methods like die casting and investment casting are commonly used in aerospace. However, during melting, aluminium reacts with oxygen to form oxide films on the surface, which can mix with the molten metal and cause defects. These defects, such as porosity and leakage, weaken the cast components and can lead to cracks [3]. Porosity can reduce the fatigue life of aluminium components by 50% with just a 1% volumetric inclusion [4]. Despite regular cleaning practices, the quality of cast aluminium remains unpredictable, with few studies focusing on cleaning methods before casting [5]. This study introduces an Ultra Clean Casting (UCC) method for A356 aluminium, crucial for aerospace applications, supported by process maps and Life Cycle Assessment (LCA).

Furnaces are essential for the melting and holding stages of casting, but their design has changed little over the past decades [6]. Maintaining aluminium in a molten state is energy intensive. A study of 209 furnaces showed an average utilization rate below 39%, with 22% operating under 25% utilization, highlighting the need for more efficient use [7]. Different types of furnaces are used in the metallurgical industry, each suited to specific needs. Despite efficiency improvements, with some claiming up to 98%, sustainable practices in casting are still critical [8].

Aluminium is the most used non-ferrous material in the industry, with demand increasing by 3.9% from 104.1 million tons to 108.2 million tons [9]. There has been a slight decrease in greenhouse gas emissions from 1.13 GT CO₂e to 1.11 GT CO₂e and a 4.4% reduction in energy intensity of primary aluminium production [10]. Primary aluminium production consumes 168,000 MJ/t, while secondary aluminium uses only 11,200 MJ/t [11]. This significant difference highlights the importance of using recycled aluminium and promoting metal recycling. However, quality issues with recycled aluminium are still challenging for the casting industry [12]. This study aims to address this by exploring the use of 80% recycled aluminium in high-value casting applications.

Research to date has not identified a process capable of utilizing recycled aluminium to produce high-quality products without generating high emissions or being energy intensive. This study aims to address this gap by investigating a newly developed method. The research will consider scenarios using 100% virgin aluminium as well as combinations of recycled and virgin materials. A cradle-to-gate assessment will be conducted to evaluate the environmental and energy impacts of these scenarios.

2 Methods

This study's methodology involved a structured research approach to evaluate the environmental impacts of manufacturing processes, specifically focusing on the Ultra Clean Cast (UCC) system. The process included detailed process mapping, data collection, Life Cycle Assessment (LCA), and benchmarking.

The research focuses on detailed process maps to represent various manufacturing stages, essential for understanding inputs and outputs. Data was obtained from literature reviews, material databases, and company websites.

Life Cycle Assessment (LCA) was used to evaluate environmental impacts, following the international standard [13], and consisting of four phases. The phases included the goal and scope, the lifecycle inventory, the impact assessment, and the results analyses.

The study used a cradle-to-gate approach, covering environmental impacts from raw material extraction to the point where the product is ready for use or transportation out of the manufacturing plant. This assessment was conducted for both compared processes. The key environmental inputs measured include input and output materials, energy consumption, and waste [14]. The final stage involved benchmarking against conventional manufacturing methods, analyzing the effects on environmental outcomes. Changes in using different percentages of recycled and virgin materials for the novel UCC method provided insights into the influence of energy and waste variables, leading to recommendations for enhancing sustainability and promoting environmentally friendly practices [15].

3 Aluminium Processing Methods

3.1 Process Maps

The investment casting process, as seen in Fig. 1 starts with machining raw materials to create dies, producing swarf. Molten wax is cooled into wax patterns, which are coated with ceramic slurry to form molds. These molds are de-waxed, reclaiming wax and leaving empty ceramic molds. Aluminum alloy (virgin) is melted and poured into the molds. The castings are then cooled using electrical energy and a cooling medium. The final step is HIPing, where castings are treated with heat and pressure in an argon atmosphere, resulting in a high-quality final product.

