Sustainability of Fused Deposition Modeling: The Role of the Plate Material

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Abstract. Fused deposition modelling (FDM) is an additive manufacturing technique providing numerous possibilities for producing complex geometries. In FDM, many heat sources make the layer-by-layer deposition mechanism a thermally driven process. Heat transfer is crucial in determining the temperature history and the interlayer adhesion of the FDMed parts. Thus, the relevance of this aspect linked to the concern about the increasing global warming leads to the investigation of solutions to reduce the environmental impact of the process. The results in the literature show that the greatest contribution in terms of power consumption during the FDM process is associated with heating the bed and keeping it warm. Thus, this study aims to provide guidelines for a better choice in the plate material of the 3D printer to reduce the energy consumption required by the process of heating the plate without renouncing to print parts that meet the industrial quality requirements.

Keywords: Sustainability · Fused Deposition Modeling · PLA · Aluminum · Steel

1 Introduction

Nowadays, the importance of the manufacturing processes from a green perspective and the growing diffusion of 3D printing devices have led to the study of a strategy for energy consumption reduction. Rapid prototyping and domestic use of 3D printers increase these machines' energy daily. Considering that the plate absorbs the main quantity of energy [1] it was assumed to investigate this aspect to pursue an energy consumption reduction strategy.

Commercial 3D printers are equipped with a steel plate with a very low thermal conductivity coefficient, so it requires a large amount of energy input to reach the target temperature and keep it constant. In this study the replacement was proposed with an Aluminum plate, in particular made of AA2024 which has 193 W/m-K thermal conductivity that is about 8 times higher than steel value.

Beyond the energetic performance, the mechanical properties of the workpieces was also evaluated because the new surface heating could generate thermal distortions and

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then a geometrical error in the workpiece [2]. Moreover, during the on/off heating cycles, it could reach temperature peaks which can cause a rapid polymer degradation of the lowest layer in contact with the plate surface [3].

In summarizing, in this experimental study were used two different plates. The energy consumption was evaluated by monitoring it during the printing process. It was carried out through tensile tests and ultrasonic inspection on the workpieces produced, using the same experimental printing strategy. The final aim is to study the best compromise between printing setup and mechanical properties from an energy-saving perspective.

2 Materials and Methods

A Polylactic Acid (PLA) sample having the dimensions 50 × 50 × 3 mm was printed by means of the 3D printer called Sharebot 42. Its printing volume is 250 × 220 × 220 mm, and its Z resolution is 50 µm. The plate temperature was fixed at 90 °C to keep the material fluid and reduce the voids. A −45°/+45° raster orientation, an infill density of 100%, a line infill pattern and a layer thickness of 0.2 mm were chosen. The number of shells was chosen equal to two, according to the best results in literature in terms of good mechanical properties obtained [4]. The filament adopted for this study is Black PLA ICE having a diameter of 1.75 mm. Table 1 contains the speed and extrusion temperature adopted to print the sample.

Table 1. Experimental plan of PLA sample manufactured by FDM.

Configuration	Speed (mm/s)	Extrusion Temperature (°C)
1	110	215

All the process conditions for 3D printing were chosen according to the best results in literature [4–6]. The sample mass was measured three times by means of the Gibertini ETERNITY 200 CAL balance, having an accuracy of ±0.05 mg. Also, 3 tensile specimens having the ASTM standard geometry were printed and tested for the configuration adopted in this study using Galdabini QUASAR 50, equipped with a 50kN load cell and testing speed 3 mm/min.

During the printing process, power and energy consumption were measured by a device called Quality Analyser CA8331 (Chauvin Arnoux), which gives records of power and energy consumption as the output of the current and tension measurements. Figure 1 shows a schematization of the experimental setup adopted in this study.

