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EVALUATING ENERGY CONSUMPTION IN ATOMIC DIFFUSION ADDITIVE MANUFACTURING VERSUS SAND CASTING

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Abstract: Human activities have caused significant disturbances to the natural environment, leading to a rise in temperatures that exceed pre-industrial levels in recent times. This has been primarily attributed to the recent rise in greenhouse gas (GHG) emissions. In order to address the increasing temperatures, it is crucial to investigate energy-efficient manufacturing methods. While traditional manufacturing (TM) methods such as sand casting have the ability to produce a wide variety of products, they are known to be energy intensive. In contrast, metal additive manufacturing (MAM), including material extrusion additive manufacturing (MEAM), is considered to be more energy-efficient as it enables the production of intricate, lightweight, and near-net-shaped products, while also streamlining the manufacturing process. Despite these advantages, there is limited scientific evidence supporting the claims of energy efficiency, especially for MEAM methods, such as the atomic diffusion additive manufacturing (ADAM) process. This study aims to evaluate the feasibility of conducting a comprehensive life cycle assessment (LCA) for MEAM, particularly the ADAM process, in comparison to sand casting. Theoretical results imply that MEAM-ADAM requires an additional 71.04 kWh/kg and 16.57 CO2 equivalent (CO2-eq) of energy to manufacture one kilogram of precipitation-hardened stainless steel (17-4 PH SS) when compared to sand casting. Therefore, the findings of this preliminary study indicate the need for future research to develop a comprehensive LCA model for MEAM, which should include a comparison of the process with other metalworking processes such as turning, milling, and investment casting.

Keywords: Additive manufacturing; metal additive manufacturing; sustainability; casting; specific energy consumption.

1. Introduction

The impacts of past climatic events have led to species extinctions, population migrations, and landscape changes, often coinciding with major developments in human evolution (Wolff et al., 2020) Evidence suggests that early humans were able to adapt to these challenges by modifying their behaviors in response to changing meteorological conditions (Stock, 2008). Similar challenges are currently faced by societies worldwide, but the frequency and intensity of these events are unprecedented in their speed and magnitude. Since the turn of the century, global temperatures have risen by approximately 1°C, and by the end of the century, they are projected to rise by 1.5°C to 3°C (IPCC, 2018). These changes have resulted in adverse effects such as flooding, droughts, loss of Arctic Sea ice, early plant flowering, and changes in animal migration patterns (Shivanna, 2022; Weiskopf et al., 2020). It is widely accepted that the release of GHGs, including those from industrial practices, has played a significant role in driving these events, with metal and alloy processing being particularly energy-intensive and contributing to approximately 15% of GHG emissions (Armstrong et al., 2022).

Together, the iron and steel as well as the aluminum industries are major sources of CO2 emissions within this sector. Both the iron and steel industry, is wholly responsible for emitting 2.6 gigatons (Gt) of CO2 equivalent annually, accounting for 7% of global emissions from energy use and 7-9% of global anthropogenic CO2 emissions (IEA, 2020). Similarly, primary aluminum production had an average global carbon footprint of approximately 275 Mt of CO2 emissions in 2021, which increases to roughly 1.1 Gt of CO2 when indirect emissions from electricity consumption are included (IEA, 2022). Although aluminum production typically emits less CO2 compared to iron and steel, it still constitutes a significant number of emissions, and efforts to reduce the carbon footprint of aluminum production are ongoing, including the adoption of renewable energy sources and improved production technologies. Although the iron and steel as well as the aluminum industries play a crucial role in today's society by supporting infrastructure and manufacturing, they are notorious for their significant energy consumption and heavy dependence on fossil fuels to sustain their operations.

Therefore, it is critical for organizations and industries to adapt and change their practices to more sustainable and responsible business models that consider the long-term environmental and societal impacts of their actions. While some organizations have already taken action, more needs to be done to effectively address these issues. This requires collaborative efforts from all stakeholders, including governments, businesses, organizations, and individuals, and a shift in mindset from short-term profit-seeking to a holistic approach that prioritizes the well-being of societies and the planet.

