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Identifying efficient solutions for additive manufacturing of short carbon-fiber reinforced polyamide 6 from energy and mechanical perspectives

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Abstract

Additive manufacturing (AM) technologies have transformed manufacturing, by providing greater control over the material deposition. Owing to its versatility and high strength-to-mass ratio, AM with composite materials has grown exponentially, founding many applications in industries. Further implementation of AM with composite materials would require the user to be able to improve FFF (Fused Filament Fabrication) efficiency regarding energy and technical aspects. For this purpose, it is necessary to assess the energetic and mechanical effects of printing parameters. In this paper, five printing parameters are evaluated: bed heating strategy, bed temperature, nozzle temperature, layer thickness and deposition speed regarding energy consumption during printing phase and ultimate tensile strength (UTS). A decision-making tool based on Ashby's material selection tool is also implemented to further discriminate different solutions. Different weights and a Pareto front have been used to illustrate the methodology's potential. Among the tested parameters, bed heating strategy has proven to be the most impactful parameter while bed temperature shows little to no effect. This study proposes a methodology as starting point for efficient FFF printing.

Keywords: Fused filament fabrication; Manufacturing cost; Energy consumption; Energy model; Multiple-criteria decision analysis; 3D printing.

1. Introduction

Additive Manufacturing (AM) techniques gain importance over the conventional subtractive manufacturing techniques, from being used for prototyping AM is, nowadays, a key element of the industry and manufacturing processes. The advantages of this technique include a greater customization parts and complex components, without using tools, and reduced waste compared to other manufacturing techniques [10, 17]. These benefits have led to an even growing adoption of AM with a 19.5 % industry growth in 2021 [19].

Applications can be found in a wide range of industries, including aerospace, automotive, medical, and consumer goods. In 2017, the aerospace industry accounts for 18.2 % of the total AM market and is a promising field of applications, mainly for non-structural parts [16]. Additionally, the limited production lot in the aerospace industry meet the limited productivity of AM. Among the different AM processes, Fused Filament Fabrication (FFF) is the most widespread AM process owing to relatively fast production, ease of access and flexibility in material [13].

Among compatible material, composite material has found success in many transport industries due to his lightweighting potential, which can be further enhanced by AM. Thereby, reducing the fuel efficiency of airplane and carbon emission in an effort to meet the International Civil Aviation Organization target to reduce aviation emissions by 50 % by 2050. Previous examples present composite materials and AM as viable approaches for improving energy the efficiency [20]. Due to its attractive strength-to-weight ratio, resistance to thermal expansion, and corrosion resistance, carbon-fiber reinforced polymer (CRFP) is a widely and frequently used composite materials [1]. Among thermoplastics matrix, polyamide 6 (PA6) is one of the most versatile semi-crystalline polymers used in automobiles and aerospace [12]. Furthermore, carbon-fiber reinforced polyamide 6 (PA6-CF) exhibit attractive mechanical durability under hydro-thermal and thermo-oxidative conditions, making it suitable for automobile and aerospace applications [15, 14].

