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THE POTENTIAL OF ADDITIVE MANUFACTURING OF METAL COMPONENTS TO REDUCE ENVIRONMENTAL IMPACTS

Additive manufacturing (AM) is used in metal part forming for its innovative character but its potential for sustainability is uncertain. The energy and material consumption required for manufacturing are significant. Thus, the research question of this article is: “What are the current uses of AM that present a real potential for reducing environmental impact?”. The WAAM (Wire Arc Additive Manufacturing) process appears to be the most energy-efficient in comparison to other AM processes. A process parameters study shows that deposition rate has a substantial impact on energy consumption. This parameter represents the amount of material deposited in a unit of time and is directly linked to productivity. It appears that an increase of the deposition rate leads to a reduction in energy consumption. Experiments on WAAM with a high deposition rate permits to create a database of energy and material consumption. This database is then used to identify cases of parts made with WAAM that offer a significant impact reduction compared with conventional manufacturing processes.

1. . INTRODUCTION

Additive Manufacturing (AM) is a process that uses a digital 3D model to produce a part by depositing material layer by layer. This specificity sets AM technology apart from other part shaping processes such as molding or subtractive processes. Among the advantages of AM are reduced material consumption, an ability to produce parts with complex geometries, with multi-materials, to repair damaged parts or even to group together parts from an assembly. Sectors such as aeronautics, automotive industry and the medical sector are increasingly making use of this potential giving AM the status of an “industrial” technology. In this context, and in view of the current issue of the sustainability of industrial activities, it is necessary to assess the positive or negative impact of AM on the environment.

The aim of this article is to identify relevant uses of WAAM involving a significant reduction in environmental impact. A state of the art on the energy consumption of metallic

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AM processes and on the environmental impact of WAAM is proposed in Section 2. The methodology used to analyze the impact of WAAM using the life cycle approach is presented in Section 3, along with the method for studying manufacturing parameters. The results are presented and discussed in Section 4. The main conclusions are given in Section 5, with prospects for future research.

2. STATE OF THE ART

2.1. METAL AM ENERGY CONSUMPTION

This section analyzes studies that consider the energy consumption of one or more metal AM processes. First, it is worth identifying and categorizing the different processes that are mentioned in this analysis. About metallic AM, we can classify processes into 3 families based on their material deposition principles (Fig. 1). Bound metal deposition (BMD) technology, which makes up the material extrusion family, is still at an early stage of development, and has therefore been excluded. Two families of processes are therefore the subject of this study. These are directed energy deposition, in which an energy source is used to create a highly localized molten bath at part level, to which material in powder or wire form is fed, and powder bed fusion, in which thin layers of powder are successively deposited while energy is fed in at certain points to fuse the zones forming the desired part. To compare the energy consumption of processes operating using various principles, the concept of Specific Energy Consumption (SEC) was selected. This is a value that can be determined for all manufacturing processes, expressed in MJ/kg, and represents the energy required to shape 1 kg of material. In the case of AM, this corresponds to the energy required to deposit 1 kg of material.

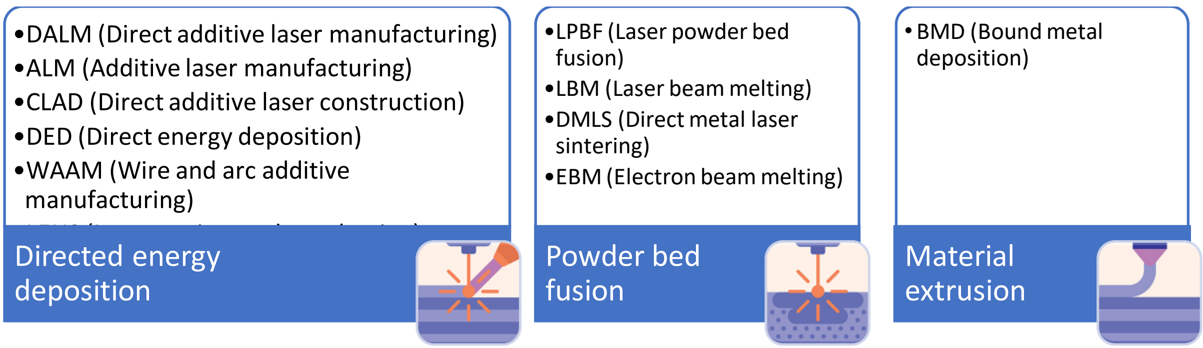

Fig. 1. Families for metal AM technologies

The first study to provide an SEC value for AM steel forming [1] looks at the energy consumption of several machines, including three laser-based powder melting machines representing two different technologies, Selective Laser Sintering (SLM) and Direct Metal Laser Sintering (DMLS). The energy consumption of DMLS is also studied in another article