Fortunately, the current ecological challenges coincide with a variety of technological innovations, particularly in the field of metal additive manufacturing (MAM). Recent advancements have enabled the development of new and efficient processing techniques that can be applied in various industries (Armstrong et al., 2022). One of the major advantages of MAM is its ability to create intricate shapes with exceptional accuracy while minimizing material usage, thus reducing waste and mitigating the environmental footprint of the manufacturing process. Moreover, MAM can minimize the need for transportation and storage of raw materials and finished products, further reducing the carbon footprint of the manufacturing process. Additionally, MAM can facilitate the use of sustainable materials and alloys that were previously challenging to fabricate using traditional manufacturing (TM) methods. For example, MAM can be used to produce parts made from recycled metal powders, reducing the need for virgin materials (Armstrong et al., 2022). However, MAM also has its own environmental implications, such as the energy required to power the machines and the disposal of waste materials. As an increasing number of companies are adopting novel additive technologies and others are considering their implementation, it is crucial for manufacturers to evaluate the ecological impact of MAM compared to TM processes, and implement sustainable practices to minimize its environmental footprint. In this regard, conducting life cycle assessment (LCA) provides an empirical and comprehensive means to discern and quantify the environmental impact of a product throughout its entire life cycle. (European Environment Agency, 2023). This includes all phases of the production process, from mining to extraction to primary material production to feedstock production, processing, post-processing, and disposal of the product.

While academia and industry have promoted MAM as a more sustainable manufacturing process, this has not been well demonstrated. There lacks a comprehensive comparison of the energy consumption of the different MAM processes (Armstrong et al., 2022). Similarly, to establish how to implement a manufacturing process responsibly, a distinction must also be made based on systematic studies of MAMs' environmental impact compared to TM processes such as casting, forging, CNC machining, and powder metallurgy. Due to the absence of clearly defined ecological distinctions, the widespread adoption of MAM may face obstacles in the future. Therefore, it is crucial to thoroughly characterize and compare the environmental impacts of this technology.

Although there has been a substantial number of publications related to additive manufacturing (AM), there is relatively limited research on LCAs for MAM as compared to TM processes. Thus, a bibliographic Boolean search was performed for studies on the LCA of MAM compared to TM from 2007 to 2021 for peer-reviewed academic journal papers indexed in the EBSCO Discovery Service database (Vaughan, 2011). The results from the search were obtained from the following 'true' subject terms: "life cycle assessment", "additive manufacturing" OR "3D printing", "metal, environmental", "traditional manufacturing", AND "conventional manufacturing". The following 'false' keywords were also used: "polymers", "plastics", AND "ceramics". A total of 18 publications were found, shown in **Table 1**. However, publications for material extrusion additive manufacturing (MEAM) are missing from the literature. This paper investigates the environmental impact of the MEAM process in comparison to TM processes, specifically atomic diffusion additive manufacturing (ADAM) and sand casting. Given the limited research in this field and the incomplete understanding of MAM's sustainability, this study aims to address the question: Is ADAM a more environmentally sustainable production method than sand casting?

Table 1. Summary of literature for life cycle analysis for MAM vs. TM processes

Reported by	MAM process	TM process	Feedstock	Indicator	Metric
(Morrow et al., 2007)	DED	Cs, Fg, and Mc	TS alloy	Energy and emission output	None
(Senyana & Cormier, 2014)	PBF	Fg	Ti alloy	Environmental impact	Eco-Indicator 99
(Wilson et al., 2014)	DED	Wld	SS	Environmental impact	PCC 2007GWP 100a V1.0 and Cumulative Energy Demand
(Huang et al., 2016)	PBF	Cs, Fg, and Mc	Al, and Ni alloy	Energy demand and CO2 emissions	Experimental
(Tang et al., 2016)	BJ	Mc	SS	Environmental impact	ReCiPe Midpoint

Reported by	MAM process	TM process	Feedstock	Indicator	Metric
(Paris et al., 2016)	DED	Mc	Ti alloy	Energy demand	Cumulative Exergy Demand
(Faludi et al., 2017)	PBF	Mc	Al alloy	Environmental impact	ReCiPe midpoint H
(Priarone & Ingarao, 2017)	PBF	Mc	Ti and SS alloy	Energy demand and CO2 emissions	-
(Paris & Mandil, 2017)	PBF	Mc	Ti alloy	Environmental impact	CExD and CML 2 baseline 2000
(Bekker & Verlinden, 2018)	WAAM	Cs and Mc	SS	Environmental impact	ReCiPe endpoints method
(Liu et al., 2018)	DED	DCs	Low alloy steel	Environmental impact	-
(Ingarao et al., 2018)	PBF	Mc and Fg	Al alloy	Environmental impact	ReCiPe endpoint H, A
(Cappucci et al., 2020)	PBF	Mc and Fg	Ti alloy	Environmental impact	IMPACT 2002+
(Yang et al., 2019)	BJ	Cs, E, Mc, and Dr	SS	Environmental impact	ReCiPe endpoint H, A
(Guarino et al., 2020)	PBF	Mc	SS	Environmental impact	Eco-indicator 99
(Torres-Carrillo et al., 2020)	PBF	Cs and Mc	Ni alloy	Environmental impact	ReCiPe midpoint H
(Peng et al., 2020)	PBF	Cs and Mc	SS	Environmental impact	ReCiPe midpoint H, A

