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Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 15 (2014) 26 – 31

www.elsevier.com/locate/procedia

21st CIRP Conference on Life Cycle Engineering

Predictive model for environmental assessment in additive manufacturing process

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Abstract

Additive Manufacturing is an innovative way to produce parts. However its environmental impact is unknown. To ensure the development of additive manufacturing processes it seems important to develop the concept of DFSAM (Design for Sustainable Additive Manufacturing). In fact, one of the objectives of environmental sustainable manufacturing is to minimize the whole flux consumption (electricity, material and fluids) during manufacturing step. To achieve this goal, it is interesting to get a predictive model of consumptions, integrated in the design step, allowing to evaluate the product's environmental impact during the manufacturing step. This paper presents a new methodology for electric, fluids and raw material consumptions assessment for additive manufacturing processes, in particular for a direct metal deposition process. The methodology will help engineers to design parts optimized for additive manufacturing with an environmental point of view.

Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien

Keywords: Additive Manufacturing; Environmental sustainability; Additive laser manufacturing; Design for sustainable additive manufacturing

1. Introduction

1.1. Additive manufacturing

Cleaner production and environmental sustainability are of crucial importance in the field of manufacturing processes where great amounts of energy and materials are being consumed [1].

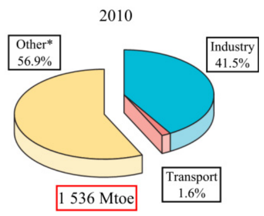

Fig. 1: World electricity consumption by sector (source IEA [1])

Fig. 1 shows the amount of world electricity consumption by sector.

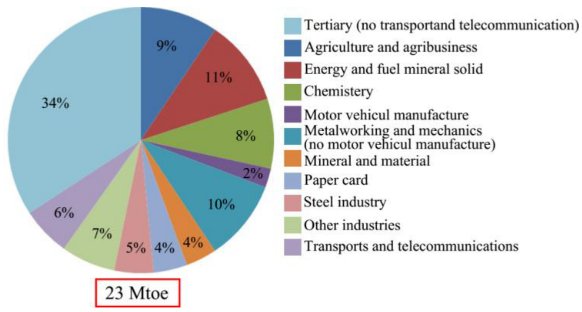

Fig. 2: French electricity consumption for industry 2010 (source RTE [2])

Industry represents 41% of the consumption. Fig. 2 represents the French electricity consumption for industry and

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doi:10.1016/j.procir.2014.06.031

by sector. Mechanical industries represent 12% of this consumption which is important and where process improvement and optimization have to be done.

Nowadays, additive manufacturing (AM) technologies allow us to manufacture functional products with high added value. Those processes are often described as "clean" processes because they only use the exact amount of material to build functional parts limiting scarps production. Furthermore, the energy consumed to produce parts is also limited, as it has been shown by Serres et al. when they compared additive manufacturing process to machining process [3]. In fact, it is possible to obtain functional part directly from CAD model with only one manufacturing step, contrary to conventional processes which need several manufacturing steps to produce a part. Insofar as environmental considerations become an important issue in our society, as well as legislation regarding environment become prominent (normalization ISO 14 044), the environmental impact of those processes have to be evaluated in order to make easier its acceptance in the industrial world.

1.2. Design for manufacturing and environment

Nowadays, several methods are used to design part with a manufacturing point of view, those methods are called Design For Manufacturing (DFM) [4]. One of the advantages of DFM is to include, during the design step, manufacturing constraints which will allow optimizing the part through the advantages offers by the process. Nevertheless, the possibilities offers by the innovative processes such as additive manufacturing are not used during the design step. In fact, most of the parts made by additive manufacturing are often design with conventional rules used for other processes as machining, molding, forging, etc. Some studies have been conducted to propose methodologies integrating the advantages of AM processes during design stage. Those methodologies are called design for additive manufacturing (DFAM).