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From a manufacturing viewpoint, FFF printing parameters are a cornerstone between energy consumption and part properties (e.g., mechanical, physical, geometry accuracy). Consequently, the need of methodology to assess and aid decision-making for printing parameters is required. Niang & al. [11] investigated the effects of speed deposition, nozzle temperature and layer thickness on the tensile properties and fracture interface of FFF CFRP parts. They found that an increase in speed deposition leads to lower interbonding between layers, while reducing the speed deposition below a certain speed also reduce tensile strength resistance. Benwood & al. [3] presented tensile tests and microstructures showing the bed temperature as the main contributor to the materials crystallinity, and tensile strength. The results provided by Christiyan & al. [4] showed that maximum tensile strength was improved by layer thickness below 0.2mm. Alafaghani & al. [2] analyzed the influence of the nozzle temperature, layer thickness, infill percentage and infill patterns on strength of FFF parts. Whilst infill percentage and layer thickness showed the highest impact on tensile resistance, nozzle temperature narrowly improves the tensile strength for small layer thickness (< 0.5 mm) and have a strong influence for larger thickness (> 0.5 mm). Regarding energy consumption, Elkaseer & al. [6] statistically evaluated the impacts of infill density, layer thickness, speed deposition, nozzle temperature and orientation on energy consumption of PLA, using Taguchi orthogonal array. Layer thickness and printing speed were found as main factors. Lunetto & al. evaluated the influence of thickness, materials and infill percentage on energy per unit of mass produced. Vidakis & al. [18] compare energy consumption, to mechanical responses (ultimate tensile strength (UTS), Young's modulus and toughness) by changing infill percentage, deposition angle, nozzle temperature, deposition speed, deposition thickness and bed temperature. These studies focused on the impact of the different printing parameters on either the energy consumption or the mechanical performances. This work combine the energy consumption and the mechanical performance data to identify the appropriate solution to a specific need. Firstly, experimental data are gathered to assess the relationship between energy consumption and ultimate tensile strength to the most critical printing parameters. Secondly, based on the collected data, a decision tool is developed to discriminate various options for printer users relative to their goals.

2. Materials and method

Experimental tests were designed using CarbonX™ NYLON 6 + CF GEN 3 (< 20 %wt) filament from 3DXTech to produce tensile specimen Type A1, from standard ISO 527-2:2012 [7], on a Raise 3D Pro2 FFF printer. To regulate humidity, filament was kept in a vacuum oven. A HOBO Plug Load Data Logger UX120-018 was used to track energy consumption. After printing and measuring the mass, raft was manually removed. To evaluate the impact of printing parameters on energy consumption and mechanical performance, two indicators were selected: energy consumption during the deposition phase and UTS. Only the printing phase is evaluated to dismiss any variability during heating phases from the machine. Tensile tests were carried out following ISO 527-2 on Instron 1362 testing system with a 5 kN load cell. Speed of tests was 3 mm/min. The strain was measured with an extensometer MTS 634.26F-26.

Five printing parameters have been selected: bed temperature, nozzle temperature, layer thickness, deposition speed and bed heating strategy. Deposition orientation and infill were also considered, as they are common variables in FFF manufacturing. However, on one hand, the best tensile resistance for CRFP will always be delivered throughout the filament orientation without affecting energy consumption. On the other hand, for tensile specimen, an infill of 100 % must be chosen for optimal performance. Three levels for each of the five printing parameters were chosen to assess evolution of energy and mechanical impacts. Levels were chosen to stay within the capability range of the printer and avoid any part manufacturing failure. Bed heating strategy is between 0% (heating for the first three layers then no heating) and 100%. 0% would correspond to prototyping cases where only printability is required. For other parameters, levels were taken from the lower range recommended by the supplier and then increased. Finally, to minimize the number of experiments Taguchi method was selected. Two repetitions of each condition was tested. Table 1 lists fixed printing parameters and Table 2 present the twenty-seven conditions of printing parameters.

Table 1. Printing parameters held constant throughout the experiment.

Parameter	Value	Unit
Outline shell	1	-
Nozzle diameter	0.4	mm
Deposition orientation	+/-45	°
Top solid layers	0	-
Bottom solid layers	0	-
Extrusion multiplier	0.85	%

3. Results and discussion

3.1. Energy consumption

Figure 1 depict impacts of the different printing parameters on energy consumption. Bed heating strategy is the predominant parameter, influencing the power demand during manufacturing. The second most important parameter is the layer thickness, affecting manufacturing duration. In contrast, bed temperature show little to no impact on energy consumption. This outcome can be explained by the fact that bed temperature mostly affects how long the heating phase lasts, but does not influence power demand and/or the duration of the printing phase. Finally, the increase of the energy with the deposition speed is counter-intuitive, as higher speed would mean a reduction in manufacturing time. The relatively small difference between the high and low factor levels may help to explain this evolution. Also, deposition speed denotes the highest value possible during printing, not mean speed. Increase in speed also mean increase in acceleration/deceleration and power demand. Figure 2 show energy consumption during printing phase for each

Table 2. Design of experiment following L_{27} Taguchi orthoganal array.