Reported by	MAM process	TM process	Feedstock	Indicator	Metric
(Priarone et al., 2020)	WAAM	Mc and Fg	Al, Ti, and SS alloy	Energy demand and CO2 emissions	-

Note: Cs = casting, Fg = forging, Mc = machining, Wld = welding, DCs = die casting, DED = directed energy deposition, PBF = powder bed fusion, BJ = binder jetting, WAAM = wire arc additive manufacturing

2. Background

2.1. The Foundry Process

The foundry industry today consists of a variety of complex and intricate production phases that typically involve smelting metals and alloys and casting them into various shapes by pouring molten metal into a mold and solidifying it (Campbell, 2015). Almost 90% of consumer products sold today include castings, which are produced with a variety of different techniques (Chougule & Ravi, 2006). The casting method used by a foundry is determined by the type of metal or alloy, the type of moulding process, and the production quantity as well as the dimensions of the product. In practice, ferrous foundries typically use lost moulds, whereas nonferrous foundries primarily use permanent moulds. The casting process selections also comprise several different techniques, each of which is influenced by the type of furnace, the moulding and core-making method (such as sand, ceramic, or metal moulds), the casting method, and the post-processing method, each of which has its own technical, economic, and environmental characteristics. Although there is a wide variety of casting processes available, **Figure 1** illustrates a generalized foundry life cycle.