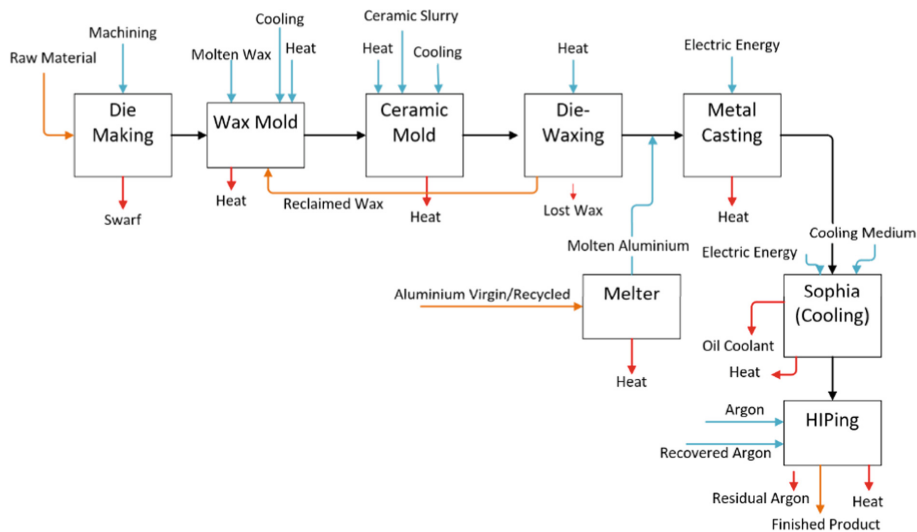


Fig. 1. Investment casting process map.

In the UCC process, Fig. 2, aluminum alloy (virgin/recycled) is melted in a dry hearth melter using natural gas, producing dross and CO₂ waste. The molten aluminum

is cleaned in an oxide sediment launder, removing impurities, and generating additional waste. The ultra-clean alloy is held in a dispensing furnace at 700 °C, creating more dross and CO₂ waste. Finally, the alloy undergoes counter gravity casting under vacuum conditions, producing the final product with minimal defects and some CO₂ waste.

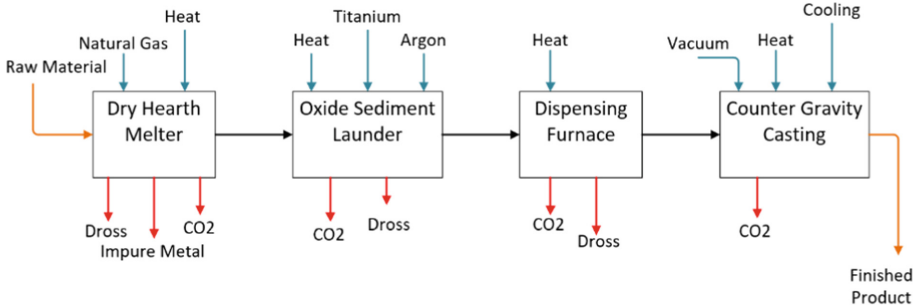


Fig. 2. Ultra Clean Cast process map.

Key differences between traditional methods and the UCC process include mold preparation, impurity removal, and final treatment. While investment casting relies on ceramic molds and HIPing for quality, UCC emphasizes ultra-clean alloy production and vacuum casting for defect minimization. In addition, this process efficiently utilizes recycled aluminum, achieving high-quality results through advanced impurity removal and controlled melting. Furthermore, this method reduces emissions and energy use, making it a sustainable option for producing high-quality components from recycled materials.

3.2 Inventory Analysis

In the lifecycle assessment of aluminium (A365) processes, it is crucial to identify and quantify the inputs and outputs at all manufacturing stages. This assessment involves not only direct measurements but also estimates derived from standard characterisation factors. These factors include the Material Utilization Factor, Energy Intensity, and CO₂ footprint, which are sourced from databases such as Granta EduPack 2024, Ecoinvent, and existing literature.

The functional unit the inventory calculations where made was for 1kg of A365 aluminium alloy.