#	Bed heating strategy	Bed temperature [°C]	Nozzle temperature [°C]	Layer thickness [mm]	Deposition speed [mm/s]
1	Stop heating after 3 layers (0 %)	80	255	0.15	75
2	0 %	80	260	0.20	80
3	0 %	80	270	0.30	85
4	0 %	90	255	0.20	80
5	0 %	90	260	0.30	85
6	0 %	90	270	0.15	75
7	0 %	95	255	0.30	85
8	0 %	95	260	0.15	75
9	0 %	95	270	0.20	80
10	Heating for 50 % of the layers	80	255	0.20	85
11	50 %	80	260	0.30	75
12	50 %	80	270	0.15	80
13	50 %	90	255	0.30	75
14	50 %	90	260	0.15	80
15	50 %	90	270	0.20	85
16	50 %	95	255	0.15	80
17	50 %	95	260	0.20	85
18	50 %	95	270	0.30	75
19	Full heating (100 % of the layers)	80	255	0.30	80
20	100 %	80	260	0.15	85
21	100 %	80	270	0.20	75
22	100 %	90	255	0.15	85
23	100 %	90	260	0.30	75
24	100 %	90	270	0.20	80
25	100 %	95	255	0.30	75
26	100 %	95	260	0.20	80
27	100 %	95	270	0.15	85

condition. The difference between the minimum and maximum usage, which ranges from 62 Wh to 304 Wh, is approximately 5 times. Those values correspond to a Specific Energy Consumption (ratio between total energy consumption and printed mass) ranging between 25 MJ/kg to 113 MJ/kg, which is consistent to SEC data available in the literature for other FFF printers [8]. As bed heating strategy is the most impactful parameter, values are colored according to the level of heating strategy. The two most consuming conditions are for full heating of the bed and a layer thickness of 0.15 mm.

3.2. Tensile test

Figure 3 shows the influence of the printing parameters on the ultimate tensile strength, and Figure 4 depicts the sorted UTS values for each condition, with a focus on heating bed strategy. The UTS is mainly affected by the heating bed strategy: a full heating improves greatly the mechanical properties of the specimen when compared to 3 layers or 50 % strategies. Since the bed heating strategy is the most impactful parameter on both energy consumption and UTS, it is a preferred variable to adjust depending on an energy saving case or a mechanical optimization case. Increasing the bed and nozzle temperatures also slightly improves the UTS, but this effect is limited. The bed heating strategy, bed temperature and nozzle temperature affect the environment temperature, which in turn influences the complex process of molecular diffusion and heat transfers that drive the consolidation of the filaments at the interface and therefore improves the UTS.

Increasing the deposition speed has a detrimental effect on the UTS, because the filament cannot uniformly reach the nozzle temperature if the deposition speed is too important. The mechanical resistance is influenced by the width of the contact between filaments [9], which explains why reducing layer thickness has a favorable impact on UTS. However, given the weak adhesion and the porosity between the filaments, the interface between the filaments is a recognized source of disruption [5], reducing the layer thickness also increases the number of contacts between filaments, raising statistically the risk of failure.

3.3. Decision-making

To help decision-making following the prior results, one can use multi-objective optimization tool from Ashby. Figure 5 plot each conditions relative to their energy consumption and the inverse of UTS. On this plot, Pareto front represents conditions that provide the best balance between the two indicators. In our case, several conditions appear as equally balanced. Additionally, a *value function* can be formulated with a slope that balance the conflicting objectives depending on the goal, the conditions minimizing the function being the overall optimum. Figure 6 represents different values of the slope, depending on the application. Additionally, relative to their goals, designers, environmentalists, printer manufacturers, and technical managers might choose different values.