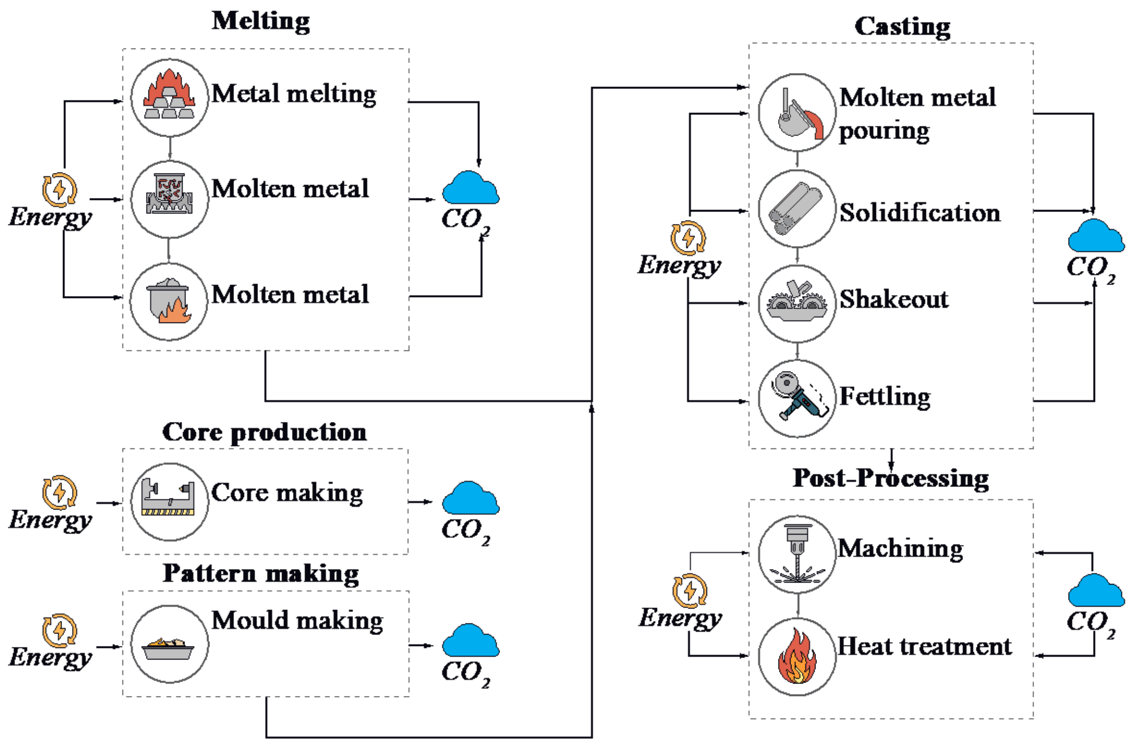

Figure 1. Schematic of a typical foundry

The sand-casting process, as shown in **Figure 2**, typically starts with the fabrication of a pattern that resembles the desired part. This pattern is then placed in a metal box called a 'flask', which consists of two halves - the top half known as the 'cope', and the bottom half which is the 'drag'. Sand is tightly packed around the pattern in the drag, covering it completely to form a mould cavity. In the subsequent steps, the mould pattern is extracted from the drag, resulting in a mould cavity with passages for sprues and risers, which facilitate the pouring and evacuation of molten metal. The cope and drag are then connected using locating pins to complete the flask assembly. Molten metal is introduced into the mould cavity through the sprue and pouring cup, and it undergoes solidification to obtain the desired shape. Once solidified, the cast is separated from the sand during the 'shakeout' phase. Subsequently, a fettling process is carried out, involving cutting and grinding to remove the sprue, risers, and other unwanted metal remnants, before further processing of the cast part to tailor various properties.

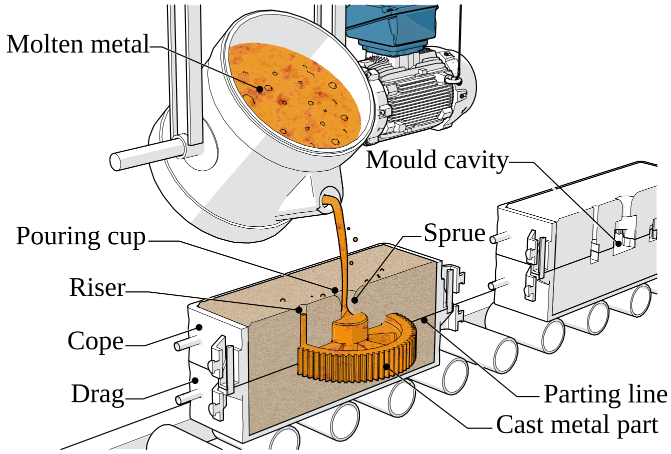

Figure 2. Illustration of a sand-casting process

2.2. The MEAM-ADAM Process

The MEAM process illustrated in **Figure 3a** is an advanced fusion of various elements derived from fused deposition modeling (FDM) and metal injection molding (MIM) techniques. It entails the utilization of a specialized feedstock in the form of a spooled filament, consisting of metallic powders bound together by a polymer that acts as the binder (Spencer et al., 2018). A typical MEAM machine is equipped with spools for the bound powder and ceramic release material, both of which are located in a heated chamber positioned above the build plate to ensure optimal processing conditions. The filament is heated in an extruder head, as shown in **Figure 3b**, and then extruded layer by layer onto a heated build plate, while ceramic material is simultaneously deposited for support of overhanging features. This results in a "brown part" with an estimated porosity of 40% (Campbell & Wohlers, 2017). The brown part then undergoes thermal debinding to dissolve the polymer binder, transforming it into a "green part" that remains porous due to voids left by the dissolved polymer. To achieve densification, the green part is subjected to high temperatures in a furnace, typically reaching 70-90% of the metal's melting point (Gonzlez-Gutirrez et al., 2012). Atomic diffusion of metal particles occurs as temperatures reach 50-75% of the metal's melting point, reducing porosity and resulting in a structure with a density of roughly 96%-99.8% (Armstrong et al., 2022). However, residual ridges and notches may be present on the part's surface due to the layer-by-layer deposition. Therefore, post-processing techniques such as machining are commonly employed to improve surface quality and enhance fatigue resistance after the procedure.

