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Life Cycle Assessment of metal additive manufacturing: a systematic literature review

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Abstract

Additive manufacturing was initially employed to create models and to prototype parts that engineers had envisioned in shorter times to provide enhanced product design flexibility. Currently, it is fully accessible to different industrial sectors. In particular, it has the potentials to be employed in the metal sector, which is a significant contributor to several types of environmental degradation issues, and it can potentially lead to a reduction of its environmental impacts. In order to understand these aspects, it is important to quantify the sustainability of metal additive manufacturing. Thus, this paper presents a systematic critical review of currently available life cycle assessment (LCA) studies on metal additive manufacturing (MAM). Additionally, it highlights the main environmental, and value generation issues connected to MAM.

Keywords: Life Cycle Assessment, additive manufacturing, metal, sustainability

1. Introduction

The production of metal objects is an important contributor to environmental deterioration [1]. In the metal industry of the aircraft sector, particularly, the footprint is high because of elevated buy-to-fly ratios, which lead to high waste volumes. Another issue is that in the automotive and aerospace industries there is a need for spare parts, thus usually there are big amounts of unutilized stock [2]. Lately, additive manufacturing (AM) techniques have been developed. Additive manufacturing, which is commonly known as 3D printing technology or Rapid Prototyping, is a manufacturing technique that starts from a digital model to produce instantly a physical three-dimensional object by depositing, solidifying, or fusing layer on top of layer ([3], [4]). Rapid prototyping has some benefits as shorter lead times, flexibility and customization of design, material and resource efficiency and it is often seen as a disruptive technology [5]. On the other hand, this technology may have

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high energy consumption per produced part ([6], [7]). The additive manufacturing techniques have been categorized and grouped into seven classes by ISO/ASTM 52900:2015: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [8]. All of them, except vat photopolymerization, which is specifically customized for photopolymers, can be used for metallic products fabrication. Currently, there is considerable research on the environmental, economic and social impacts of additive manufacturing. These investigations often undertake a life cycle thinking approach and consist of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) studies. For instance, [9] presented a comprehensive literature review and suggestions for future studies of Life Cycle Assessment (LCA) applied to additive manufacturing (AM) processes. [10] identified multiple LCA methods based on both analytic and experimental models for Binder Jetting, Direct energy deposition, Powder Bed Fusion technologies. [5] focused on Environmental Impact Assessment (EIA) and LCA for Material Extrusion, Inkjet Printing, Sheet Lamination, Direct Energy Deposition, VAT-photopolymerization, and Powder Bed Fusion. To our knowledge there is not a scientific publication with a specific focus on reviewing LCA of metal additive manufacturing**.**

The aim of this short paper is to introduce a literature review about metal additive manufacturing (MAM) sustainability aiming to answer to the following research question:

How sustainable is metal additive manufacturing, what are important environmental and value generation aspects of it, and how can it be measured?

Thus, journal articles, book chapters and conference papers that focused on environmental, economic, and social sustainability of additive manufacturing undertaking a life cycle thinking approach were analyzed. Then, they were categorized to identify the main findings and overarching principles and provide suggestions on how to improve the eco-efficiency of MAM techniques.

2. Sustainability of metal additive manufacturing (MAM)

The systematic literature review was started by searching scientific articles by keywords on Scopus and Web of Science. The expressions considered were: “3d-printing", "life cycle assessment”, “additive manufacturing", and "sustainability”. This initial outcome brought to the analysis of 502 papers. Afterwards, the author proceeded with the title analysis and made sure that there was not repetition. This led to reducing the number of articles to 139. During the abstract analysis, the numbers went down to about half. Finally, 62 papers were selected for the literature review on metal additive manufacturing. The majority of the publication focused on environmental sustainability, were written in Europe and USA, and consisted of journal articles (see Table 1).

Table 1: type and location of scientific publication, and triple bottom line.