For the case where energy consumption and UTS are both equally important, then $\alpha = 1$ (slope = 1), and thus, condition #25 is the optimum (Figure 6a). As a middle-ground compro-

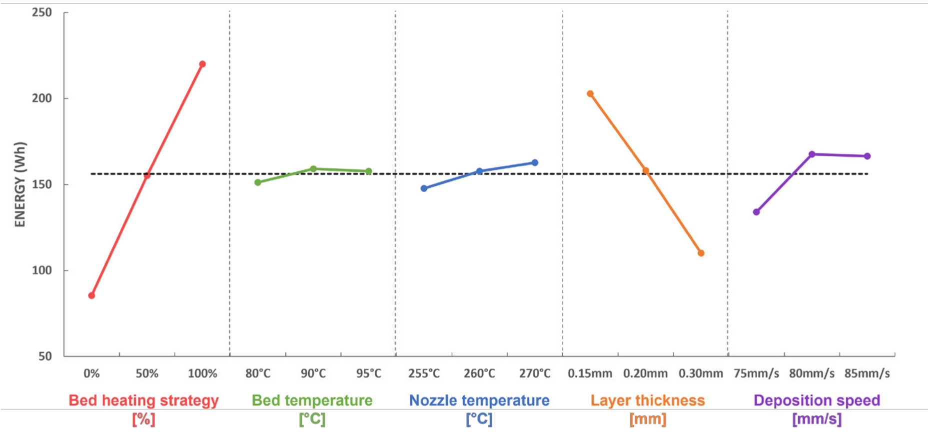

Fig. 1. Impact of the different printing parameters on energy consumption during printing phase.

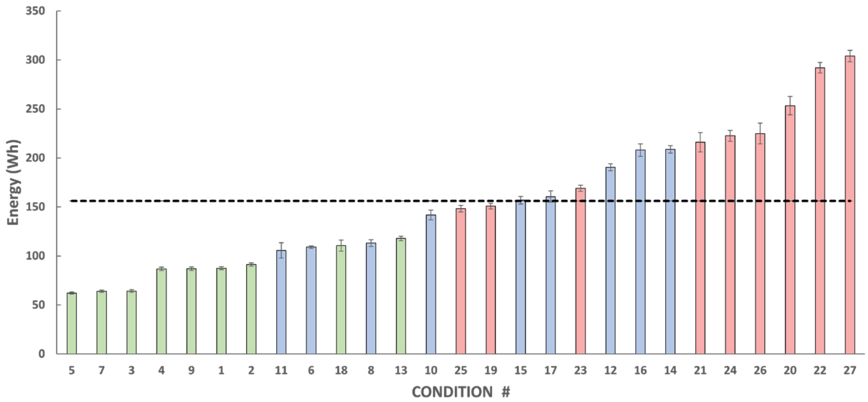

Fig. 2. Sorted energy consumption values for the twenty-seven conditions. In green, bed heating strategy of 0 %; in blue, heating for 50 % of the layers; in red, 100 %. Black doted line represents mean value. Error bars represent 95 % confidence interval.

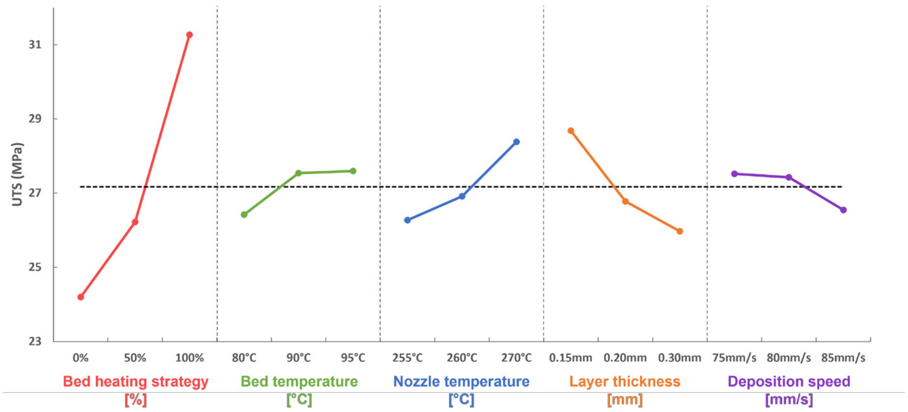

Fig. 3. Impact of the different printing parameters on UTS during printing phase.