[2], in addition to Electron Beam Melting (EBM) technology, which is a powder bed fusion technology using an electron beam rather than a laser. Also, a study [3] deals with another laser powder bed fusion technology with Laser Beam Melting (LBM) in comparison with the conventional hot turning process.

Other articles [4, 5] focus on the consumption of a directed energy deposition process, Laser Engineered Net Shaping (LENS), using a laser as the energy source and depositing the material in powder form. Several studies [6, 7] compare WAAM, which is also a directed energy deposition process based on the principle of arc welding, with other processes such as LENS or machining. These values are grouped together in Fig. 2 to obtain an SEC interval for the various AM technologies found in the literature. Based on these values, WAAM appears to be the most energy-efficient metallic AM technology.

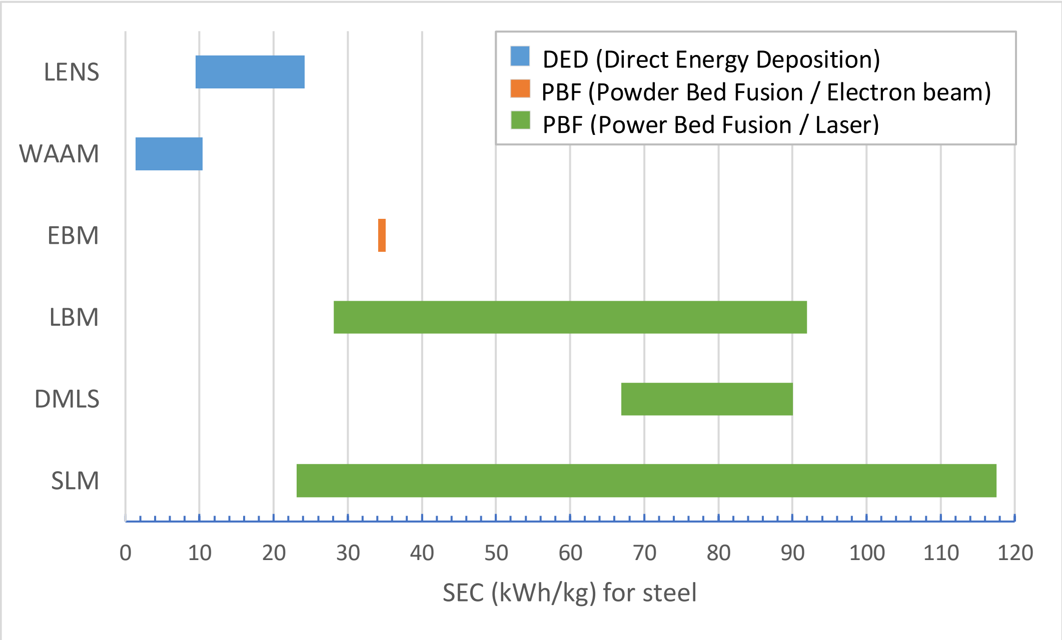

Fig. 2. SEC intervals for AM

2.2. WAAM ENVIRONMENTAL IMPACT

The potential environmental impact of AM technologies is a relatively new area of study, which is explained by the youth of these processes and their lack of maturity. Indeed, it is difficult to carry out an environmental analysis of a process that is still benefiting from major developments to meet the requirements demanded in an industrial context. The fact that these processes have not yet been widely adopted by industry is another obstacle to this type of study, which looks at the entire life cycle surrounding the manufacturing process. The first studies identified dealing with WAAM's environmental impact [6, 8] are relatively recent and focus mainly on the process's energy consumption, comparing it with that of another metal AM process, LENS. A striking feature of these studies concerns the type of parts manufactured for comparison. These are very simple parts: a plate (dimensions 100 mm, 100 mm, 1.5 mm) for the first article, and a tensile test sample for the second. In addition, these articles offer a comparison of energy consumption within a small perimeter around the manufacturing stage, considering the production of wire or powder and a finishing phase. Articles listed below offer insights in four areas. The first concerns the processes used to compare with WAAM. These comparisons may involve traditional processes such as machining or casting [9] or other metal AM technologies such as SLM [10]. The second axis of evolution incorporates more environmental elements into comparisons, such as quantifying CO2 emissions in addition to the energy aspect [11], or using methods such as ReCiPe to provide a more comprehensive study of numerous standardized criteria [12, 13]. The third axis goes with the previous one by broadening the life cycle considered for environmental analyses. This approach moves away from the reduced life cycle seen above, with studies proposing more complex and comprehensive approaches, with scenarios incorporating the repair of a part [14] or providing more detail on the production stages of raw materials and post-treatment [15]. The fourth axis concerns the parts studied for the comparisons which are becoming more complex. We therefore have studies using industrial parts in their comparison, such as blades for the nautical sector [16] or parts designed specifically for WAAM technology with the topological optimization of an I-beam [17].