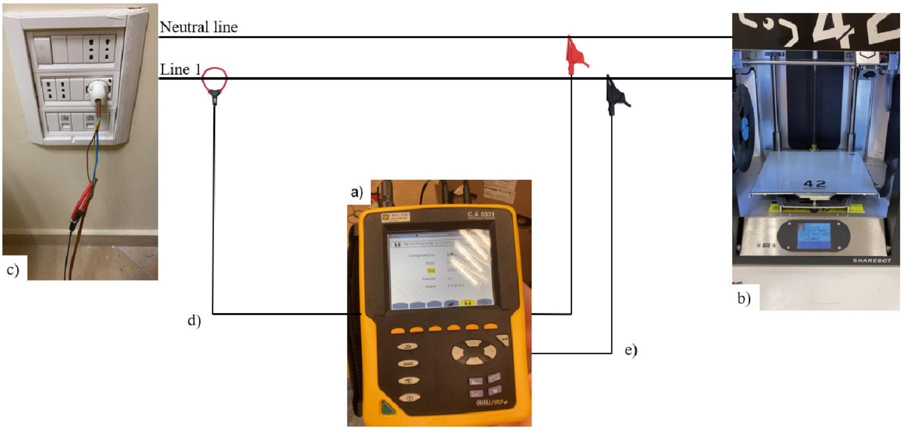

Fig. 1. Experimental setup: (a) the power and the energy analyzer Chauvin Arnoux CA 8331, b) the 3D printer (Sharebot 42), c) the electrical cabinet, d) the current sensor, e) the tension cables.

Two samples, having the same geometrical dimensions, of the same configuration were printed: one by using a 2024 aluminum plate and another by using a AISI 430 stainless steel plate to compare the results obtained in terms of energy consumption and mechanical properties.

The Specific Energy Consumption (SEC) was calculated to evaluate the efficiency of the energy consumption strategy. The formula of the SEC is the following:

$$SEC = E/m \tag{1}$$

where E is the energy consumption during 3D printing and m is the mass of the sample.

3 Results and Discussion

As mentioned in the previous section, power consumption was measured during printing the samples by using both the steel and aluminum plates. The power trends are observable in Fig. 1 and Fig. 2.

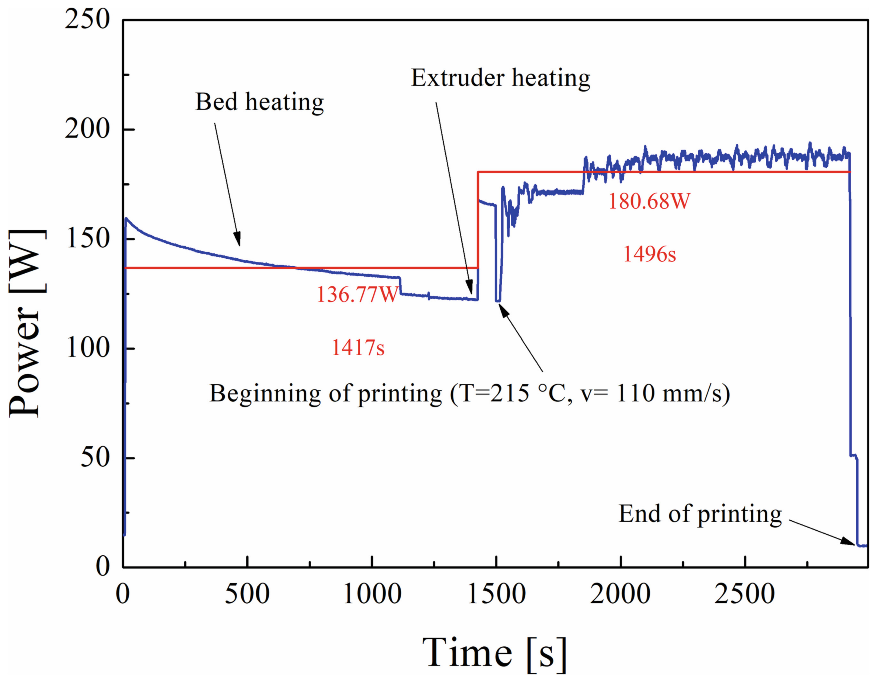

Fig. 2. Power trend over time during the FDM process of the configuration 1 in Table 1 by using the steel plate.