Moreover, a few methods are used to quantify the environmental impact of the product (Carbon Assessment, Life Cycle Assessment, etc.) during the design stage. The only scientific and normalized method used to evaluate the environmental impact during the product life cycle is Life Cycle Assessment (LCA) [5]. Few studies are conducted in order to quantify and predict the environmental impact of the part directly during the design step. However, the design step is a crucial step for the life cycle of the product. In this step, taking into account the advantages of additive processes can helps designers to define parts, which will be lighter, optimized and could integrated more specific features than they could do with conventional processes. All these specificities allow decreasing the environmental impact of the product during its life cycle.

It becomes important to develop a new methodology called design for sustainable additive manufacturing (DFSAM) for AM processes which includes both points previously cited:

- Design for additive manufacturing (DFAM) [6,7];
- Environmental impact assessment.

1.3. Design for sustainable additive manufacturing

As it was previously defined, concerning additive manufacturing, there is a lake of methods and rules to design a product taking in consideration all the advantages of this process. Nevertheless, some studies have recently been conducted allowing to define rules in order to design part for additive manufacturing processes [6]. Ponche et al. [7] define a new methodology taking into account the advantages of additive manufacturing processes. In this methodology, topological optimization is coupled with both design requirements and manufacturing constraints to obtain part design without any anticipate idea of the final part. In addition several rules are proposed in order to design a product which will be produced by additive manufacturing. Now, it seems important to develop tools in order to evaluate the environmental impact of parts model during design step. These tools have to take into account specificities of additive manufacturing (no lubricant use, no scraps production, no mold use, etc.) but also the possibilities of additive manufacturing (lighter and more complex parts for the same usage, for example).

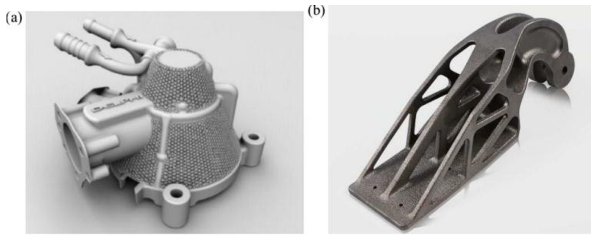

Fig. 3. (a) Design of heat exchanger; (b) Nacelle hinge bracket for aeronautic

The figures above show two examples of part made with additive manufacturing processes. Fig. 3 (a) shows an optimized design for additive manufacturing process of a heat exchanger reducing its mass and increasing its efficiency with intern shape optimized (DELPHI design courtesy). Fig. 3 (b) is an aeronautic part where the external shape is optimized for additive manufacturing process.

Fig. 4: Example of improved part design: prototype of an optimized Airbus A380 bracket made by AM from stainless steel powder, with conventional bracket behind. Source: EADS

In a recent study between the aeronautic and defense group manufacturers, EADS and the additive manufacturing machine manufacturers, EOS, have shown the advantages, in term of environment, to use additive manufacturing process to produce part (Fig. 4). Their study shows that it is possible to "cut material consumption by 75% and CO_2 emission by 40%" [8].

However, no tool has been developed to quantify precisely, during the manufacturing stage, the environmental impact of design part while this stage is one of the more impacting during life cycle.

In the following paper, we will deal with the definition of a predictive model for environmental impact assessment, in section 2. In section 3, we will develop the models used to evaluate the environmental impact of ALM process. In section 4, we will apply this model to an industrial example.

2. Predictive models for environmental impact assessment

Few studies have been conducted in additive manufacturing, which is a younger process than machining for example, to determine its environmental impact. Most of the studies are focused on the electrical consumption of the machine during the process [9,10]. Those studies allow to classify the different machines regarding their electrical consumption (Le Bourhis et al. [11] resume those different studies about electrical consumption of machine) but the whole energetic flux and material flux are not taking into account in those studies.

From the LCA method a new methodology has been developed integrating accurate models in order to evaluate the environmental impact of the manufacturing stage. Fig. 5 allows understanding the scope of our studies.