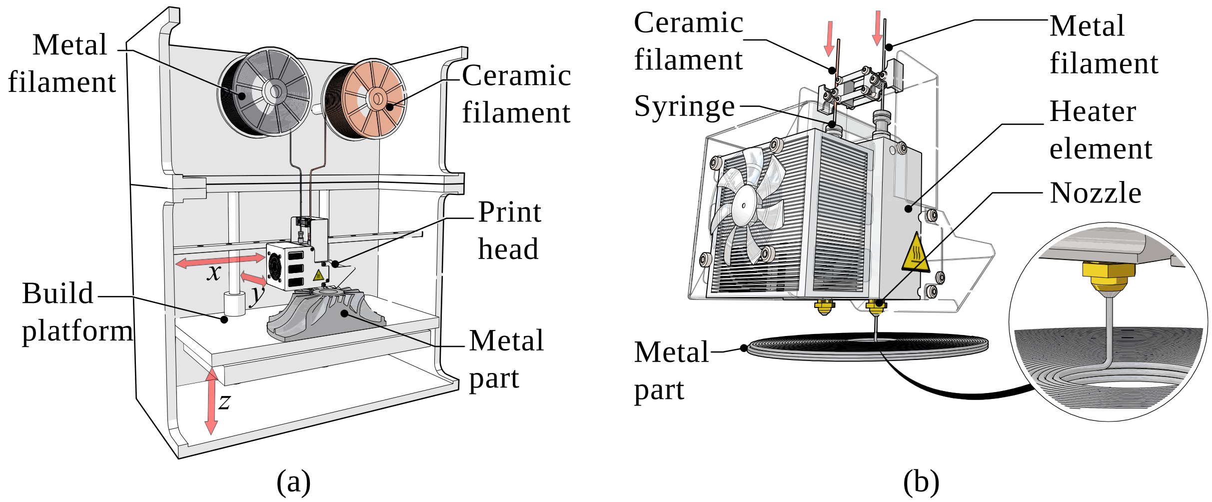

Figure 3. (a) MEAM machine and, (b) MEAM print head mechanism (Armstrong et al., 2022)

3. Life Cycle Assessment (LCA)

An LCA is a holistic approach used to evaluate the ecological implications of a product throughout its entire life cycle (ISO 14040, 2006). The LCA process generally consists of four stages:

- Goal and Scope Definition (GSD)
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation

3.1. Goal and Scope Definition (GSD)

The GSD phase of the LCA takes into account various aspects, such as the proposed application, justifications for conducting the study, and whether the results will be used for comparative assertions to be disclosed publicly (ISO 14040, 2006). Therefore, this initial paper serves as an introductory discussion aimed at facilitating further research on the sustainability characteristics of MEAM-ADAM, which are not as well-documented compared to the sand-casting process. The ultimate goal is to promote the adoption of environmentally friendly metal production processes. Additionally, as per the ISO standard, the study scope should include the function unit (FU) and system boundaries (SB).

3.1.1. Functional Unit (FU)

The FU is the appraisal of identified functions of the product, serving as a reference for relating inputs and outputs to ensure comparability of LCA results, following (ISO 14040, 2006). For this study, the selected FU is based on the impact per kilogram of 17-4PH stainless steel, as shown in **Figure 4**.

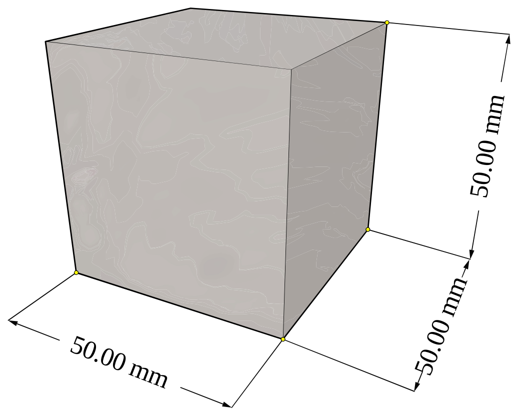

Figure 4. FU dimensions

To determine the production rate of the FU, the Markforged Eiger platform is utilized. The computer-aided design (CAD) file which defines the geometry of the part is uploaded, and various parameters are calculated, with 17-4PH stainless steel and solid infill chosen. The part is scaled by approximately 20% by the software to account for shrinkage. The production data is summarized in **Table 2**.

Table 2. Production data for MEAM-ADAM

Variables	Measurements
Pre-sintering dimensions, mm	251 × 96 × 13
Post-sintering dimensions, mm	210 × 80 × 11
Print time, hrs.	59
Debinding time, hrs.	12
Pre-sintering mass, kg	1.4
Post-sintering mass, kg	1

3.1.2. System Boundary (SB)

The SB in the LCA encompasses all the processes involved in the production of the FU, including raw material acquisition, manufacturing inputs and outputs, transportation, fuels, electricity, heat, waste disposal, as well as operational aspects like lighting and heating, in accordance with (ISO 14040, 2006). For this study, initial boundaries for sand casting (**Figure 1**) and ADAM (**Error! Reference source not found.**) are proposed to characterize the SB for the FU. In order to enable a comprehensive comparison between the sand casting and MEAM-ADAM processes, this study and subsequent research endeavors will strive to evaluate corresponding phases in each life cycle. Hence, in this study, the phases that contribute to the production of the FU, such as casting for sand casting and printing for MEAM, are evaluated, while melting will be compared to powder atomization in future studies. This approach allows for meaningful comparisons between the different processes and their environmental impacts.

