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Energy and material efficiency strategies enabled by metal additive manufacturing – A review for the aeronautic and aerospace sectors

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Abstract

Conventional manufacturing of aeronautic and aerospace parts requires substantial amount of resources (energy and materials) while generating high quantities of waste and carbon dioxide emissions. Metal additive manufacturing (MAM) has the potential to reduce resource consumption, which is particularly important for energy-intensive materials such as titanium. We undertake a systematic literature review of MAM processes for the aerospace/aeronautic sector focusing on energy and material efficiency. Relevant literature was classified and discussed based on the life cycle stages at which resource efficiency strategies for MAM were identified: (1) product design; (2) material development and sourcing; (3) processes development, control, and optimization; (4) end-of-life extension and circular economy. Results highlight the key factors required to optimize MAM and the relevance of assessing its environmental impact compared to conventional manufacturing. Material and energy efficiency vary significantly between different MAM processes due to several factors directly linked to the process but also associated with the supply chain, e.g. electricity mix or material sourcing. Further research could explore new trends in technological development for circularity or multi-material MAM.

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Keywords: 3D print; Additive manufacturing; Energy efficiency; Carbon emissions; Resource efficiency; Sustainability

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Abbreviations

AM	Additive Manufacturing
BtF	Buy-to-Fly
CM	Conventional Manufacturing
DED	Direct Energy Deposition
DMD	Direct Metal Deposition
EBFFF	Electron Beam Free Form Fabrication
EBM	Electron Beam Melting
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LMD	Laser Metal Deposition
MAM	Metal Additive Manufacturing
PBF	Powder Bed Fusion
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
WAAM	Wire Arc Additive Manufacturing
WLAM	Wire Laser Additive Manufacturing

1. Introduction

Additive manufacturing (AM) is a disruptive manufacturing technology that enables the production of new complex geometric parts, not possible, or challenging to built, by conventional manufacturing (CM). Compared with CM subtractive processes, AM may significantly reduce the materials used and the waste generated, with higher design freedom. Metal Additive Manufacturing (MAM) especially attracted attention of high demanding sectors, including aeronautic and aerospace. Reducing the material Buy-to-Fly (BtF) ratio of parts, which is the mass of raw material required per mass of final part, is highly desirable in these sectors to promote lower material acquisition costs, embodied energy, and operational fuel consumption. Key players such as Boeing and NASA have been investing in MAM, producing already a number of MAM airplane and satellite parts [1].

Metal industry, including mining and manufacturing, is responsible for 12% global carbon dioxide (CO_2) emissions. Furthermore, aviation accounts for 9% of CO_2 emissions of all transport means, and the number of commercial flights increased steadily from 2009 till 2019, resulting in 918 million tons of CO_2 emissions in 2019. To achieve carbon neutral targets and promote sustainable manufacturing it is imperative to study the resource efficiency (material and energy) whilst reducing the environmental impact of MAM processes and products. While some studies have focused on the advantages, limitations, and potential sustainability of broad AM [2], others have analyzed the efficiency of specific MAM technologies based on empirical case studies. Gisario et al. [1] and Yusuf et al. [3] reviewed current practical applications for aerospace sector, but a review of MAM resource efficiency strategies for aeronautic and aerospace context was not found.

This study aims to present an overview of current energy and material efficiency strategies enabled by MAM for aerospace and the aeronautic sectors, identifying the key aspects influencing potential MAM benefits at different levels. This was done through a systematic review of studies focusing on MAM processes for the aerospace and aeronautic with reported benefits for energy and material efficiency, including life cycle analysis, and other sustainability aspects. Studies were grouped and discussed based on the level at which sustainability strategies were identified: (i) MAM product design; (ii) MAM material development and sourcing; (iii) MAM processes development, control and optimization; (iv) MAM end-of-life extension and circular economy. In terms of innovation, the review is presented in the structure of a framework that could support the development of energy and material efficiency policies and practices for the sustainable design of MAM in these sectors.

2. Methods

A literature search was performed focusing on sustainability studies that intersect with the MAM field using the process shown in Fig. 1.

