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Energy and Material Flow Analysis of Binder-jetting Additive Manufacturing Processes

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Abstract

Manufacturing, where great amount of energy and materials are being consumed, should take response to have cleaner production and to improve its sustainability. Additive manufacturing (AM) technology shows potential to reduce environment impact as a more sustainable manufacturing method; however, the lack of well documented energy consumption and material flow data limits the development of Life-Cycle Inventory (LCI) analysis of AM technology. This paper presents an energy and material consumption model of Binder-Jetting (BJ) process. A Unit-Process (UP) level model is created and validated by experimental data to provide LCI data for further Life-Cycle Analysis (LCA) of BJ additive manufacturing processes. The accurate process model provides a tool to industry to understand the energy consumption and material efficiency aspect of the binder-jetting process and to allow comparisons with traditional processes.

Keywords: sustainability models and analysis, additive manufacturing, binder-jetting, material efficiency, power consumption

1. Introduction

In the past few decades, Additive Manufacturing (AM) also known as 3D printing technology has drawn more and more attention from the industry world. Compared with traditional subtractive manufacturing, AM has three main advantages:

1. Freeform fabrication: AM remove the traditional manufacturing restrictions and provides the design freedom for innovative product [1].
2. Short supply chain: AM can reduce the supply chain of fabrication and enhance the profit space for manufacturers [2].
3. Sustainable manufacturing: AM has a huge potential to reduce the environmental impact that normal manufacturing has [3].

Because of these promising characteristics, AM has been applied in industrial field for a long time and plenty of researches have been conducted on the aspect of process control and product quality. However, while claiming the

advantage on the environmental aspect, there is still very limit research on the sustainability aspect of this technology. Another issue is, because of the lack of well documented life-cycle data, it is difficult to conduct an exact Life-Cycle Assessment (LCA) or sustainability analysis for AM technologies. To take a step forward in the sustainability area, this paper provides a method to build a Unit-Process (UP) level Life-Cycle Inventory (LCI) data model for Binder-Jetting (BJ) technology which is one of a commercial mainstream AM technologies. This research contributes to a better understanding on the sustainability aspect of the BJ process. Furthermore, this research also develops a systematic approach to capture the data required to build up an energy and material flow model to establish the LCI model. Thus, LCI models for other AM technologies can also be derived by the similar approach.

This paper is organized as follows: first the backgrounds of LCI and BJ technology are introduced. Previous works relevant to LCI calculation are summarized to illustrate the context and meaning of this research. Secondly, a method to

create LCI data model for BJ process is presented. The work flow to achieve this model is described step by step. The measure method and network are introduced as well. Experimental data are collected and analyzed to achieve the correlations between parameters and LCI results. After the correlations being set into the model, test printing are conducted to check the accuracy of the model. Finally, conclusions are drawn, results are documented and future outlooks are discussed.

Nomenclature

E_i	Energy used by the sub-process i
P_{max}	Maximum power of the heater
$\%heater$	Percentage of heater's power set by user
$t_{process}$	Duration of the printing process
Eff_i	Efficiency of the device i
H_{part}	Height of the part
t_{layer}	Mean time between printings of two consecutive layers
H_{layer}	Layer thickness
$t_{printlayer}$	Mean time for printing one layer
N_{layer}	Number of layers
M_j	Mass of the product j
Cp_j	Specific heat capacity of the product j
$T(t)$	Refers to the inside temperature
S_k	Internal surface of device k
T_{mean}	Mean temperature during a heating process
$t_{increase}$	Total duration of the temperature increasing phases
$T_{maintain}$	Temperature of the maintain phases
$t_{maintain}$	Time of the maintain phase
R_k	Thermal resistance of the device k
h_{int}	Convection coefficient inside the oven/furnace
h_{ext}	Convection coefficient outside the oven/furnace
ρ_{binder}	Density of binder
Vb_{layer}	Volume of binder used per layer

1.1. LCI of manufacturing

This paper works on the LCI model of BJ process. Therefore, relevant works about definition and methods of LCI are cited here. LCI is introduced to support the LCA. In ISO 14040 [4], LCI is defined as a phase of LCA which compiles and quantifies inputs and outputs of a given product system throughout its life cycle. LCI data are the result of this phase. To some extent, LCI data are a list which containing the quantities of energy and materials consumed and pollutants released. Thus, LCI provides the fundamental data for LCA. However, with adaption LCI results can also serve outside the realm of LCA as well. For instance, the process level LCI can support the sustainability indicator approach[5]. As LCI serves as a data source for sustainability assessment, the accuracy of the sustainability measurement also strongly relies on the accuracy and details of LCI process and mistake of LCI are

reflected in the result. As a result, suitable approaches have been developed to get reliable LCI data.