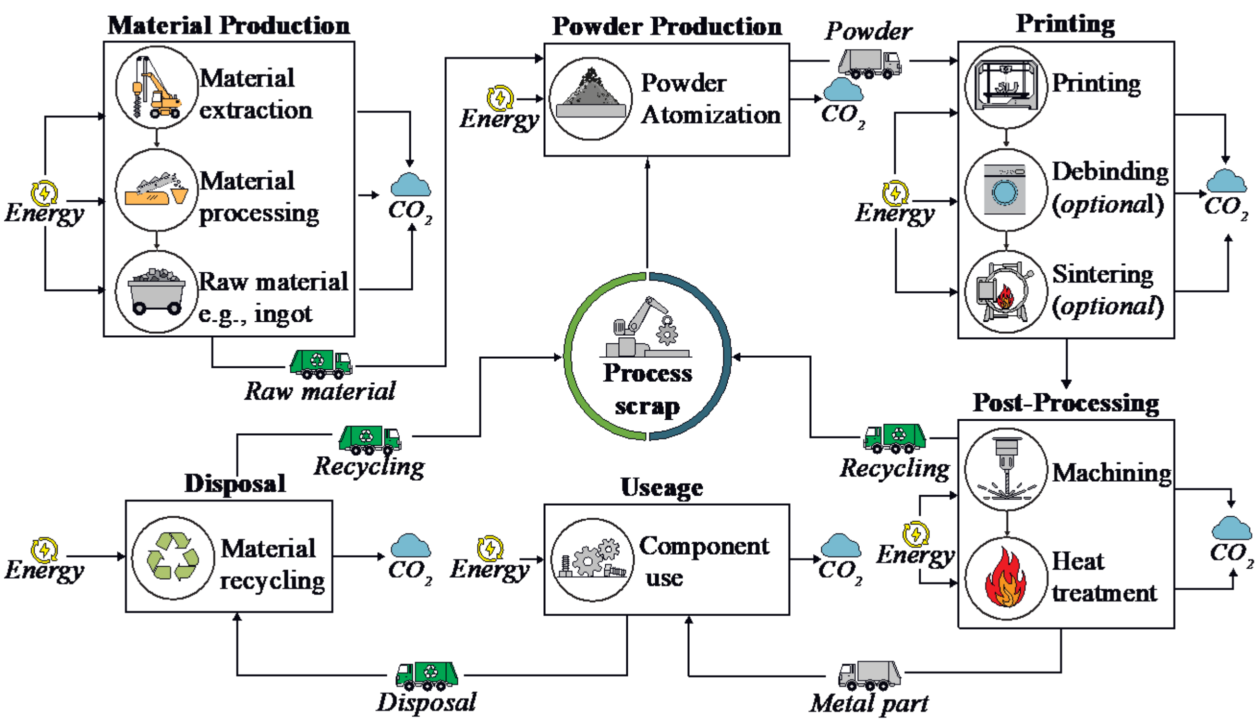

Figure 5. Lifecycle and system boundary for a typical MEAM process (Armstrong et al., 2022)

3.2. Life Cycle Inventory Analysis (LCI)

The LCI encompasses the cumulative resources utilized in the production of the FU throughout its entire life cycle, which are categorized as either inputs or outputs. In this preliminary study, we will focus on the basic inputs and outputs associated with the sand casting phase and the MEAM-ADAM printing phase, as depicted by the dashed lines in **Figure 1** and **Error! Reference source not found.**, which represent the SBs. The quantity of material in a MEAM-ADAM process is determined by the systems software, in this instance it is the Markforged Eiger 3D printing software. Markforged has shared with the authors the average energy consumption rates, which are included in **Table 3** along with the inputs and outputs for the ADAM SB.

Table 3. MEAM-ADAM generalized inputs and outputs

Inputs	Outputs
Metallic feedstock (e.g., metal powder, polymer)	Printed structure Ancillary structures (e.g., raft)
Ceramic material (e.g., release material)	Ceramic waste
Energy (grid mix e.g., coal, hydro, gas, nuclear, etc.)	Emissions to air, water and land

The Ansys Granta EduPack database (ANSYS Inc., 2022) can be used to derive the required energy demand data for sand casting. Additionally, an initial attempt has been made to classify the inputs and outputs for the raw materials needed to produce 1 kg of steel. **Table 4** presents the inputs and outputs for a sand-casting SB.