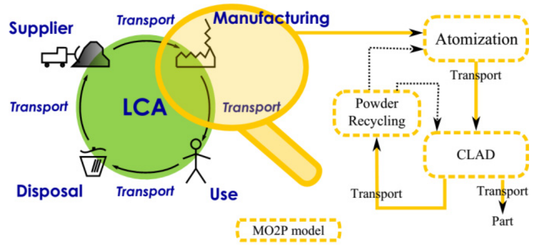

Fig. 5: Manufacturing LCA view

The models developed enable to evaluate, during all manufacturing steps (from atomization to powder recycling), the environmental impact of the whole flux consumed (electricity, material and fluids). In fact, in LCA method we have to consider the whole flow, from and to nature, for a system during the life cycle inventory.

3. Application to additive laser manufacturing

3.1. Introduction to additive laser manufacturing (ALM)

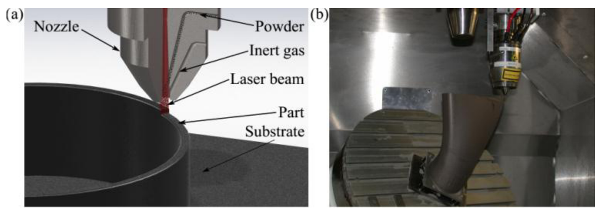

Fig. 6: (a) CLAD nozzle; (b) Example of part made by ALM process

This study is based on an ALM process, also known as CLAD process, which manufactures 3D metallics parts from CAD model. In this process, a five axes deposition nozzle, where metallic powders are injected into the laser beam, create a small melt pool on the workpiece which is cooled down when the laser beam moves on. The part is built as the nozzle moves. Fig. 6 (a) and Fig. 6 (b) show the design and the real nozzle with the different inputs (powder, laser, inert gas).

The machine is equipped with two kinds of nozzles, called, respectively, MacroCLAD and MesoCLAD. The two nozzles allow obtaining welding bed width, respectively, of 4mm and 0.8mm. These nozzles are put on five axis machine tool (Huron KX8) and placed in parallel to a conventional machining spindle. In addition, it has been added two powder feeders and a 4kW fiber laser on the machine.

The following sections will be focused on this ALM process.

3.2. Atomization of raw material

As we can show on figure 5, the first step for our process is to produce powder (metallic, ceramic, glass) which will be introduced in the machine. To obtain this powder we used an atomization process (Fig. 7). In this process, raw material (from block or cylinder) are heated until melting point in a chamber and then atomized with an inert gas (argon). This atomization step consists to compress, under high depression, the metallic fluid which will be atomized in small droplet in reaction to depression.

In this process, many values can be saved and it is possible to establish a model for the atomization step. The model is made with experimental values such as:

- Gas consumption,
- Water consumption,
- Electrical consumption.

These values will be given for 1kg of metallic glass atomized.

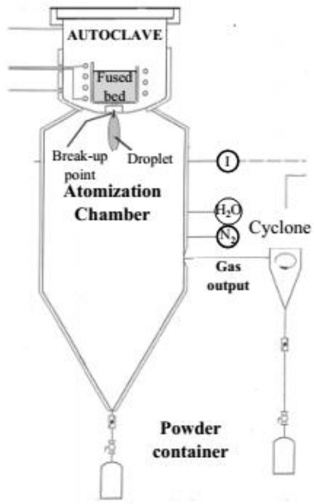

Fig. 7: Atomization process [13]

<u>*Gas consumption*</u>

Gas consumption is due to the volume of the inert chamber and the atomization step. Fig. 8 shows the variation flow of argon in the chamber.

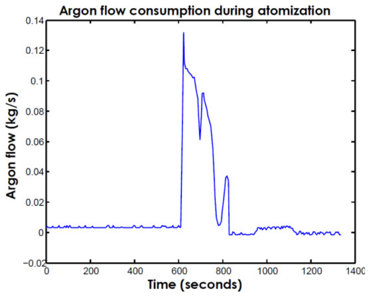

Fig. 8: Argon flow consumption

From this model, we can determine an empirical model for gas consumption such as:

$$V_{argon} = \frac{1}{\rho} * \int_0^{t_{atomization}} d_{argon} * dt \quad (1)$$

Water consumption

In this system, water runs in close-loop system. However, we have to release used water in the nature and get fresh water because the cooling system is not enough efficient.

$$V_{water} = d_{water} * t_{atomization} \quad (2)$$

Electrical consumption

Electrical consumption is due to different features of the machine (inductor, pre-heater, vacuum pump). Fig. 9 shows a profile of inductor electrical consumption during the atomization process.