The red lines In Fig. 2 and Fig. 3 indicate the power average during the main subphases of the FDM process: bed heating and printing. During the printing subphase, the power average is very similar by comparing steel and aluminium plate. However, it lasts less time using the aluminium plate due to its higher thermal conductivity. Thermal conductivity of the aluminium is k = 235 W/m K while that of the steel is k = 45 W/m K. For the same reason, the bed heating subphase lasts less time by using the aluminium plate than by using the steel plate.

For better visualization of the results obtained, the percentages in terms of energy consumption for each subphase of the FDM process by using both the steel and aluminum plates are represented in the pie charts in Fig. 4 and Fig. 5.

It can be observed in Fig. 4 and Fig. 5 that a great amount of energy from the whole FDM process is consumed for heating the bed, agreeing with the literature [1]. Moreover, according to the results observed in the power trend graphs (Fig. 2 and Fig. 3), by fixing the process conditions, a higher energy consumption to heat the bed is required by using the steel plate because of the higher thermal conductivity of the aluminium plate.

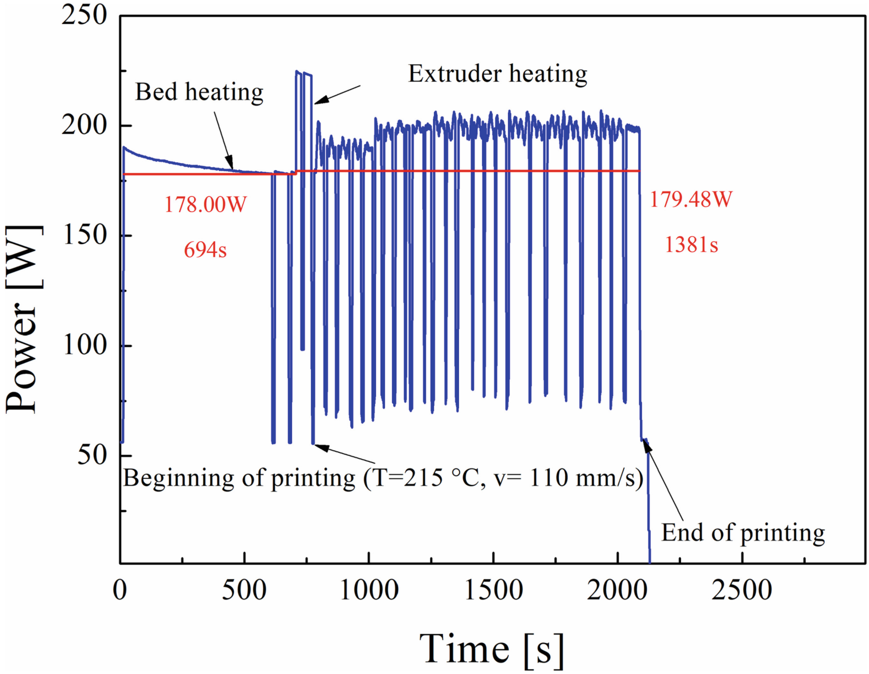

Fig. 3. Power trend over time during the FDM process of the configuration 1 in Table 1 by using the aluminum plate.

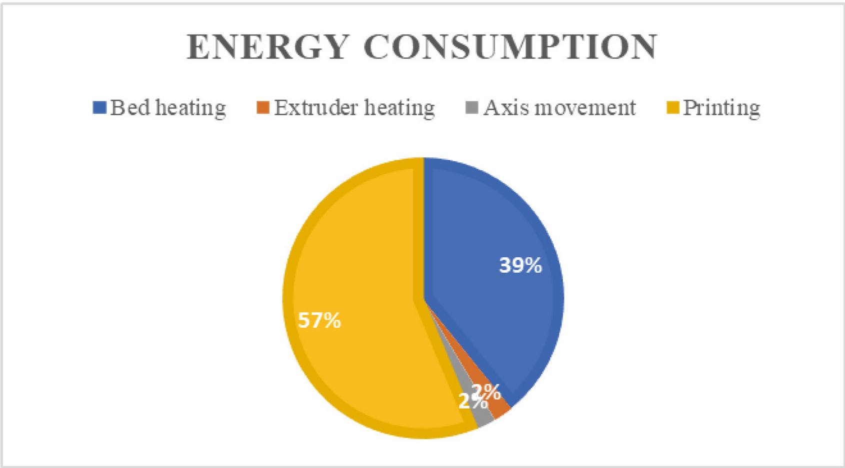

Fig. 4. Pie chart of the energy consumption during the main subphases of FDM process by using the steel plate