To accurately calculate the environmental impacts associated with each stage of the aluminium casting processes depicted in the process maps, the following equations were employed:

$$\text{Input Material Mass} = \text{Mass Produced} \times \text{Material Utilization Factor} \quad (1)$$

$$\text{Consumed} = \text{Mass Produced} \times \text{Energy Intensity Factor} \quad (2)$$

$$\text{Equivalent CO}_2 \text{ Emission} = \text{Mass Produced} \times \text{CO}_2 \text{ Intensity Factor} \quad (3)$$

The input and output data for both processes are showcased in Tables 1 and 2 below.

Table 1. UCC DLMM inventory.

Process	Input Material (kg)	Input Energy (MJ)	CO2 Emissions (kg)	References
A356 Raw material	1.2	119.5	8.6 kg	SimaPro9
Dry Hearth	1.2	3.5	0.4	Dynamo Furnaces
Oxide Sediment Launder	1.17	0.05	0.006	Kanthal Furnaces
Dispensing Furnace	1.16	0.05	0.006	Kanthal Furnaces
Casting	1.15	Negligible for 1kg	Negligible for 1kg	EduPack

Table 2. Investment casting inventory.

Process	Input Material (kg)	Input Energy (MJ)	CO ₂ Emissions (kg)	References
A356 Raw Material	1.2	119.5	8.6	SimaPro9
Die Making	1.2	1	0.05	EduPack
Wax Mold Creation	1.2	1	0.05	EduPack
Ceramic Mold Creation	1.2	1.5	0.1	EduPack
De-Waxing	1.19	0.5	0.03	EduPack
Melting	1.18	2	0.1	EduPack
Pouring and Solidification	1.17	0.5	0.03	EduPack
SOPHIA Cooling	1.17	0.5	0.05	Signicast/ZOLLERN
HIPing	1.16	1.1	0.22	EduPack, Argon recovery method

For the inventory analysis of both processes, material databases and recipes from SimaPro 9 software were utilized. For the investment casting method, the cooling step, known as SOPHIA, was estimated by assuming similar equipment to the cooling process, due to the lack of available literature on this specific process [16, 17].

4 Results

Inventory data were analyzed using SimaPro 9 and the Midpoint ReCiPe method for two scenarios for UCC process. Scenario 1 (S1) utilizes 100% virgin grade A356 alloy. The results (Fig. 3) show that raw materials dominate the environmental impact, contributing over 97% of the total energy (123.1 MJ/kg) and CO₂ emissions (9.01 kg/kg). Excluding raw materials, the dry hearth melter stage is the most impactful. Scenario 2 (S2) uses 20% virgin and 80% recycled alloy. This scenario significantly reduces energy use to 62 MJ/kg and CO₂ emissions to 4.8 kg/kg.

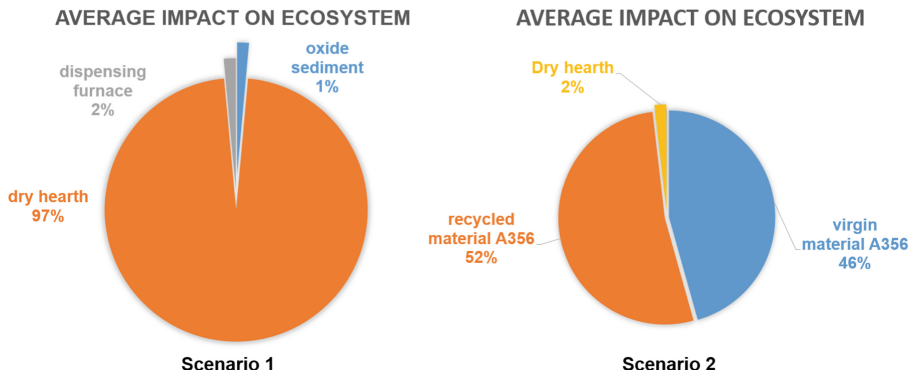


Fig. 3. Scenario 1 and 2, 100% Aluminium virgin material impact vs 80% recycled 20% virgin.

When UCC is compared with investment casting by implementing the inventory data to the LCA tool in SimaPro9 the outcome results show that UCC-S1 (100% virgin alloy) has the highest environmental impact, followed by Investment Casting, and UCC-S2 (80% recycled alloy) has the lowest impact, as seen in Fig. 4 below.