Type of scientific publication		Triple bottom line		Location of the authors of the study			
Journal	30	Environmental	47	Europe	22	Central & South America	3
Literature review	17	Social	7	USA	16	Canada	5
Conference paper	8	Economic	12	Asia & Oceania	6	India	2

2.1. Overarching principles

Some of the papers lacked consistency in product life cycle assessment application on case studies. For example, many considered different set of sustainability factors, as amount of material, energy, health impact and CO_2 emissions ([11], [12], [13]). Other presented just few midpoint impact categories of Life Cycle Impact Assessment (LCIA) method without a clear justification of the choice ([14], [15]). Another overarching principle that emerged during the literature review is the lack of consistency in Metal Additive Manufacturing design optimization combined with LCA framework at early stage product development. Indeed, a group of researchers suggested to combine CAD design optimization with product LCA [16], other proposed a more generic framework for sustainable design optimization for additive manufacturing [14]. Only few studies assessed the triple bottom line (i.e. social, environmental, and financial) all together for metal additive manufacturing ([12], [17]). When this was the case, the social sustainability evaluation was often the least investigated and was focusing on workers' health damages solely. In addition to that, there is a diffuse lack of consistency about the functional unit definition. This is sometimes mass-based ([18], [19]), or the printed product ([15], [20]), but the function of the product itself is never considered in the functional unit definition. Moreover, many of the studies focused on cradle-to-gate LCA ([7], [21], [22], [17]). Few of them justified the exclusion of the other life cycle stages because they were equivalent ([11], [20], [21], [22]). A simplified framework of how life cycle assessment has been majorly developed in the scientific community so far is illustrated in Figure 1.

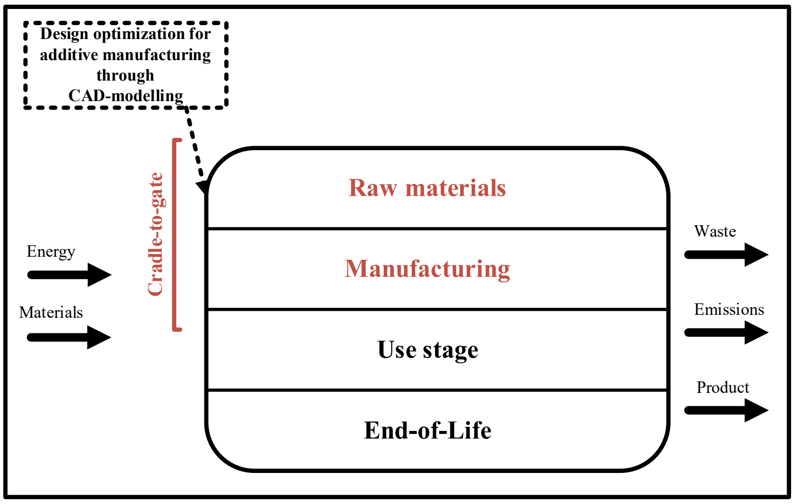

Figure 1: Generic framework of current LCA studies on metal additive manufacturing. In materials often are considered: metals, ancillary materials, process gases and capital goods. Most studies only include cradle-to-gate life cycle stages.