What emerges from this state of the art on WAAM's environmental impact which shows the diversity of approaches and ways of assessing this impact, is the need to define a methodology for analyzing these studies to propose a synthesis. In this way, it will be possible to identify energy consumption by life-cycle stage, environmental impact associated with this consumption and the influence of WAAM manufacturing parameters.

3. METHODOLOGY

3.1. SUMMARY OF WAAM LIFE CYCLE ANALYSES

To obtain an overview of the potential impact of WAAM, a methodology for analyzing the various studies has been developed. The aim of this overview is to extract from the individual case studies a synthesis that will enable general observations on the WAAM process.

The approach adopted for this analysis is based on the creation of data sheets for each study. These sheets have been standardized to only bring together the information required for our final synthesis. It is composed of five parts in addition to the general information.

- The first of these points introduces the case study used in the article to perform the environmental analysis. In addition to the technical characteristics of the part (geometry, dimensions, materials, etc.), it describes the context in which it was studied, providing information on its manufacture, the constraints it must meet, and whether it is integrated into a system. This section also presents the other processes that are compared with WAAM.

- The second part is the most important, proposing process trees for the different scenarios and processes in the study. These trees respond to the major problem concerning the synthesis of the different articles results, which is that each of them has a different way of presenting the framework and the stages of its life cycle, and they each present the data in a different form. Thus, the process of reconstructing these trees in a single form, with a single vocabulary, greatly facilitates comparison between the different articles, and hence the synthesis work.

- The third section contains technical data on parts manufacturing, providing information on the WAAM's operating parameters, which can vary greatly from one piece of equipment to another. These data also show the effect that a parameter can have on material or energy consumption, and therefore on environmental impact.
- The fourth part groups together the various inventories associated with the unit processes through which the part passes. It thus corresponds to the flow of materials and energy required throughout the life cycle. These inventories are differentiated by type (energy, gas, materials, etc.), by process stage and by manufacturing process. These raw data can be formatted, for example by calculating SEC for each stage, and are mainly used to complete process tree flows.
- The final section looks at how environmental impacts are assessed and compared. It presents the comparison criteria, approaches and methods used.

3.2. WAAM ANALYSIS OF PART MANUFACTURING PARAMETERS

One aspect of life-cycle analysis that crucial to determine the environmental impact of WAAM is the influence of manufacturing parameters on energy and material consumption. From parts three and four of the data sheets described above, i.e. technical data and flow inventories, it is possible to associate a set of parameters with energy consumption, which in our case is expressed in the form of an SEC. And so, by generalizing this approach to the various studies, a link can be established between the evolution of one or more parameters and that of energy consumption. Once this link has been established and verified, it can be used to define an approach to WAAM manufacturing that will enable an impact reduction.