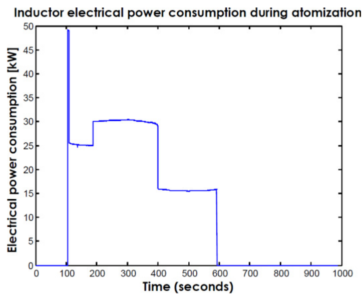

Fig. 9: Inductor electrical power consumption

From this model, we can determine an empirical model for electrical consumption such as:

$$E_{electrical} = P_{depression} * (t_{atomization} + t_{vacuum}) + U * I * t_{pre-heating} + \int_0^{t_{atomization}} P_{inductor} * dt \quad (3)$$

Nomenclature

V_{argon}	Volume of consumed argon (liters).
d_{argon}	Argon flow rate (kg/s).
ρ	Gas density (kg/l).
$t_{atomization}$	Time for atomized raw material (seconds).
V_{water}	Volume of consumed water (liters).
d_{water}	Water flow rate (l/s).

Table 1. Atomization of 1kg of glass powder.

Input consumption	**Value**
Gas consumption	7 m^3
Water consumption	155 liters
Electrical consumption	4 kWh
Efficiency	46%

3.3. Environmental model for a ALM process

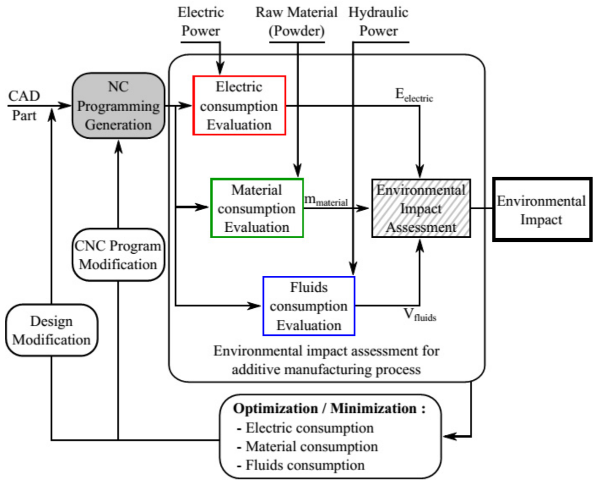

Fig. 10: Global methodology to evaluate the environmental impact of CAD part

In this ALM process, we evaluate the environmental impact of three inputs:

- Electrical consumption,
- Material consumption,
- Fluids consumption.

Fig. 10 summarizes the different step of the methodology. The Eco-Indicator 99 method is used to evaluate and normalized the environmental impact in mPts (milli-points). This method enables to compare the different input share.

For each input's consumption, a model based easier on empiric model or analytical model have been developed. These models allow evaluating the global environmental impact of the part from its CAD model. From CAD model, a G-code file is created which will give the instruction for the machine. From this file, each parameters required to evaluate the environmental impact are extracted. For each G-code file created there is a different environmental impact because the instructions are not the same. The process parameters, such as rate of deposition, are linked to the part which will be produce.

Fluids consumption

Fluid consumption is due to the inert gas used during the process which allow to project and protect metal powder in the melting pool. In this study, the inert gas is argon; it is the same gas for the two functions. Its consumption varied during the manufacturing step and depends on the part morphology. An environmental impact is associated to the inert gas consumption during manufacturing step, according to the following equation:

$$E.I._{fluids} = [d_c + d_f] * t_{man} * fc_{argon} \quad (4)$$

<u>Material consumption</u>

Now, the focus is put on the determination of the powder consumption during part manufacturing. In fact, an advantage of additive manufacturing process is to project and fuse exclusively the necessary powder. However, this is not the reality and an amount of powder will not be fused. The studied technology used two different kinds of nozzle of which have different efficiencies. The efficiency of each nozzle depends on the desired powder flow rate.