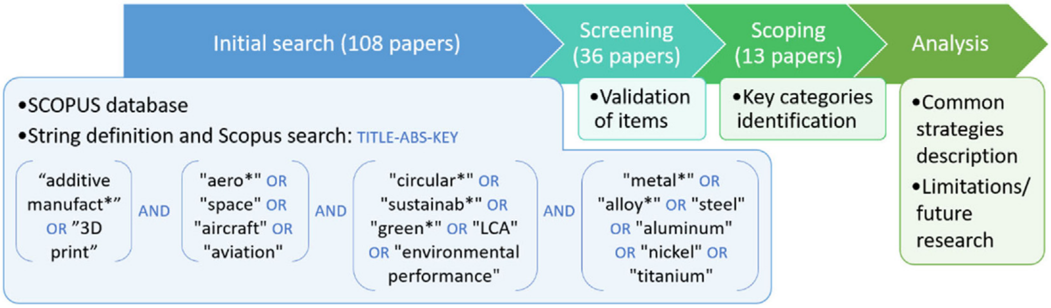

Fig. 1. Review method and number of items for each step.

The initial search yielded 108 items. The list of papers was narrowed down through a sequence of filters and the results were assessed according to a set of key categories. Firstly, the items were filtered to consider only those that directly address resource efficiency and/or sustainability analysis. Secondly, a scoping review was undertaken to identify the key categories and levels at which strategies were applied in the MAM for the aeronautics/aerospace sector. These categories aligned with the strategies proposed by Ford and Despeisse [2]. Leading papers presenting developments of MAM state of the art were also consulted for background knowledge. The information found in the literature was used to outline the most common strategies applied towards a holistic resource efficiency approach in MAM. It also identified gaps in the development and implementation of these strategies in the aeronautics/aerospace sector.

3. Results and discussion

The reviewed literature is presented based on the level at which energy and resource efficiency strategies were identified (shown in Fig. 2).

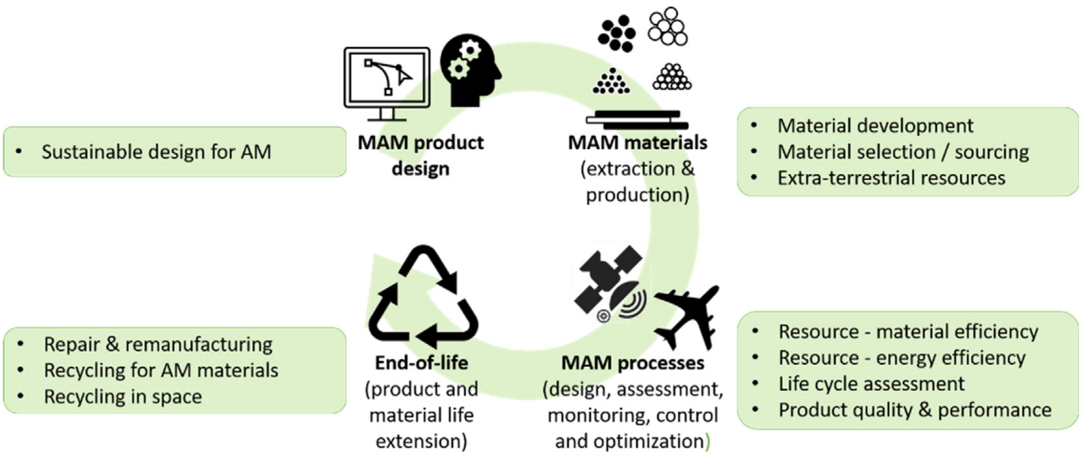

Fig. 2. Categories of resource efficiency strategies applied in MAM for the aeronautic/aerospace sectors.