The CO2PE! [6] (Cooperative Effort on Process Emissions in Manufacturing) defined two ways to make the LCI: the **screening approach** and the **in-depth approach**. The screening approach provides a first estimation and relies on industrial data and engineering calculations while the in-depth approach consists in measuring relevant inputs and outputs of the process unit regarding environmental issues. In-depth approach is used in this research as this research aims to provide a detailed and accurate LCI model. Furthermore, research about energy consumption model for traditional manufacturing process also provide valuable experience for creating the LCI model of BJ process. In the research of Li* and Kara [7], an energy consumption model was developed based on power measurements under various cutting conditions. This model can take account the energy requirement of tool tip for material removal as well as the energy used for auxiliary functions, which provide a method for predict the total energy for turning process. In another their research[8], an empirical model to characterize the relationship between energy consumption and process variables for material removal processes was represent. This model showed a high performance in energy consumption simulation with an accuracy of more than 90%. Junk and C  t   [9] studied the process variables' influence on the sustainability of AM technologies. Their paper researched the material and energy consumption of a 3D color printing (3DP) machine. In addition, several process variables, such as part volume, surface area, part position and batch size, in which resource consumption can be reduced are investigated and compared.

1.2. BJ AM technology

The first task of analyze the process flow of BJ is to understand how this technology fabricate raw materials into functional parts. With sufficient understanding of this technology, the process flow then can be abstracted from the real manufacturing process.

Binder-jetting is one of commercial 3D printing technologies. This technology is original developed at MIT at 1990s [10] and commercialized in 2010. It can handle materials including sand, glass and metal. Printing process of



Fig. 1 Printing system of BJ technology

BJ technology can be divided into the following steps: printing, curing, de-powdering, sintering, infiltration, annealing and finishing.

The core step of BJ which different it from other AM technologies is the printing process. Fig. 1 shows a schematic of printing process of BJ. The printing system is made up by a print bed, a feed bed, a roller, a drying unit, and a print head.

The whole printing process work as follows: initially, the print head start to jet binder onto loose powders (2) according to layer profile. When one layer is finished, pulley-belt system places the layer under an electrical heater (4) to dry the binder. The next step is to lower print bed (2) of one layer thickness and rise feed bed (3). Then the roller (5) evenly spread powder a new layer of powder over the printed layer. This process is repeated layer by layer until printing part been fully built.

2. Method

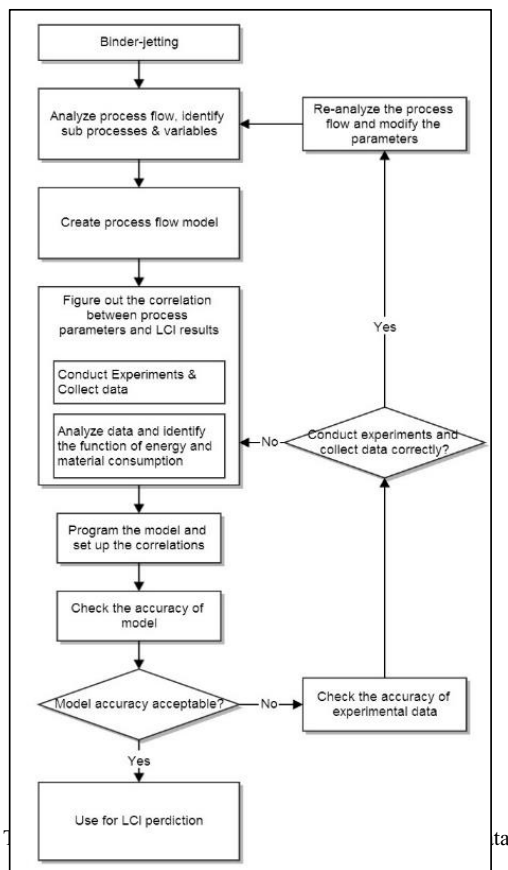


Fig. 2 Flow chart of the method

model for a BJ manufacturing process. Fig. 2 shows an

overall work flow for achieving such a model. According to the flowchart of Fig. 2, the LCI model of BJ technology is achieved by the following steps:

- 1) The first step is to analyze the process flow of BJ technology. Consequently, sub-processes of the BJ technology are identified. Another target of the analysis is to identify the variables of the process. These variables are the process parameters which have significant influences on the LCI result of the sub processes.
- 2) The second step is to create a process flow model in the LCA software Umberto [11]. Firstly, based on the analysis work, a clear IDEF0 flowchart which contains all necessary information of sub processes and process parameters is generated. Based on the IDEF0 diagram, the process model of BJ is created in Umberto.
- 3) Then, printing experiments are conducted to find out the correlations between LCI data and process parameters. Once the correlations been quantified, they are set into the process model in Umberto. To some extent, at this stage, a LCI data prediction model is generated. However, the accuracy of the model still needs to be verified.
- 4) Test printings are conducted. Real LCI data are collected and compared with the data generated by the model to check the accuracy. If the test data and simulated data agree with each other well, then it's safe to say the model is valid and can be used for further sustainability research. If the accuracy is not acceptable, the whole process will be conducted again with adjusts on process flow model, measuring and parameters.

This process is conducted iteratively until get the valid model. The details of these steps are explained in the following section.

3. Modeling of Binder-Jetting process

3.1. Sub-processes

The first step in modeling the BJ process in terms of consumption (energy and materials) is to define the boundaries of the study. In the reported research the process itself is analyzed, i.e. from the filling of the machine with materials to the final sintered part. In further work the manufacturing of the materials and the disposal issue will be studied to make a complete life cycle assessment.

To model the BJ process the sub processes involved in the manufacturing of a part are identified. Once this identification has been done the material and energy inputs and outputs of each sub-processes are defined. To finalize this identification step an IDEF0 model of BJ process has been created from the filling of the machine with material to the sintering step at the end of which the final part is obtained (shown in Fig. 3)

For the sake of simplicity the displacement of the platform to the different locations is not considered her as a sub-process on its own and each displacement is included in its relative sub-process.