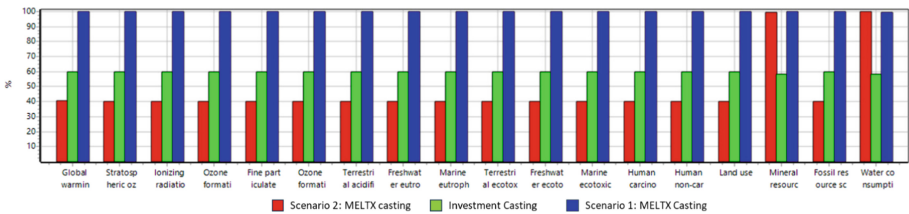


Fig. 4. Life cycle assessment comparison of midpoint results.

More specifically, UCC Scenario 1 (blue) consistently shows the highest impacts due to the use of virgin materials. Investment Casting (green) shows moderate impacts, while UCC Scenario 2 (red) demonstrates significantly lower impacts across almost all categories. This highlights the environmental benefits of using recycled materials in the UCC process, especially in reducing global warming potential, resource use, and other environmental burdens.

Finally, a comparative analysis was done to study the difference between energy consumption and CO₂ emissions for different % of virgin and recycled alloy as the initial charge in the process, as seen in Fig. 5 below.

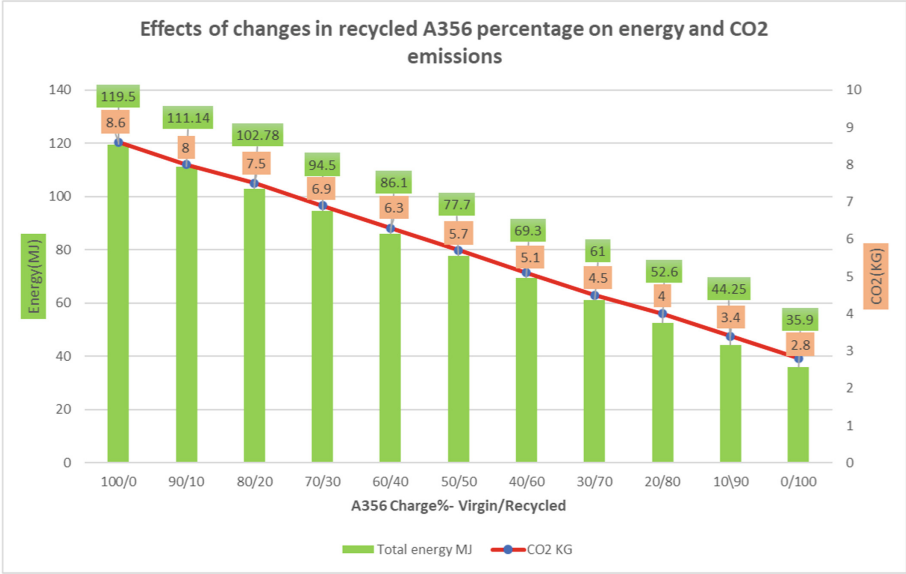


Fig. 5. Effects of changes in recycled A356 percentage on energy and CO2 emissions.

The figure shows that increasing the proportion of recycled A356 alloy in the charge significantly reduces both energy consumption and CO₂ emissions. At 100% virgin alloy, energy use is 119.5 MJ and CO₂ emissions are 8.6 kg/kg. Shifting to 100% recycled alloy lowers energy use to 35.9 MJ and CO₂ emissions to 2.8 kg/kg, illustrating the substantial environmental benefits of using recycled materials.

5 Conclusion

The results of this study highlight the environmental implications of the UCC process compared to traditional investment casting. Initial assumptions suggested a higher impact for UCC, but further analysis revealed that using a higher proportion of recycled aluminum significantly reduces its environmental footprint, making it a more sustainable option.

Proprietary data restrictions from foundries limited the accuracy of efficiency, energy consumption, and material loss estimates. Future research should incorporate cleaning methods in benchmarking, provide detailed information on casting processes, and use a functional unit for more precise comparisons.

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