2.2. Main environmental and value generation aspects of metal additive manufacturing

A benefit that additive manufacturing (AM) could bring to society is the local repair, manufacturing, control and product on-demand ([23], [24]). This means savings in transport, and storage cost, but also capabilities of responding to the explicit demand for products, as well as creating new infrastructure that advances local employment, empowerment and ownership ([23], [25]). [26] illustrated and quantified the shorter manufacturing times that could be reached by additive manufacturing. [12] quantified the threshold by which 3D printing could become economically more competitive than conventional manufacturing methods, such as milling. [10] highlighted the reduction of assembly difficulties and costs, since AM allows eliminating fasteners, joints and connectors. In addition, AM allows to produce lightweight product with improved design, and this can mean savings in fuel consumption during the use of the product ([24], [27]). Moreover, near-net shape and topology optimization allows increasing material-use efficiency and lower environmental impact, which show to have a proportional correlation ([15], [18]). For example, [28] identified that the major contribution to the total environmental impact are caused by the feedstock (i.e. nickel-alloy), process gas and electricity for manufacturing. Then, they suggested that the impact can be reduced through optimized design of the reactor, and replacing the feedstock with other metals that have similar properties but a lower environmental impact or enhancing the recycling of the feedstock (e.g. stainless steel) [28]. [14] compared the cradle-to-gate LCA of an aircraft component produced with Binder Jetting to CNC milling, and evaluated the influence of redesign with topology optimization for improved product performance functionality. The additive manufacturing (AM) technique resulted to reduce the energy consumption of approx. 24%, and CO_2 emissions of about 58% mainly due to a decrease of product volume (i.e. 47%), but also increase the human toxicity of roughly 49%. Indeed, also [29] identified some environmental issues as the fact that Binder Jetting technology uses a quite toxic liquid bonding agent, but also the importance of recycling quality and methodology of the metal powder for production of new materials. Furthermore, some researchers argued that higher layer deposition rate can result in more deformation, and this might lead to higher need of further machining, meaning that amount of metal scrap and the demand of energy during manufacturing can potentially increase ([11], [18]). The same authors also noticed a direct correlation of the deposition rate of the metallic layers with the total environmental impact ([11], [18]). In particular, energy and process gas were shown to have a relevant contribution to the environmental impact ([18], [20]). [18] investigated the life cycle assessment (LCA) of Wire Arc Additive Manufacturing (WAAM) against the one of CNC milling and green sand casting. They discovered that WAAM has a lower impact than the two conventional manufacturing processes. This is mainly caused by the more efficient resource-use through WAAM, which has potential to decrease component weight by topology optimization. Then, [18] underlined the importance of the deposition rate, because 44% of the impact is caused by energy input, and 48% is caused by the shielding gas usage. A summary of the identified environmental and value generation aspects of metal additive manufacturing is illustrated in Table 2.

Table 2: MAM environmental and value generation aspects

Value generation aspects	Environmental aspects
Lightweight design	Reduction transport and packaging
More complex shapes	Product lifetime extension
Topology optimization	Complex recycling
Eliminate/reduce product components	Deposition rate
Near-net shape	Reduction waste during manufacturing stage
Add on parts on semi-finished product	Reduction energy/fuel consumption during use stage
Reduction stocks	Reduction material use for product manufacturing
Local and faster repair	Reduction amount critical metals use

2.3. Potential future improvements for MAM sustainability

An aspect generally suggested by researchers to reduce the environmental and economic impact of metal additive manufacturing (MAM) is to apply product redesign with topology optimization ([12], [14], [19], [20], [28],

[27]), but only in few studies this was investigated. [27] quantified the benefits of this feature and realized that the advantages are not only during the manufacturing phase, but also the use stage. In this case, the product analyzed is an aircraft component, and a lighter weight of it has potential benefits on reducing fuel consumption during flight. Thus, a recommendation is to include all life cycle stages in the LCA, in order to not neglect potential benefits of additive manufacturing. A further recommendation is to perform a minimal process contribution and sensitivity analysis to disclose possible errors and test the robustness of the model [9]. In connection to what previously said, it would be useful to assess the environmental performance of a product or service taking into account topology optimization for additive manufacturing.

3. Conclusions

Overall, metal additive manufacturing (MAM) seems to be a well-suited technology for the substitution of conventional metal manufacturing processes, as it has the potential to fabricate products with more complex shapes, implement lightweight design, reduce product components and metal waste due to its ability to produce near-net shape products. Moreover, it can allow to reduce transport, packaging and have a more local production. On the other hand, some studies highlighted that there might be adverse environmental or toxicity impacts due to auxiliaries of the technology (i.e. binders, shielding gas), and metal powder recycling. Therefore, it is relevant to quantify the environmental, economic and social impact of this technology in order to consolidate it in the future and combine it with design optimization. Future works should focus on combining the improvements in manufacturing that can results from MAM, eg. material and energy efficiency, with a life cycle perspective that relates to circular economy strategies. For example, the latter could concern product lifetime extension, that is suggested to be an advantage by some authors [30]. Additionally, more attention could be given to undertake more similar product analysis approach to improve the comparability between studies and achieve more robust conclusions.

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