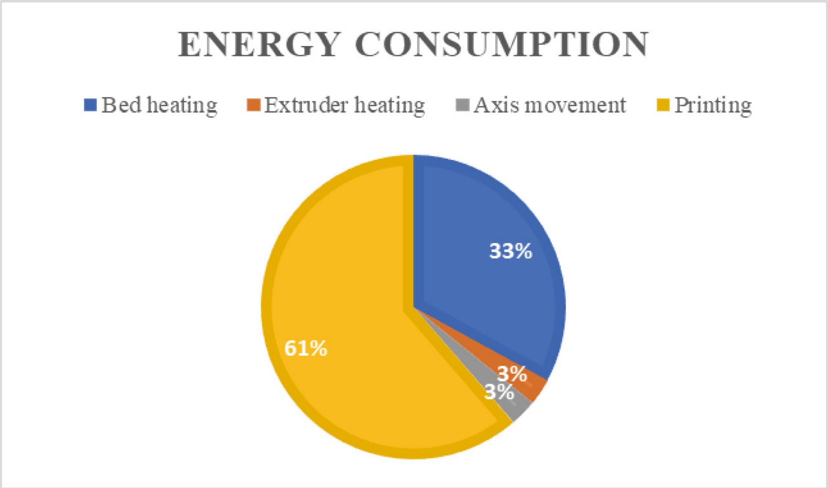

Fig. 5. Pie chart of the energy consumption during the main subphases of FDM process by using the aluminum plate

Finally, the results obtained in terms of SEC, calculated by Eq. 1, and UTS are contained in Table 2.

Table 2. Experimental plan of PLA samples manufactured by FDM.

Plate material	SEC (kJ/g)	UTS (MPa)	UTS/SEC
steel	29.8	50.6	1.7
aluminum	25.5	48.3	1.8

It can be seen that by fixing all the process conditions and by only varying the plate material of the 3D printer, more energy is required for each unit mass (1 g) to be printed by using the steel plate. In fact, specific energy consumption of 29.8 kJ/g is required by using the steel plate, while specific energy consumption of 25.5 kJ/g is required by using an aluminum plate. Concerning the UTS, very similar results are obtained in two conditions (Table 2). A joint analysis of the results obtained introduced an efficiency index given by the ratio between the SEC and the UTS.

As observable by the results in Table 2, the choice of the plate material hangs in the direction of aluminum rather than steel since the efficiency index is higher by using an aluminum plate.

4 Conclusions

This article deals with the study of the effect of the plate material on both the energy consumption and mechanical properties obtained. One configuration of process conditions particularly extrusion temperature and speed was adopted among the best technological results in literature by using two plate materials, steel and aluminum. The main conclusions of this study are the following:

- The greatest contribution in terms of power consumption during the FDM process is heating the bed and keeping it warm.
- The aluminum plate takes less time than the steel plate to reach the desired temperature. This result allows for saving energy during the bed heating subphase of the FDM process.
- The average power during the printing subphase is lower by using the aluminum plate than the steel plate. This result allows for saving energy even during the printing subphase of the FDM process.
- Using the aluminum plate rather than the steel plate saves up to 20% energy consumption for the entire FDM process.

Therefore, it is recommended to choose an aluminum plate under the same process conditions. Further investigation of this study may include the thermal imaging camera analysis to study the heat transfer between the plate and the material and between the layers and ultrasonic inspection to detect the quality of the printed PLA parts for better optimization of the FDM process conditions from an energy-saving perspective.

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