4. RESULTS AND DISCUSSION

4.1. WAAM ENVIRONMENTAL IMPACT

A summary of the articles dealing with the environmental impact of WAAM allows us to establish several general results about this process.

4.1.1. WAAM ENERGY CONSUMPTION

By reusing inventory data on the most studied aspect in the articles, i.e. energy consumption, it is possible to brings together the energy consumed for three life-cycle stages for different metals. The choice was made to limit the synthesis to these three stages (raw material production, wire production (which includes rolling and drawing) and WAAM manufacturing), as they are the most represented stages and have enough values for a comparison between the different articles. From this, it is possible to establish, for each material, the consumption shares of a stage in the cycle, to determine which stages, consume the most energy, and whether this distribution changes from one case study to another. This work (Fig. 3), carried out for two materials, steel and titanium alloy, shows that the distribution of consumption is only slightly affected by the different study cases, and that the premanufacturing stages (production of raw materials and wire) consume more energy than manufacturing, with the accentuation of this phenomenon for titanium alloy.

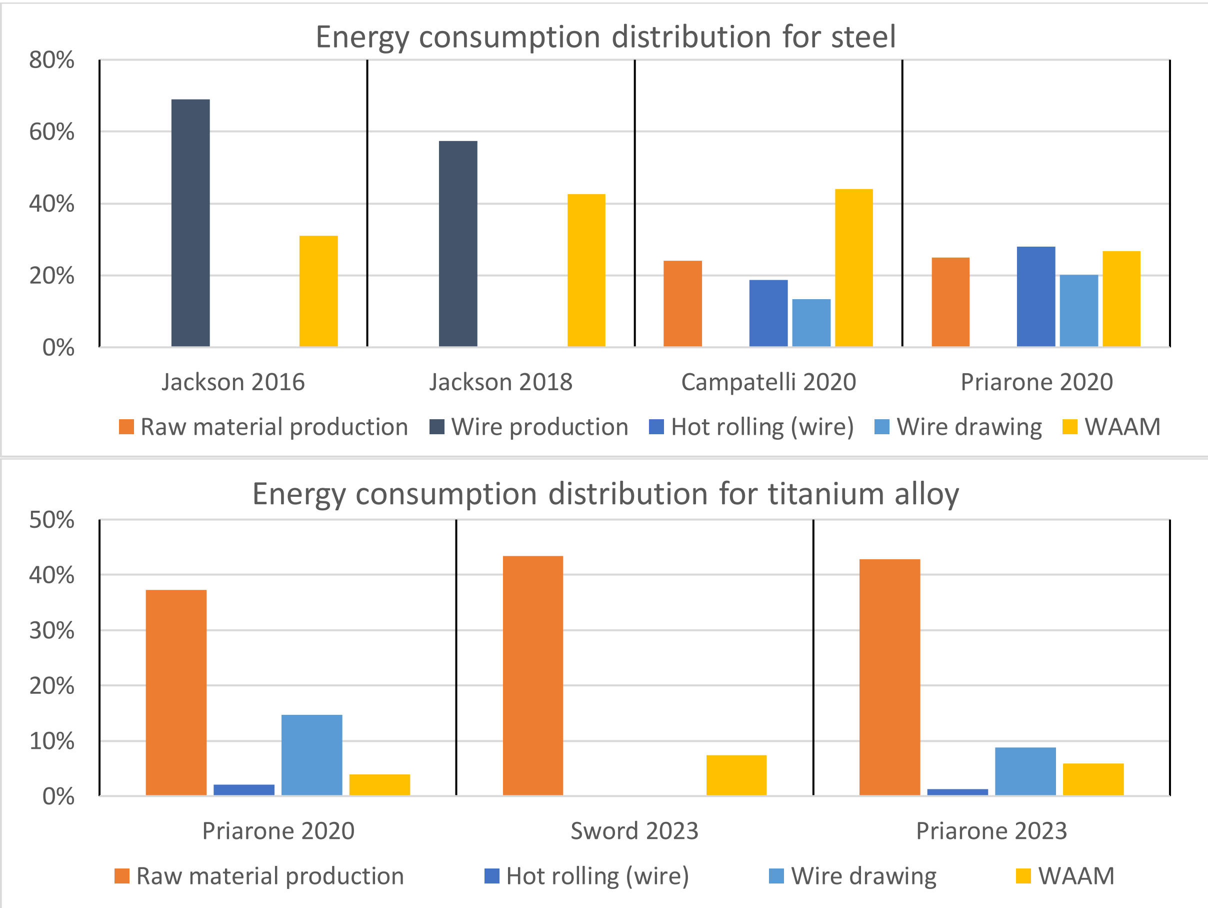

Fig. 3. Breakdown of energy consumption for steel and titanium alloy

4.1.2. ENVIRONMENTAL IMPACT CONVERSION

The next step in the analysis of energy consumption is to convert it into an environmental impact in the form of CO_2 emissions. Table 1 shows this conversion, with emissions expressed in $kgCO_2/kg$ of deposited material. This calculation is based on SEC or total energy values calculated from the inventories obtained in the data sheets. This energy is then compared with the value of CO_2 emissions per MJ of electricity produced by the French energy mix, which corresponds to 8.33g of CO_2 per MJ produced.

Table 1. WAAM environmental impact based on energy consumption

Reference	Material	WAAM energy consumption (MJ/kg)	Associated emissions ($kgCO_2$ /kg)