mise, condition #25 corresponds to the full heating of the bed. Other parameters are fixed at 95 °C and 270 °C temperatures for bed and nozzle respectively, 0.30 mm layer thickness for 75 mm/s. Figure 6b), present the case where for each increase of a unit of energy consumption we accept an increase of 10 units of UTS (slope = 0.1). Condition #3 having the fifth lowest UTS but third less consuming. For this energy saving case, the bed is only heated at 270 °C for the first three layers, nozzle temperature is 80 °C, layer thickness is 0.30 mm and speed deposition is at 85 mm/s. And vice versa for the case in Figure 6c), where each increase of a unit of UTS we accept an increase of 10 units of energy consumption (slope = 10). In this case #27 and #24 are the optimums. Condition #27 having the highest of all UTS but also most consuming. For this mechanical performance oriented case, all parameters are set at optimal levels mechanically (100 %; 95 °C; 255 °C; 0.15 mm; 85 mm/s).

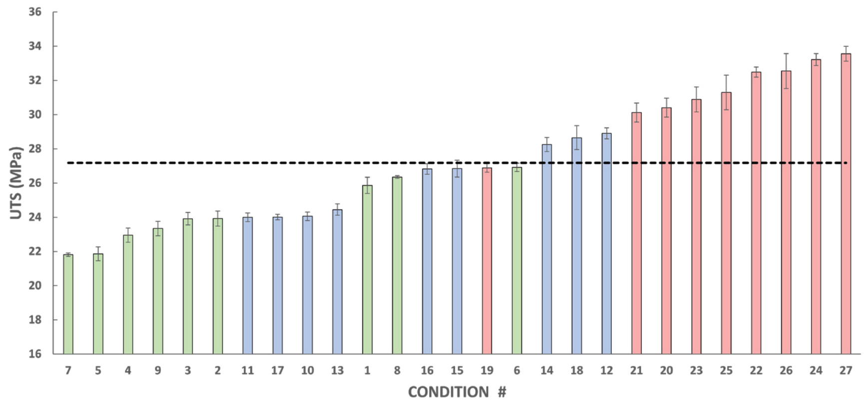

Fig. 4. Sorted UTS values for each condition. bed heating strategy of 0 %; in blue, heating for 50 % of the layers; in red, 100 % of the layers. Black doted line represents mean value. Error bars represent 95 % confidence interval.

These findings suggest a weak and inverse correlation between energy use and tensile resistance. As the highest consumption condition does not always have the highest UTS, indicating space for efficiency. Similar to this, the lowest consuming condition did not result in the lowest UTS.

4. Conclusion

This study presents a framework for efficient FFF printing to confront various solutions regarding their energy and mechanical performances. Each printer user can then adapt this comparison methodology to identify the set of printing parameters adapted to a mechanical, energy or balance AM fabrication.

First, the impacts of five printing parameters for composite PA6-CF materials, revealed the bed heating strategy and the layer thickness as main contributor to energy consumption and UTS. While full heating of the bed appears to be more appropriate to display the highest mechanical resistance, no heating may be more suited for prototyping. Inversely, bed and nozzle temperature have a relatively low impact on the mechanical properties and energy consumption during printing phase.

Secondly, Ashby's multi-objective optimization tool was applied to the various conditions to help decision-making. The Pareto front first display conditions with the best compromise between the two indicators (here energy consumption and UTS). Although the correlation exists, an increase in energy consumption does not lead directly to the most optimal mechanical solution, and vice versa. Then, the weight associated to the two indicators will further distinguish conditions. In future work, this methodology can further be expanded by investigating other AM process and/or material. Moreover, interactions between printing parameters and integrating the economic aspect could give additional information to optimize the process.