3.1. MAM product design

Design for AM is one of the research areas that has the potential to revolutionize manufacturing and improve resource efficiency in aeronautic/aerospace. With fewer limitations than CM, AM enables components' re-design for their specific function, eliminating redundant material through complex geometries [4], thus allowing new topology-optimized parts to be developed [5]. For instance, a topologically optimized aerospace bracket, weighting 326 g, achieved a 64% weight reduction (32% by material change and 32% due to design) when compared to a CM part, [1]. Complex lattice structures have a higher stiffness-to-weight ratio than the original bulk material and the use of multi-materials also offer improved and additional functions to be embedded in a part (e.g., conformal cooling channels along the part). Zhang et al. [6] proposed a model for developing AM bio-inspired sustainable product design (e.g. biomimicry), integrating design for AM factors (e.g. raw material quality, process parameters, part functionality), and a sustainability assessment through life cycle assessment (LCA) and life cycle costing (LCC). The model served to select the material structure at an early design stage. The authors explored three bio-inspired geometries for a titanium (Ti) part built with selective laser sintering: diamond-, honeycomb-, and bone-structure. Results showed that bone-structure had the lowest cost and environmental impact through bio-inspired lightweight design. Thus, MAM bio-inspired design strategies allow lighter parts, lowering the BtF ratio, material waste, and costs. Different parts can also be consolidated in a single part with the same (or additional) functions reducing assembly time [7], part certification (less parts), supply chains, and the need for tooling and fasteners and the associated failures [1].

As aircrafts' fuel consumption is directly related with weight, lightweight aeronautic components are highly desirable to lower operational costs and CO_2 emissions. A 100 kg lighter aircraft is estimated to save 5050 GJ of fuel a year [1] and 13.4–20 TJ during a 30 year lifetime [3]. This is highly significant from an environmental point of view if adopted at a fleet level. In addition, a weight reduction in primary components also induces a reduction in secondary components. Huang et al. [8] estimated the change in life cycle primary energy and CO_2 emission associated with the use of MAM, instead of CM, to produce light metal aircraft components for all US aircraft industry, by 2050. The results showed that, in 2050, the life cycle primary energy could be lowered by 70–173 million GJ/year, achieving 1.2–2.8 billion GJ cumulative saving, which would result in 92.1 to 215.0 million metric tons of cumulative CO_2 emission reduction. In addition, thousands of tons of material resources (Ti, nickel, aluminum alloys) could be annually saved in 2050.

Girdwood et al. [9] proposed a framework to produce the most resource efficient AM product based on 14 process factors, split into 3 groups: design, planning and qualification. The latter includes quality control (geometrical precision, surface finish, etc.), energy consumption, time (setup, waiting, and programming), material wastage, and costs. They validated the framework building a Ti aerospace component. Even without geometric optimization, AM material savings were measured, compared to CM, and the improvements could have been higher if process parameters and efficient utilization of manufacturing machine capability were better known.

3.2. MAM materials — development and sourcing

Aerospace requires high performance materials (with high toughness, heat- and corrosion-resistance), to assure safety. The Ti6Al4V (or Ti64) has the highest strength-to-weight ratio. Being an expensive alloy, and with high embodied energy, it is one of the most used alloys in aeronautic/aerospace sectors. Due to the electrochemical compatibility with carbon fiber polymer composites, which are highly used in aircrafts, the demand for titanium is likely to continue to increase. Nickel (Ni) alloys are also used in aerospace, nevertheless these have showed up less in our sample of reviewed studies. Regarding aluminum (Al) alloys, despite their lower toughness, they are attracting interest for their lightweight potential, namely, to understand Al parts potential defects and quality [10]. Metal powder production still needs further study, to better understand their embodied energy requirements. Another strategy, potentially enabling resource sustainability in aerospace sector was identified, which consists of using MAM as an on-site manufacturing technology for space exploration activities. This means that the required components will be locally produced by exploiting new extra-terrestrial materials (new raw materials' source), instead of transporting all the materials from Earth [11].