Table 4. Sand casting generalized inputs and outputs

Inputs	Outputs
Molten metal (e.g., ingot, scrap metal)	Cast structure Waste metal Cooling water
Foundry sand	Recycled sand
Energy (grid mix e.g., coal, hydro, gas, nuclear, etc.)	Emissions to air, water and land

3.3. Life Cycle Impact Assessment (LCIA)

The LCIA assesses the likely impacts on the environment as well as human health of the FU based on data from the LCI. Emissions and resource data from the inventory are translated into ecological impact scores using characterization factors, which provide information on the environmental impact per kilogram or emission released (Hauschild & Huijbregts, 2015). This allows for a comparison of the relative impacts of different processes, such as metal MEAM and sand casting, to determine their ecological effects. Among the available impact assessment methods, the ReCIPe model (National Institute for Public Health and the Environment, 2011) is commonly used in Europe and is proposed for this study. Characterization factors can be obtained at two levels: midpoints and endpoints. Thus, an LCIA typically consists of four steps after selecting the relevant impact categories:

a. *Classification:* qualitatively determines each environmental intervention to which impact categories it contributes,

b. *Characterization:* quantitatively determines the impact score per environmental category,

c. *Normalization:* used to relate the environmental impact of the FU to the impact on its surroundings,

d. *Weighting:* a combination of the normalization scores to a single environmental index with the help of weighting factors.

3.4. Interpretation

The LCI phase involves systematically collecting and summarizing the results obtained from the LCIA phase. As per ISO guidelines, this phase aims to provide a comprehensive and easily understandable representation of the LCIA findings, ensuring their consistency with the GSD (ISO 14040, 2006).

4. Theoretical Results

A preliminary evaluation has been performed to analyze MEAM-ADAM and sand casting in terms of specific energy consumption (SEC) in an attempt to quantify the energy needed to produce 1 kg of 17-4 PH SS. SEC can also serve as an indicator of energy performance for evaluating efficiency or benchmarking purposes. Furthermore, CO2-eq, which measures the global warming potential of a gas relative to CO2, has been utilized to assess the environmental impact.

4.1. MEAM-ADAM Printing SEC

Measurements for MEAM-ADAM have been conducted by Markforged Inc., and the results have been shared with the authors, although specific details on the methodology for obtaining these figures have not been disclosed. The disclosed data indicates an average energy consumption of 12-15 kWh per day. To enable a comparison of SEC, an average value of 13.5 kWh per day has been utilized by taking the midpoint of the provided range, as shown in equation (1):

$$(13.5) / 24 = 0.5625 \text{ kWh} \tag{1}$$

Thus, the computation of the SEC involves multiplying the total number of printing hours for 1 kg by the hourly energy consumption, as per equation (2):

$$0.5625 \times 59\text{h} = 33.19 \text{ kWh/kg} \tag{2}$$

4.2. Sand Casting SEC

The SEC is obtained from the CES database for 17-4 PH SS, cast, H900. The value provided is 3.15 kWh/kg (ANSYS Inc., 2022).

4.3. Sand Casting CO2-eq

Utilizing the SEC data, it is possible to estimate the combined CO2-eq emissions. The greenhouse gas (GHG) reporting conversion factors of 0.23314 kgCO2/kWh, can be used (Hill et al., 2020). Thus, an estimated equivalent (kg/CO2-eq) can be calculated using equation (3) for sand casting and equation (4) for MEAM-ADAM.

$$3.15 \times 0.23314 = 0.73 \text{ kg/CO}_2\text{-eq} \tag{3}$$

$$33.19 \times 0.23314 = 7.74 \ \text{kg/CO}_2\text{-eq} \quad (4)$$

In order to comprehensively evaluate the ecological implications of the entire MEAM-ADAM process, it is crucial to consider not only the energy and emissions during printing but also the debinding and sintering processes. To this end, data provided by Markforged Inc. is also utilized to assess the impacts of both debinding and sintering.