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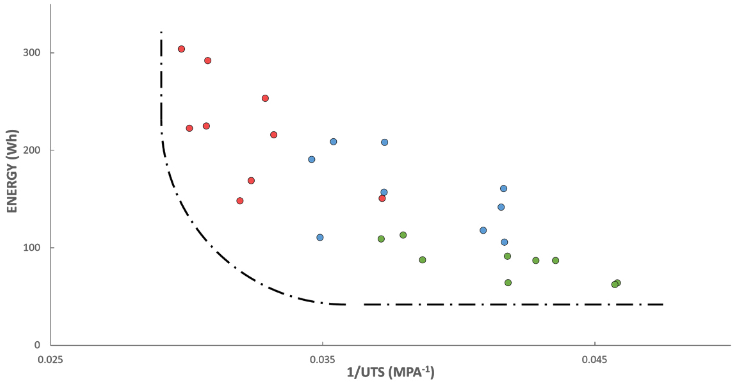

Fig. 5. Plot of energy consumption with respect to 1/UTS for each condition. In green, bed heating stopped after 3 layers; in blue, heating for 50 %; in red, 100 %. Black doted line represent the Pareto front.

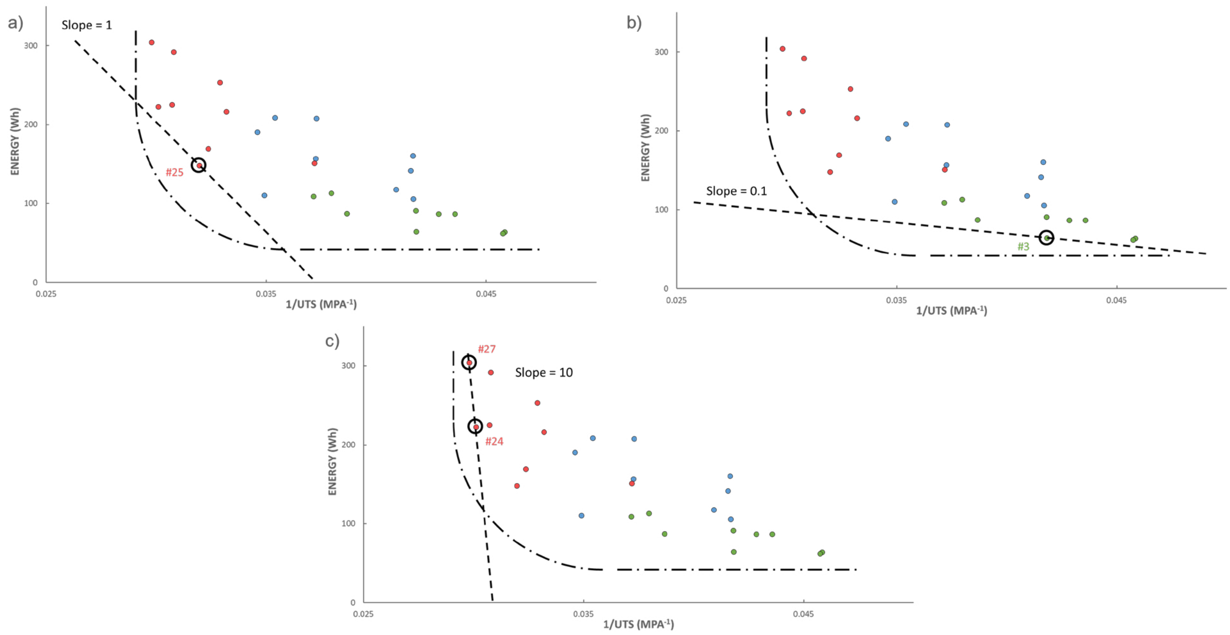

Fig. 6. Plot of energy consumption with respect to 1/UTS for each condition, with Pareto front, and value function with: a) slope = 1 (no preference between energy consumption and UTS); b) slope = 0.1 (low energy consumption is preferred); and c) slope = 10 (UTS is favored). The black circle correspond to optimized condition for each slope.

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