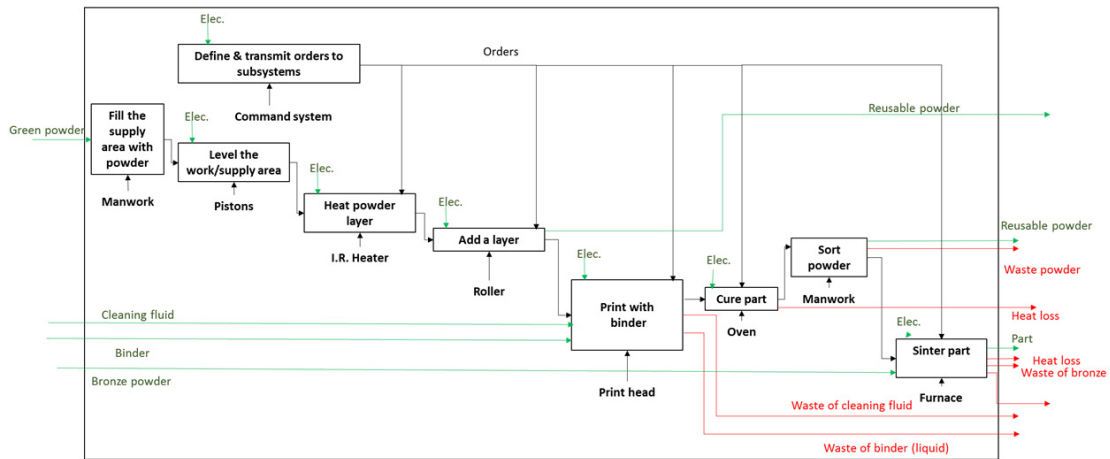


Fig. 3 IDEF0 of BJ process

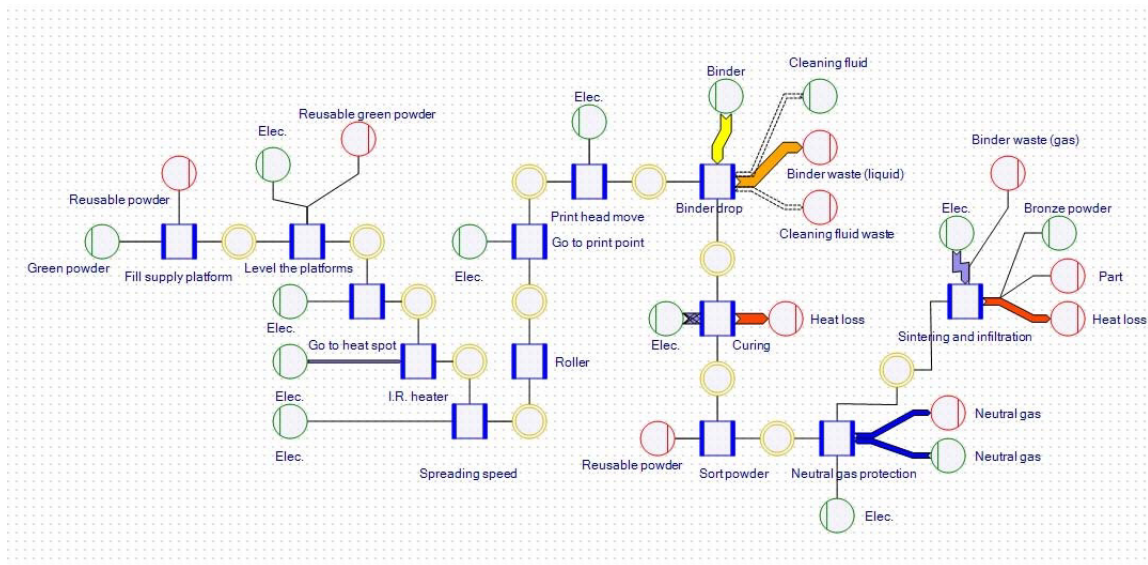


Fig. 4 UMBERTO model of BJ process

3.2. Model on UMBERTO NXT LCA

Once this identification of sub-processes and flows is done the model is created in the UMBERTO NXT LCA which the formulas defined in this research relate the inputs to the outputs. The choice of UMBERTO NXT LCA is due to its ability to deal with parametrical and non-linear

In this section, the main equations that influence the energy and material consumption in the process are explained.

(shown in Fig. 4) software which will make the calculation of the flows and the environmental impact estimation. In this model each sub-process is defined as a “black box” in

models that other software is lack of.

3.3. Formula

3.3.1. Energy consumption

Infra-red heater

The infra-red heater power is set as a percentage of its maximum power by the operator on the machine and is running during all the process. The heating time of the

powder is defined by the time the platform stays under the heater. The energy used by the heater is defined as following:

$$E_{heater} = \frac{(P_{max} \times \%heater \times t_{process})}{Eff_{heater}} \quad (1)$$

$$\text{With : } t_{printing} = \frac{H_{part} \times t_{layer}}{H_{layer}} \quad (2)$$

The maximum electrical power used by the heater is measured and the maximum power of the heater is found in the machine documentation.

Uncap print head

Each time the print head print a layer, it has to be uncapped. To do so, an actuator has to be activated. Its power consumption is constant so:

$$E_{uncap} = P_{uncap} \times t_{printlayer} \times N_{layer} \quad (3)$$

Curing

The curing oven is modeled as a hermetically closed oven which walls are made of one material of surface thermal resistance R. The estimation of this resistance will be discussed later. The curing profile consists in a linear increasing of the temperature and a maintain period of the final temperature. The energy needed is split into the energy for heating the powder and the apparatus and the energy needed to maintain the temperature in the oven.

$$E_{heating} = (M_{powder} \times Cp_{powder} + M_{support} \times Cp_{support}) \times \Delta T \quad (4)$$

$$E_{maintain} = \int_0^{t_{fin}} \frac{S_{oven} \times (T(t) - T_{ext})}{R + \frac{1}{h_{int}} + \frac{1}{h_{ext}}} \times dt \quad (5)$$

$$E_{maintain} = \frac{S_{oven} \times (T_{mean} \times t_{increase} - T_{maintain} \times t_{maintain})}{R_{oven} + \frac{1}{h_{int}} + \frac{1}{h_{ext}}} \quad (6)$$

Sintering

The sintering profile consists in several linear temperature increasing followed by temperature maintain. By analogy we define the sintering energy as:

$$E_{heating} = (M_{powder} \times Cp_{powder} + M_{support} \times Cp_{support} + M_{supportpowder} \times Cp_{supportpowder}) \times \Delta T \quad (7)$$

$$E_{maintain} = \frac{S_{oven} \times (T_{mean} \times t_{increase} - \sum(T_{maintain} \times t_{maintain}))}{R_{furnace} + \frac{1}{h_{int}} + \frac{1}{h_{ext}}} \quad (8)$$

Idle state energy

The main source of energy consumption of the printing

has been found to be the idle state energy consumption, consisting in computer consumption (60 W), lighting consumption (12 W) and other sources such as controllers (50 W). These elements are running during the whole printing process which explain their importance in the general energy consumption of the machine.

Others

Experiments have shown that all the other component's energy consumption represent less than 1% of the total energy consumption. They are however included in the model in view of further studies but are not described in this paper.

