LIFE CYCLE ASSESSMENT (LCA) OF A NEWLY DESIGNED METAL ADDITIVE MANUFACTURING PROCESS: MAPS (METAL ADDITIVE MANUFACTURING USING POWDER SHEETS)

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ABSTRACT

Additive manufacturing (AM), a transformative technology in modern manufacturing, offers design freedom and reduced material waste. However, understanding the environmental impacts of AM processes is imperative for sustainable adoption. Metal additive manufacturing using powder sheets (MAPS) is a newly designed process to overcome powder handling and recycling issues associated with the powder bed fusion (PBF) processes. This transformative approach in 3D metal printing reduces safety risks, boosts efficiency, and enables the creation of complex multi-material components. In this study, MAPS process was investigated from the perspective of sustainability and circular economy using a life cycle assessment (LCA) method. The results provide critical insights into the sustainability performance of AM technologies, specifically the MAPS process, offering valuable guidance for informed decision-making in the context of eco-conscious manufacturing. This study might also serve as a pivotal reference for advancing the ecological credentials of AM in diverse industrial applications.

Keywords: Additive manufacturing, 3D printing, sustainability, LCA, circular economy

1. INTRODUCTION

Additive manufacturing (AM), a transformative technology in modern manufacturing, offers design freedom and reduced material waste. However, understanding the environmental impacts of AM processes is imperative for sustainable adoption.

In this study, life cycle assessment (LCA) of a newly designed MAPS (Metal additive manufacturing using powder sheets) process was investigated from the perspective of sustainability and circular economy. The well-known steps of the LCA analysis have been followed, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation. As a holistic approach, a bibliometric analysis has also been performed to be able to see the big picture by means of the literature review.

The bibliometric analysis has been performed based on the Web of Science (WoS) literature search performed on 06/11/2023 using the following terms simultaneously in all fields: Additive manufacturing, life cycle assessment, and sustainable. The total number of documents published is 145 with a time span of 1945-2023, sum of the times cited is 3295, average citations per item is 22.72, and h-index is 29. The bibliometric analysis has been performed using the VOSviewer software (version 1.6.19). After processing the exported citation tab delimited file (with full record and cited references, WoS) in the VOSviewer software, 50 of the documents have met the analysis threshold and those have been published during the period of 2018-2024. The analysis has been performed considering the largest set of connected items which consists of 41 items.

Several studies have explored the environmental impacts of AM processes, employed diverse methodologies, and focused on various aspects. Bourhis et al. (2013, 2014) developed methodologies considering all consumed flows, including material, fluids, and electricity. Faludi et al. (2015) compared AM machines with a traditional CNC milling machine, quantitatively assessing environmental impacts for the first time. Cerdas et al. (2017) evaluated centralized versus 3D printing-supported distributed manufacturing, emphasizing energy consumption optimization and its link to printing material. Colorado et al. (2020) aimed to raise awareness of AM possibilities and implications for sustainable development. Kokare et al. (2023) conducted a systematic literature review of 77 LCA studies on AM, identifying shortcomings in existing research. Nyamekye et al. (2017) investigated process sustainability with PBF and CNC machining, with a focus on SS304 powder. However, their study lacked a full LCA. This study aims to fill this gap by conducting the first LCA on PBF of SS304 using innovative powder sheet additive AM technology.

2. MATERIALS AND METHODS

MAPS process includes three main processes which are metal powder solution preparation, tape casting of the metal powder film sheets, and sintering/3D printing using the cast metal powder film sheets. A trial in the laboratory has been performed from the beginning of the process for recording mass and energy values during the whole these three processes. In the metal powder solution preparation step, stainless-steel (SS304) powder was mixed with a polymer solution. Then tape casting operation has been performed using this metal powder solution and film sheets have been formed. As a final part, approximately 1 cm2 square metal piece has been printed using the Realizer SLM-50 selective laser melting device with the following settings:

- Number of layers: 20
- Layer thickness: 25µm
- Laser time: 23 sec/layer
- Total time: 2 min/layer
- Laser power: 100W
- Speed: 300 mm/sec

All the data related to mass and energy amounts have been recorded for the whole process. After finalizing the inventory analysis, all the data have been plugged to the OpenLCA software (version 2.0.0) by activating the environmental footprints database (ef_secondarydata_202202). Flows have been created specific to the MAPS process components. For the energy flow, readily available electricity flow has been used. After creating the flows, processes that use these mass and energy flows as inputs and outputs have been created by plugging the mass and energy amounts. After that product systems have been created using the three different processes. Calculation step has been performed for each process using the ReCiPe 2016 Midpoint (H) impact assessment method. Finally, in the last step, MAPS product systems have been investigated by comparing these three product systems all together using the CML-IA baseline impact assessment method under the projects folder.

3. RESULTS AND DISCUSSION

After finalizing the calculation under the projects folder of the OpenLCA software, a report, containing the comparative results, has been generated and the results have been exported and tabulated in Table 1.

Table 1. Life Cycle Assessment Results for the Metal Powder Solution Preparation, Casting, and Sintering/3D printing

Impact category	Reference unit	Metal powder solution prep	Casting	Sintering/3D printing
Abiotic depletion	kg Sb eq	1.34E-08	1.41E-02	4.40E-03
Human toxicity	kg 1,4-DB eq	8.50E-03	8.97E+03	2.79E+03
Terrestrial ecotoxicity	kg 1,4-DB eq	7.34E-05	7.74E+01	2.41E+01
Marine aquatic ecotoxicity	kg 1,4-DB eq	5.26E+01	5.55E+07	1.73E+07
Abiotic depletion (fossil fuels)	MJ	7.61E-01	8.03E+05	2.50E+05
Global warming (GWP100a)	kg CO2 eq	6.87E-02	7.24E+04	2.26E+04
Acidification	kg SO2 eq	3.62E-04	3.81E+02	1.19E+02

Ozone layer depletion (ODP)	kg CFC-11 eq	2.11E-09	2.23E-03	6.95E-04
Photochemical oxidation	kg C2H4 eq	1.38E-05	1.46E+01	4.55E+00
Eutrophication	kg PO4--- eq	1.97E-05	2.08E+01	6.47E+00
Fresh water aquatic ecotox.	kg 1,4-DB eq	2.90E-03	3.06E+03	9.53E+02

Considering all the impact category results, the casting process appears as the worst throughout the whole MAPS process by means of the sustainability. However, some improvements are already in place in the casting process like recycling. After finishing the casting operation, all the scrapped film sheets have been collected, recycled, and used in the casting process again. Hence it is a closed loop process and no waste produced in the casting process. Another advantage of the MAPS process is saving time with the sintering/3D printing time. It takes 2 hours to print the same size of a part that produced in this study with the conventional PBF process. In comparison, it only takes 1 hour (half of the time) to print with the MAPS process.

4. CONCLUSIONS

The advantages of the MAPS process lie in easy powder handling and a simplified recycling process, reducing labor-intensive tasks. This study offers crucial insights into the sustainability of AM technologies, particularly MAPS, guiding eco-conscious decision-making. It serves as a key reference for bolstering the ecological credentials of AM across various industrial applications.

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