An analytic model is proposed for the material consumption estimation during part manufacturing, according to the following equation:

$$E.I._{material} = [e_n + k * (1 - e_n)] * d_p * t_{man} * fc_{material} \quad (5)$$

<u>Electric consumption</u>

Electric consumption assessment of a process is one of the priorities for the evaluation of its environmental impact. Many studies have been conducted about this issue to evaluate the mass energy needed to manufacture a part for a specific machine in order to compare the machines themselves. Nevertheless, a global estimation could not allow foreseeing a future optimization. In this section, it is propose an electric consumption models for each feature of the machine.

In each machine, we can classify electric component into two categories. Some features have constant energy consumption such as electrical cabinet and hydraulics components. For the other components, their electrical energy consumption depends on the part design but also on machine parameters. Many models have been developed and published in a previous article [11], in this paper we will summarize the results. The following equation shows the share environmental impact of each component.

$$E.I._{electricity} = \begin{pmatrix} g(P_l)*t_{laser} + Pc_{standby}*t_{man} \\ + (Pc_{on} - Pc_{standby})*t_{on} \\ + \left(\sum_{i=1}^{5} \int_0^{t_{man}} Pe_{axei}(t)*dt \right) \\ + Pe_{constant} \end{pmatrix} * fc_{elec} \quad (6)$$

Nomenclature

fc_{argon}	1.78 mPts/kg.
$E.I._i$	Environmental impact due to substance i (mPts).
t_{man}	Manufacturing time (seconds).
d_c	Desired carrying gas (kg/s).
d_f	Desired forming gas (kg/s).
$fc_{material}$	86 mPts/kg.
k	Weighting factor allowing to weight the impact of lost powder compared with fused powder.
d_p	Powder flow rate (kg/s).
e_n	Nozzle efficiency.
fc_{elec}	12 mPts/kWh for French electricity production.
$g(P_l)$	Function for laser electrical power consumption.
t_{laser}	Switch-on time for such as $t_{man} = t_{laser} + \overline{t_{laser}}$.
$Pc_{stand\text{-}by}$	Power consumed in stand-by mode.
Pc_{on}	Power consumed when the cooling system works.
Pe_{axei}	Electrical power consumed by each axis.
$Pe_{constant}$	Constant electrical power consumed.

3.4. Recycling of lost powder

In this process, a non negligible amount of material is projected but not fused. It seems important to propose a method to recycle this powder. In fact, those processes could be seen as environmentally friendly only if all the powder projected is used. The lost powder cannot be used without treatment. In fact, this powder could cause several damages to the machine and need to be sieved and dried before to be reused. Some studies will be conducted to know if this recycled powder has the same mechanical properties than new powder.

4. Industrial example

The example bellow will able to illustrate the methodology previously developed. This example is an aeronautic part which is, at this time produce by conventional machining. More than 80% of raw material is machined to produce this part. In this example, the focus is on nozzles choice. As we mentioned previously, this ALM process use two kinds of nozzle. We would like to know which one is more "environmentally friendly".

4.1. Part

The part presented (Fig. 11) is composed of a pocket of 200 mm square and 80 mm depth. The part thickness is 4 mm. In this study we would like to know which nozzle is better to manufacture the pocket. In fact, it possible to chose in the NC program generation which nozzle we will use.

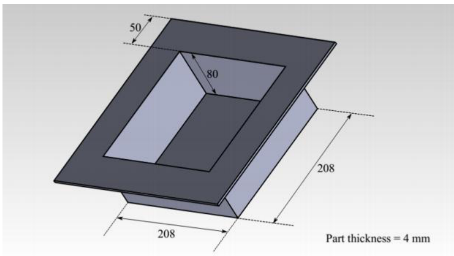

Fig. 11: Part model

In a previous paper [11], we demonstrated that for manufacturing processes, in particular for additive processes, the strategy, and specifically the trajectories, used to manufacture the part can change the environmental impact during this step. In our case, if we use the nozzle called MacroCLAD, we can produce the part in one trajectory by layer but we a high power laser (around 3 kW). However, if we used the nozzle called MesoCLAD, we have to produce the part with five trajectories of 0.8 mm width by layer with a smaller laser power (around 250 W). The model developed allows us to choose which nozzle we have to use to minimize the environmental impact of the machining process.