3.3.2. Material consumption

Print with binder

Because of its viscosity characteristics, binder has to be washed out the system frequently. These cleanings are made every two layers with the M-Lab machine, a reference of ExOne company, and our settings. The binder and cleaner consumption are therefore linear with the number of layers:

$$M_{binder} = \frac{\rho_{binder} \times V_{blayer} \times H_{part}}{H_{layer}} \quad (9)$$

$$M_{cleaner} = \frac{\rho_{cleaner} \times V_{clayer} \times H_{part}}{H_{layer}} \quad (10)$$

Powder

In this study all the powder that has been used in the process but has not been printed is considered reusable because the unused powders are combined with new powders for new rounds of printing. No significant mechanical property change has been observed when old and new powders are used together. The overall amount of reusable powder is therefore the mass of powder used to fill the supply system minus the mass of the part.

3.4. Determination of thermal resistance

In order to determine the thermal resistances used in 3.3.1. , the oven was run empty until the curing temperature. At this point the temperature was maintained until the energy consumption is constant. The equation of power consume is then:

$$P_{oven} = \frac{S_{oven} \times (T_{oven} - T_{ext})}{R_{oven} + \frac{1}{h_{int}} + \frac{1}{h_{ext}}} \quad (11)$$

$$R_{oven} = \frac{S_{oven} \times (T_{oven} - T_{ext})}{P_{oven}} - \frac{1}{h_{int}} - \frac{1}{h_{ext}} \quad (12)$$

The same method is used to determine the furnace thermal resistance.

4. Results

To verify the LCI models, three different experiments have been conducted: one for the printing process, one for the curing process and one for the sintering process.

4.1. Energy consumption

Printing process

To determine the energy and material consumption of the printing process, a part of $5 \times 7 \times 3$ mm has been printed and its energy, binder and cleaner consumption have been recorded. In parallel the parameters in the model have been set and the model has been calculated. Fig. 5 shows the power consumption of the printing process. The recorded energy consumption is 96Wh. The model gives an energy consumption of 98 Wh i.e. a precision of 98%.

Curing process

For the curing process, three printed cylindrical samples of diameter 10mm and height 30mm has been cured in the oven. The curing profile consists in a $10^\circ\text{C}/\text{min}$ increase from 20°C to 175°C and 4 hours of temperature maintain at 175°C . Fig.6 shows the power consumption during the process.

Recorded energy consumption is 1.39 kWh whereas the model calculation gives a consumption of 1.29 kWh, i.e. a precision of 93%.

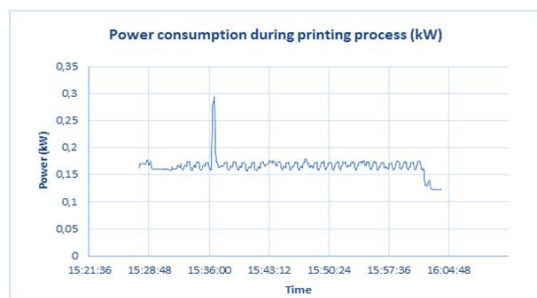


Fig. 5 Power consumption during printing process

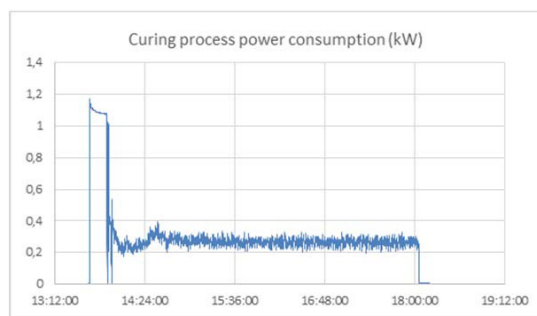


Fig. 6 Power consumption during curing process

Sintering process

Three tensile test samples have been sintered to estimate

the accuracy of the model of the sintering sub-process. The results give an accuracy of 95%

5. Conclusion

The modelling of the Binder-Jetting process could be useful to predict or compare the consumption (energy and materials) during a manufacturing process. The actual model for M-Lab machine from ExOne is precise enough to get estimations of these consumption.

Also, more statistical controlled test should be performed to verify the proposed model. Experiments should be made on the machine with various width, length and height in order to evaluate the influence of the part's dimension on the accuracy of this model. Moreover this model should be tested on larger machines to verify if it can be adapted. The use of a parametrical model for the process eases the transition to different machines. Therefore, it is believed that the proposed method can be applied for larger industrial scale binder-jetting processes. However, the model parameters need to be re-measured and validation case studies should be conducted with the industrial scale machine

Furthermore, an estimation of environmental impact of materials production and of disposal is necessary to get a full Life-Cycle Assessment.

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