Jackson 2016	Steel ER70S-6	32.3	0.269
Jackson 2018	Steel ER70S-6	37.5	0.313
Bekker 2018	Stainless steel 308L	9.79	0.082
Priarone 2019	Steel ER70S-6	4.54	0.038
Campatelli 2020	Steel EN S235JR	19.76	0.165
Priarone 2020	Aluminium AA2319	6.3	0.053
Priarone 2020	Steel ER70S-6	23.7	0.198
Priarone 2020	Titanium Ti-6Al-4V	33.4	0.278
Priarone 2021	AISI H13 steel	6.7	0.059
Dias 2022	AISI 316L	9.77	0.081
Kokare 2023	Steel ER70 HSLA	4.22	0.035
Shah 2023	S355 steel	8.85	0.074
Reis 2023	ER90 steel	4.98	0.042
Reis 2023	ER90 steel	7.2	0.060
Reis 2023	ER90 steel	8.1	0.068
Sword 2023	Titanium Ti-6Al-4V	14.9	0.124

4.1.3. COMPARISON WITH CONVENTIONAL PROCESSES

The synthesis also enables comparisons with other processes, and in particular with machining and casting that are the two processes for which the most comparative data is available. These comparisons cover two aspects: energy and material consumption.

As far as energy is concerned, studies have shown that the WAAM process achieves an average 28% reduction in consumption compared with machining, and equivalent consumption compared with casting.

In terms of raw material use, WAAM also has an advantage over the other two processes, with an average 65% reduction (up to 89%) compared to machining, and a 25% reduction compared to casting.

It is necessary to point out that all the comparisons presented here are made for the same part: one of the specific features of additive manufacturing is its ability to produce parts with complex geometries, and it is highly adaptable to design approaches such as topological optimization, which optimizes the shape and mass of a part to meet mechanical constraints. In this case, illustrated by (Fig. 4) which shows two beams, one conventionally manufactured and the other topologically optimized for WAAM, we observe a 47% reduction in the use of raw materials. This is an interesting result given that the manufacture of a conventional beam is characterized by very little material loss.

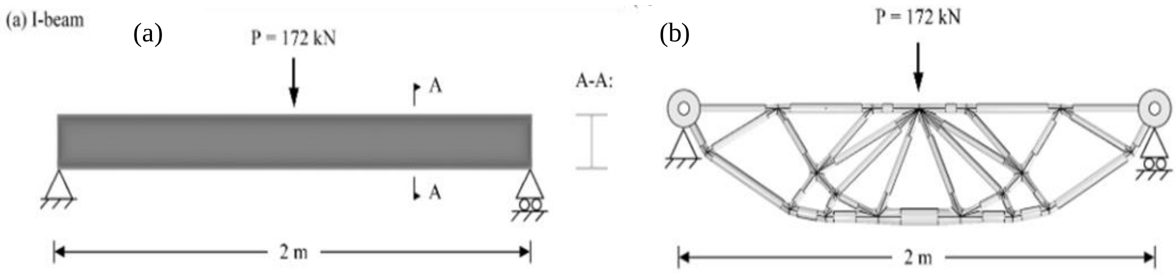

Fig. 4. (a) Conventional I-beam, (b) Topologically optimized beam for WAAM [17]