4.2. Results of environmental impact

The model used enable to evaluate the environmental impact of each manufacturing strategy. This methodology is formalized on an informatics tool for designers. The first step is to read the G-code of the CAD model and extract all values needed to evaluate the environmental impact such as (laser power, trajectories, axis speed).

From these values it is possible to compute, pre-process, the expected consumptions. The results are given either in scientific units (kWh, liters or grams) or in environmental units (mPts). The second unit allows comparing the different flows consumption amongst them. These results are shown on Fig. 12 and Table 2. This table shows that, even if the power laser is more important for MacroCLAD, the total energy consumption, to build the same part, is less important. Furthermore, the efficiency of this nozzle being more efficient (around 80% contrary to 35% for MesoCLAD) thus the powder consumption is less important too. For this part, it should be interesting to manufacture it with the MacroCLAD nozzle.

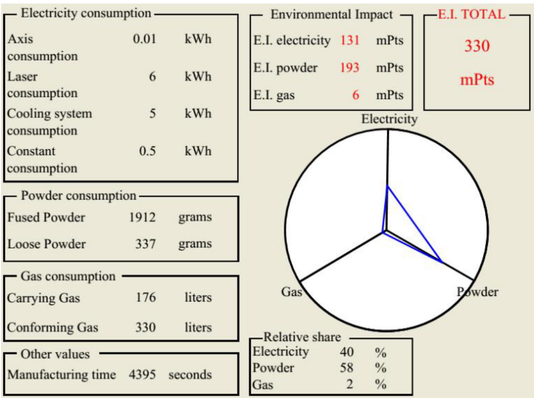

Fig. 12: MacroCLAD results

Table 2: Study results

Input consumption	Scientific units		Environmental impact	
	MacroCLAD	MesoCLAD	MacroCLAD	MesoCLAD
Electricity	12 kWh	109 kWh	131 mPts	1332 mPts
Powder	2249 grams	3824 grams	193 mPts	328 mPts
Fluids	0.5 m^3	9.5 m^3	6 mPts	122 mPts
Time	4395 s	78872 s		

4.3. Optimization

In the methodology developed, Fig. 10, there is a feedback loop which allows optimizing the environmental impact of the part. This optimization is based on the electrical, material or fluids consumption which can be evaluate pre-process. So, the model proposed is able to evaluate many manufacturing strategies and chose which one has a lower environmental impact to produce the same part from its CAD model.

4.4. Perspective

In this methodology, one point has not been developed. In fact, it should be interesting to consider the quality of the part produce. It is interesting to produce part minimizing flows consumption; however, if the quality is not acceptable, the part will not be used. This remark will be developed in futures studies. In those studies, environmental impact of manufacturing process will be coupled with part quality.

Finally, to promote additive manufacturing process in industrial world, the advantages of part made by these processes (for example lightens parts) have to be considered during the whole life cycle of the product. Life cycle assessment of parts designed and made for and by additive process will be realized in order to compare these parts, manufacture with innovative processes, with same parts made by conventional processes.

5. Conclusion

The authors propose a new methodology in order to evaluate, with accuracy, the environmental impact of a part from its CAD model. In this methodology, the work is not only focused on electrical consumption but also on fluids and material consumption which also contribute to the environmental impact. Table 2 shows that for some strategies, the environmental impact due to electrical consumption is not the more impacting. In this case, material consumption has an important impact and has to be evaluated.

In addition, in this methodology the authors used the set of part-process which allow taking into account different manufacturing strategies and their influences on the global environmental impact.

The methodology developed is based on both analytic models (validated by experiments) and experimental models. Furthermore, this methodology will be extended to other manufacturing processes.

Acknowledgements

The authors would like to thanks students Kevin Audoux and David Roszczypala for their works on powder recycling.

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