3.3. MAM processes analysis, control and optimization

Current MAM processes available are Powder Bed Fusion (PBF), Direct Energy Deposition (DED), binder jetting and sheet lamination. In the aerospace and aeronautic sectors, PBF and DED are the most commonly used [12]. PBF uses a thermal source (laser or electron beam) to induce fusion (melting or sintering) of metal powder particles placed in a bed, layer by layer. PBF includes Selective Laser Melting (SLM), Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) processes. DED simultaneously deposits and melts the powder or wire material;

	Process	Energy source [W][1]	Process efficiency[1]	Material type	Closed chamber	Inert gas (IG) or vacuum	Weld pool size [mm][2]	Deposition speed [kg/h][1,2]	Comments
Powder Bed Fusion (PBF)	Selective Laser Sintering (SLS)	Laser		Powder	-	-			Similar to SLM, but less used.
Powder Bed Fusion (PBF)	Selective Laser Melting (SLM)	Laser 100-1000	2-5%	Powder	x	IG: argon	0.3	0.1-0.18	For small and complex parts. Smoother surface than EBM; higher cooling rates; more mechanical defects and residual stress than EBM. Requires thermal treatment to reduce residual stress.
Powder Bed Fusion (PBF)	Electron Beam Melting (EBM)	Electron beam 3500	15-20%	Powder	x	vacuum at const. high temp.	1	0.2-0.36	High accuracy: density and mechanical properties close to CM; lower yield stress and higher strain at break than SLM. Usually do not require thermal treatment. Lower fatigue resistance (due to less smooth surface) than SLM. Low energy efficiency (20%)
Directed Energy Deposition (DED)	Laser Metal Deposition (LMD)	Laser 500-3000	2-5%	Powder	x	IG: argon	Smaller than WAAM		Lower power efficiency for very reflective alloys in which reflectance can be 40-95%; better dimensional properties than WAAM, but lower deposition rate and material efficiency. Powder accuracy allow to repair high-value parts (e.g., turbine blades). Reduction of lead time[1].
Directed Energy Deposition (DED)	Electron Beam Free Form Fabrication (EBFFF)	Electron beam		Wire	x	vacuum		2.3-7 < 18	High energy efficiency (90%) even with very reflective alloys
Directed Energy Deposition (DED)	Wire Arc Additive Manufacturing (WAAM)	Electric arc 2000-4000	70%	Wire	-	IG: e.g., argon		0.5-4 (up to 10)	High material efficiency (90%) and energy efficiency (70%). Cost reduction to produce large and less complex parts. Rough surface, lower accuracy than PDF and LMD (subject to distortions, and residual stress), thus, requiring more surface finishing, heat treatment. Cold-high pressure rolling may be used in large components.
Directed Energy Deposition (DED)	Wire Laser Additive Manufacturing (WLAM)	Laser		Wire	-	IG: argon or helium			Better dimensional properties that WAAN but a lower deposition rate and material efficiency.

Fig. 3. MAM processes and their characteristics.
Source: Based on data from [12] and [1].

it includes Laser Metal Deposition (LMD) and Electron Beam Free Form Fabrication (EBFFF) (which are both Direct Metal Deposition (DMD) processes), Wire Laser AM (WLAM), Wire Arc AM (WAAM) processes. Fig. 3 presents MAM processes characteristics. PBF and LMD processes allow more complex geometries and have been more studied than wire-fed processes [1]. However, DED and wire processes have higher production volumes and higher deposition rates than PBF, being more cost effective for large parts [12].

Many MAM studies characterize parts quality through mechanical tests. To improve mechanical properties and surface quality, thermal energy treatments are usually applied. One of the barriers to MAM implementation is the lack of process monitoring and control systems. Different studies focus on improving process monitoring through infrared data and cameras to understand the relation of different operational parameters and final part properties. Yet, there is no established automated process monitoring and control system for MAM [1].

It is important to understand the environmental impact of MAM processes to better inform technology selection and adoption. Different studies assessed MAM processes using LCA and compared them with CM. Paris et al. [13] compared EBM and CM (milling) of a 13-blade aeronautic turbine (53.56 cm3) made in Ti alloy. The scope of the LCA was cradle-to-gate and did not include the product's use phase. By CM, a 406 cm3 cylinder block was milled (BtF of 7) consuming 27.5 kWh, while EBM consumed 41.05 kWh and required additional supports for the blades. Using LCA, EBM presented lower environmental impact than CM in all impact categories. A sensibility analysis for different BtF ratios was performed, showing that EBM was preferable to CM for BtF above 4.5 for abiotic depletion, acidification, global warming impact categories. For other categories a BtF above 6 was required. Since CM chips are recycled and EBM has high energy consumption, EBM is only a preferable alternative for parts with a high BtF ratio. EBM energy consumption is a critical factor, which is affected by regional electric mix.