4.2. INFLUENCE OF DEPOSITION RATE ON ENERGY CONSUMPTION

4.2.1. STUDY OF MANUFACTURING PARAMETERS

The set of technical databases extracted from the articles provides access to WAAM manufacturing parameters. Table 2 shows the connection between these data and the SECs associated with WAAM manufacturing. A striking feature of this table is the fact that no parameters are available for all cases, due to the lack of information available in the articles. However, it is possible from the data available to calculate a deposition rate in all cases where it is not explicitly given. Our study can therefore focus on this parameter, which is expressed in kg/h and represents the amount of material deposited per unit of time. This definition makes it an interesting parameter to study, since it has a direct impact on part production time.

Studying the SEC associated with deposition rates, we note that for values which are all around 1kg/h, the SEC varies little between 4.22 and 8.1MJ/kg apart from a value of 23.7MJ/kg which is higher due to the use of a plasma technology (PAW) which is more consuming than the GMAW technology which is used otherwise.

Table 2. Experiemntal literature data for WAAM manufacturing

Reference	Machine type	Material type	Shielding gas	Shielding gas flow (L/min)	Wire feed speed (m/min)	Wire diameter (mm)	Deposition rate (kg/h)	Deposition speed (mm/min)	Waiting time (s)	SEC (MJ/kg)
Priarone 2019	CNC / GMAW	Steel		14	4.55	0,8	0.9	300	100	4.54
Campatelli 2020	CNC / GMAW	Steel	82% Ar, 18% CO2	14	4,6		1.06	200		6.64
Priarone 2020 (2)	Multi axis robot / PAW	Steel		14			0,94			23.7
Kokare 2023		Steel	82% Ar, 18% CO2		3	1	1.1	360		4.22
Reis 2023 (1)	GMAW	Steel	88% Ar, 12% CO2	16	3	1	1.1	360	180	4.98
Reis 2023 (2)	GMAW	Steel	88% Ar, 12% CO2	16	3	1	1.1	360	180	7.2
Reis 2023 (3)	GMAW	Steel	88% Ar, 12% CO2	16	3	1	1.1	360	180	8.1

4.2.2. DEPOSITION RATE EXPERIMENT

The deposition rate values extracted from the literature do not allow us to determine its influence on energy consumption. We have therefore set up an experiment proposing SEC measurements for different deposition rate values. The experiment was carried out at the RM Platform of the Ecole Centrale de Nantes, using WAAM equipment based on CMT (Cold Metal Transfer) technology.

The SEC calculation is based on the energy consumption of the generator powering the arc during the deposition of a steel bead (Fig. 5). To this is added a fixed consumption for the equipment moving the torch, consisting of a 7-axis Yaskawa robot. The total energy is then divided by the deposited mass for a single bead (Eq. 1). This approach is repeated, increasing the deposition rate from 0.8 to 4.4 kg/h. Increasing the deposition rate involves adapting the deposition parameters to obtain similar beads for each test. For example, the ratio between wire feed speed and torch travel speed remains constant to ensure the same amount of material deposited per unit area.

$$SEC = \frac{E_G + E_R}{m_d} \tag{1}$$

where: E_G – energy consumption of the CMT generator, E_R – energy consumption of the Yaskawa robot, m_d – deposited mass for the steel bead