4.4. MEAM-ADAM Debinding SEC

The daily energy consumption of the debinding machine is reported to be 22 kWh. Thus, equation **Error! Reference source not found.** is used to obtain the hourly energy consumption rate:

$$(22) / 24 = 0.92 \text{ kWh} \quad (5)$$

To determine the energy demand for the FU, the energy consumption of the debinding equipment, as provided in the data (22 kWh per day), is multiplied by the total number of debinding hours listed in **Table 2**. This calculation yields the cumulative energy demand for the debinding process, as depicted in equation (6):

$$0.92 \times 12\text{h} = 11 \text{ kWh/kg} \quad (6)$$

4.5. Sintering SEC

The authors have received data from Markforged Inc., indicating that their sintering furnace consumes 30 kWh of energy per run. This valuable information sheds light on the exact electricity usage during every operational cycle of the furnace. As a pivotal element within the manufacturing process, the sintering furnace relies on this energy to attain the essential temperature and create optimal conditions for the sintering of materials.

4.6. Debinding and Sintering CO2-eq

After determining the energy requirement, it becomes feasible to approximate the kg/CO2-eq emissions for debinding and sintering, as illustrated in equation (7) and equation (8) respectively.

$$11 \times 0.23314 = 2.56 \ \ \text{kg/CO}_2\text{-eq} \tag{7}$$

$$30 \times 0.23314 = 6.99 \ \ \text{kg/CO}_2\text{-eq} \tag{8}$$

4.7. MEAM-ADAM SEC compared to other MAM technologies

The combined SEC for the complete MEAM-ADAM process is compared alongside the SEC for the sand-casting process in **Table 5**.

Table 5. Comparison of SEC and CO2-eq emissions for MEAM-ADAM and sand casting

Method	SEC, kWh/kg	CO2-eq, kg/CO2-eq
MEAM-ADAM	74.19	17.30
Sand casting	3.15	0.73

Table 6 presents the SEC for different MAM technologies. The literature suggests that SEC values for different MAM technologies can vary significantly. While the MEAM-ADAM process shows a relatively high SEC, some laser-based systems such as selective laser melting (SLM), exhibit variable SEC values ranging from. This indicates that energy efficiency can vary among different MAM technologies, with some laser-based systems potentially being less energy efficient compared to MEAM-ADAM. However, it is important to consider the specific characteristics and parameters of each MAM process when evaluating their energy consumption and sustainability performance.

Table 6. SEC for different MAM technologies per kg of printed steel-grades

Study	Process	Steel grade	SEC, kWh/kg	CO2-eq, kg/CO2-eq
Current	MEAM-ADAM	17-4 PH SS	33.19	7.74
(Guarino et al., 2020)	SLM	316L SS	17.55	4.09
(Peng et al., 2020)	SLM	316L SS	18.86	4.40

(Bekker et al., 2016)	WAAM	308L SS	1.84	0.43
(Baumers et al., 2011)	SLM	316 SS	29.44	6.86
(Baumers et al., 2011)	SLM	316 SS	163.33	38.08
(Baumers et al., 2011)	DMLS	17-4 PH SS	94.17	21.95

5. Conclusion

The current study finds that the MEAM process requires significantly more energy than sand casting for producing 1kg of 17-4 PH SS. The MEAM-ADAM process, excluding debinding and sintering, is also more energy-intensive than other MAM technologies. The cumulative SEC for MEAM-ADAM is estimated to be 74.23 kWh/kg with a CO2-eq of 17.31, while sand casting has SEC and CO2-eq of 3.15 kWh/kg and 0.73 kg/CO2-eq, respectively. Among the MEAM-ADAM subprocesses, printing consumes 44.73% of the total energy, followed by sintering (40.44%) and debinding (14.83%). Sand casting is therefore considered a more environmentally friendly manufacturing process from a theoretical perspective. One advantage of AM is the ability to optimize part geometry while maintaining strength, using infill-type structures to minimize weight and material usage. This leads to reduced print and debinding time, as well as decreased SEC and CO2-eq for MEAM-ADAM. Additionally, printed parts are near-net-shaped, reducing the need for post-processing machining. However, for fair comparisons, it is important to use the same FU (e.g., by mass) between processes. The findings provide valuable initial insight for researchers and industrialists in selecting environmentally sustainable manufacturing processes. Furthermore, the data from this study can serve as a comparative reference point for evaluating MEAM-ADAM against other metalworking processes using a comprehensive LCA as well as the methodology outlined in this paper to further characterize the environmental performance of each method through ReCIPe impact scores. This will assist in decision-making and contribute to the development of policies that promote sustainable practices in metal manufacturing.

It is important to acknowledge the limitations of the study, including the use of indirect data for the ADAM process and a focus solely on lifecycle phases affecting the FU. Further research should involve empirical power monitoring experiments for the ADAM process to verify the findings to fully understand its ecological impact.

Acknowledgement

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