Le and Paris [14] used LCA to assess the environmental impact of a lightweight Ti64 part (0.18 kg) produced by EBM+final machining (EBM+FM) or by CM. The study assessed the effect of different process parameters such as building height, batch size or number of parts per print, and mass of support material waste. By CM, a workpiece of 1.08 kg was required (BtF of 6) while EBM required only 0.23–0.44 kg of Ti64 depending on the scenario. The EBM+FM's environmental impact depends on the EBM parameters since energy significantly increases with building height. Results showed that EBM+FM is preferable to CM when a batch of at least 3, 5, and 12 parts is printed for building heights of 30, 50, and 150 mm, respectively. In addition, if the material support mass required for EBM is higher than 60% of the part's mass, CM may be preferable. Therefore, the positioning of parts and the required supports are critical from an environmental point of view.

Priarone et al. [15] also compared EBM+FM and CM estimating the production costs and the embodied primary energy based on a cradle-to-gate LCA for three Ti64 parts. Overall, for a part with a high BtF ratio, EBM had lower embodied energy than CM (most of which due to EBM energy consumption), but it had a higher production cost. Priarone et al. [16] compared WAAM with CM applied to medium to large size parts. The study evaluated life cycle energy and CO_2 emissions and concluded that reductions in resource consumption and CO_2 emissions could be achieved by WAAM. Costs depended on the material used and part geometry built. Nevertheless, wire materials are cheaper than powder metals, and WAAM has higher energy efficiency that PBF technologies.

Ingarao et al. [17] also used LCA to compare three processes (SLM, CM, and forming) to produce four aluminum components and assessed the BtF influence and product's use stage on the overall environmental impacts. Due to the high energy consumption and low energy efficiency of SLM for aluminum powders, the CM parts had lower cradle-to-gate embodied impact than the SLM. However, considering the effect of lightweight AM parts (50% weight reduction) on an aircraft fuel consumption, the higher embodied energy of SLM part was offset in one month.

Chan et al. [18] assessed the sustainability of SLM and wire-DED to support process selection at the planning stage to produce ten Ti64 parts (38.48 kg or 8687 cm3 each). Using LCA, LCC and social-LCA, the results showed that DED wire-fed process has advantages over SLM: DED, had a faster deposition time and used 4423 kWh to produce 10 parts, whilst SLM required 70,905 kWh. Similar trends were obtained for CO_2 emission, production cost, non-fatal injuries, and illnesses. Improving SLM melting rate is required to perform as well as wire-DED in terms of sustainability metrics. One advantage of SLM is final geometry accuracy which may be better for smaller parts.

Min et al. [5] compared the environmental life cycle performance of SLM, EBM, and LMD (DED) to produce a Ti64 rocket bracket, topologically optimized for each powder MAM technology. Besides operational energy consumption and material inputs, this study considered the influence of the embodied impact of MAM machines, the potential benefits (credit) of recycling wasted powders, the maximum batch size per print, and operation time along the estimated lifespan of each MAM equipment. The three MAM processes had different heating and melting energy consumption, protection gas (argon) consumption, and powder waste ratio. Rather than consider the environmental impact based on a one-time single part per print, the authors evaluated LPBF (Renishaw AM250), EBM (Arcam A1), and LMD (DMD IC106) processes considering the total production volume along with the expected lifetime (8, 10, and 5 years, respectively) based on their building capacity (batch size per cycle of 12, 8, and 18 parts, respectively), assuming an operation of 8h-shift during 250 days a year, which resulted in different total production volumes. The authors argued that, when considering the AM machine embodied energy, if each process is not assessed based on the potential production volume during the life span, the relative contribution of embodied impacts could significantly change. In fact, the embodied impact of AM equipment dominates the environmental impacts. For instance, it accounts for over 80% of the environmental impact per part, in countries with low-impact electricity mixes (e.g., Quebec), where printing energy has less environmental burdens. Thus, improving MAM machines to last longer, having higher production volumes, and reducing their embodied impact is also very important. Results showed that the preferable solution (lower impact per part) depends on the number of parts required. If impacts are tracked considering the total production volume along lifetime of each alternative, EBM has the lowest impact per part, followed by SLM and LMD. Whereas to produce a smaller number of parts an inversion may occur.