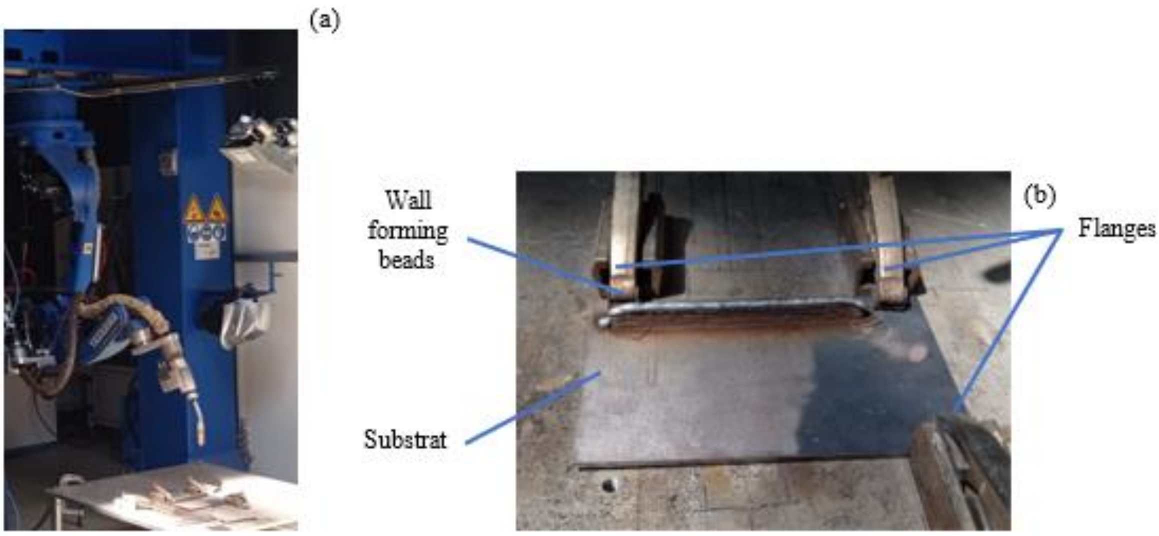

Fig. 5. (a) WAAM equipment, 7-axis Yaskawa robot, (b) Beads deposited during experimentation

The SEC evolution of this equipment can therefore be presented as a function of the deposition rate used (Fig. 6). An increase in SEC is observed as the deposition rate increases, with a maximum value of 1.95 MJ/kg for a deposition rate of 4.4 kg/h. These values are lower than those reported in the literature (Table 1 mentions values higher than 4 MJ/kg), which may be explained by a lower energy input which is characteristic of CMT compared with other WAAM technologies.

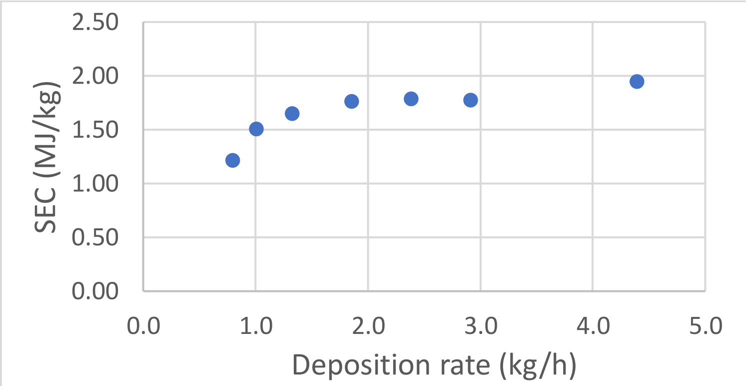

Fig. 6. Evolution of SEC with deposition rate

These results show that the use of WAAM, especially CMT technology, with a high deposition rate results in a controlled energy consumption, making WAAM a high-performance, low-impact AM technology.

5. CONCLUSIONS

In this article, a state-of-the-art analysis of the energy consumption of metallic AM processes was carried out in the form of SEC analysis. This enabled us to identify WAAM as one of the most energy-efficient processes, and therefore one with great potential for impact reduction. WAAM was therefore the subject of a more in-depth literature review on environmental analyses. To enable an effective comparison of these studies, a synthesis methodology in the form of data sheets was put in place, with the reconstruction of process trees and the presentation of the data inventory used. This enabled a comparison to be made between WAAM and traditional processes (machining and casting) in terms of energy and raw material consumption. The comparison shows that WAAM has an advantage in these criteria regarding the case studies we found.

This also enabled us to put forward an experiment looking at the evolution of the SEC as a function of the deposition rate, showing a slight increase in energy consumption for high deposition rates.

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