3.4. MAM end-of-life and circular economy

Another MAM benefit, is the potential to extend the components life through DED custom-made repairing, remanufacturing, or on-demand production of spare components [2]. Combining LMD with machining was proven to successfully repair high-value components such as turbine blades, avoiding the production a new component. [1,19]. Still, the impacts of metal powder production, namely through atomization, should be considered. For end-of-life of small parts with a low BtF ratio, the production of a new part by CM may be preferable if the end-of-life part could be recycled into secondary material for other applications. LCA is a useful tool to compare alternative scenarios. More research is needed to assess new circular economy strategies, to recycle metals into functional MAM material (powders or wires). This would reduce the embodied impact of MAM processes. Particularly for aerospace, some progress has been achieved in the development and testing of in-situ recycling technologies and AM with scrap materials, including customized packaging materials designed for being recycled in space [20]; however, the question is whether this can be also replicated to metallic scrap.

4. Conclusions

Energy and material efficiency strategies at MAM product design level can transform manufacturing in aeronautic/aerospace, significantly reducing resource consumption and costs. Thus, studies regarding the selection of design, planning and qualification parameters are highly valuable. These strategies have a direct influence at manufacturing stage, due to significant material and weight reduction of topology-optimized parts or parts with complex lattice (e.g. bio-inspired) geometries, but foremost at future aircrafts' use stage. Fuel savings from AM-enabled lightweight structures, may significantly decrease energy, CO_2 emissions, and flying costs at a worldwide scale.

New material development strategies are also important to increase the number of MAM applications. Studies accounting for the embodied impacts of MAM powders and wires are highly important to select alternatives with lower embodied impact, namely through energy efficient processes and a higher incorporation of recycled metals. In addition, MAM is also expected to allow to exploit extra-terrestrial raw resources, to build parts during future space exploration, and to lessen the need for earth resources. In addition, qualifying remanufacturing and repairs of high-value components with high BtF can extend the useful life of components, being resource efficient and cost effective.

As different MAM technologies are available, it is important to understand which specific manufacturing technology is preferable, to avoid problem shifting. LCA studies have identified critical factors to consider, namely: (a) AM is preferable when the part BtF ratio by CM is high (>5); (b) for EBM the building height (the building direction) is highly important since melting energy increases for higher deposition heights and supports may be required; (c) maximum batch size per print and the total production volume during a technology life span highly influence the relative share of embodied energy of MAM technologies (which barely has been considered in most studies); (d) the local electric mixes highly influence the PBF manufacturing embodied impacts. Despite fewer studies on DED (specially wire-fed technologies), these have lower energy consumption and embodied impact than PBF technologies being interesting for larger parts. Overall, more studies having a broad life cycle perspective are needed to assess not only MAM technologies but also the embodied impact from materials, the required post-treatments, and components' use stage. Nevertheless, literature show that MAM has the potential to positively affect aeronautic components life cycle and the environment.

Further research could also explore whether multi-material MAM could support further energy and material efficiency, i.e. the ability to mix multiple metals in a solid part to create new products with optimized thermal, electrical, magnetic, and/or mechanical properties and functionalities. In theory, this technology requires less complexity and fewer steps, thus optimizing speed, resource consumption, and cost [21]. However, more empirical studies are required to confirm these benefits.

CRediT authorship contribution statement

Helena Monteiro: Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Gabriel Carmona-Aparicio:** Investigation, Visualization, Formal analysis, Validation, Writing – review & editing. **Inês Lei:** Investigation. **Mélanie Despeisse:** Investigation, Formal analysis, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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