INFLUENCE OF SELF AND EXTERNAL HEATING ON ELECTRICAL PROPERTIES OF CONDUCTIVE 3D PRINTED FILAMENT

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ABSTRACT

3D printing has become a widespread technology to design the complex geometries. There are numerous technologies that allow to implement the 3D printing process. Among them the Fused Deposition Modelling (FDM) is a one of a common technique using filaments made by different materials such as thermoplastic, metal, wood or composite. In this paper we will focus on the carbon particules-PLA filament (CP-PLA) which is easy-to deform when heated above the glass transition temperature (Tg) and the PLA is the most widely used thermoplastics in 3D printing. The effect of joule's heating and the oven heating on the resistance of the CP-PLA composite has been studied. The results show that resistance evolution is highly dependent on heating method and printing parameters such as layer height and direction. Indeed, the resistance was found to increase faster when heated by an oven than by joule effect.

1. INTRODUCTION

3D printing has rapidly evolved in recent years, showing great potential for multifunctional applications in aerospace, civil, defense and bio-engineering sectors [1]. Different manufacturing techniques are commercially available in additive manufacturing [2] but among all the different methodologies, Fused Deposition Modelling (FDM) is the most widely used technique [3], with high versatility to print components based on thermoplastic polymers. FDM presents a large variety of printing parameters (e.g. layer height, printing angle, filling) to produce complex geometries. All these parameters have an influence on the mechanical properties [4]. It is therefore possible to create anisotropic structures and reduce weight by topological optimisation. FDM process allows for much more versatility while compared to classic manufacturing processes and enables designs which would have been impossible otherwise, all this at a very competitive cost. However, the technology is not mature enough (overwhelmingly used with soft thermoplastics, weak interlayer properties) in terms of mechanical performance to create reliable components for primary structural applications [5].

One current FDM application is the in-situ printing of electrical circuits in structural components using conductive thermoplastic filaments [6]. Electrical properties of commercial conductive filaments are available in the literature [7], but these studies are usually focused on bulk material properties instead of printed filaments. To the author's knowledge, the influence of different processing parameters such as filament height or orientation on the electrical properties of the 3D printed component are unexplored. Additionally, electrical properties also depend on the polymer temperature, and are usually affected by heat, either Joule effect self-heating or an external source, such as oven heating. For instance, Daniel et al. showed that the baseline resistance shifts when exposed to thermal cycles [8]. Considering these findings, there is a need for a detailed thermo-electrical characterisation of conductive polymeric filaments to design reliable sensors for industrial applications [9]. However, is it important to notice that the state of the art on FDM conductive filament hardly consider the electrical behavior above the glass transition temperature (Tg)[6-8].

In this paper, we characterize the thermoelectric properties of conductive 3D printed PLA components. The influence of processing parameters and heating technique (self and external) on the final thermo-electrical properties below and above Tg were investigated. The study is conducted as function of two processing parameters, the layer height and the filament orientation. Two methodologies to increase the temperature of the 3D printed component are analysed and compared; self-heating by joule effect *vs* external heating in an oven-controlled environment. The overall goal of this initial study is to assess the viability of polymers with different electrothermal properties for actuation and 4D printing purposes.

2. MATERIALS & METHODS

2.1 Materials

For the present study, a commercial Polylactic Acid (PLA) filament with brand name Proto-Pasta supplied by the company Protoplant was selected. The filament is based on the natureworks 4044 PLA polymer with a melt point of 155 ºC and doped with proprietary carbon black filler to increase the electrical conductivity. The specimens were manufactured with a Prusa i3 MK3S FDM printer. A hot-end temperature of 225 °C and a printing bed temperature of 60 °C was used as recommended by the manufacturer. The filament was extruded through a 1 mm diameter nozzle, at 100% extrusion ratio.

2.2 Sample preparation

The size of the samples were 15x70mm with a thickness of 2.4 mm. Three different layer heights of 0.05, 0.1 and 0.2 mm were selected. The filaments were laid down perpendicular (90°) or parallel to the printing direction (0°). A conductive silver paint was applied at each samples end section and wires were subsequently glued with araldite to minimize the contact resistance and ensure a strong adhesion.

2.3 Electrical characterization

2.3.1 Joule effect self-heating

To investigate the self-heating behavior samples were subjected to a 30 volts DC current over a period of 5 minutes using a TENMA 72-2540 generator. The resistance was recorded with a built-in software of the same name provided with the generator. Temperature distribution was monitored with a FLIR A655SC thermal camera and registered with the ReshearIR software at the same time, as shown in Fig.1. The thermal camera monitored the temperature profile and homogeneity, as well as potential contact resistance issues. Fig.2 exhibits an example of a) high contact resistance / non homogenous heating and b) low contact resistance / homogeneous heating. The samples were preheated for 5 minutes, which was always sufficient to stabilise the resistance values.

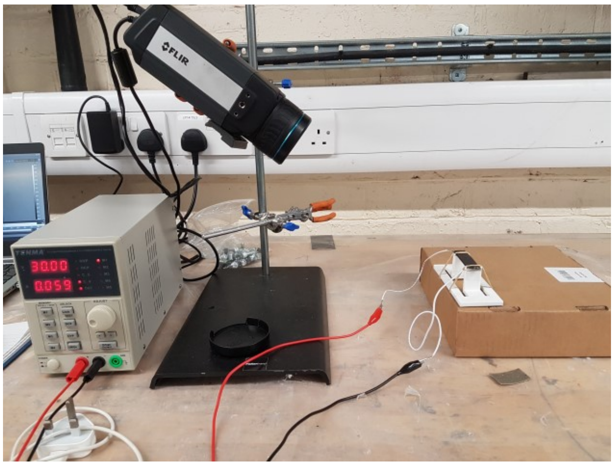

Figure 1: Experimental set-up for Joule self-heating investigation

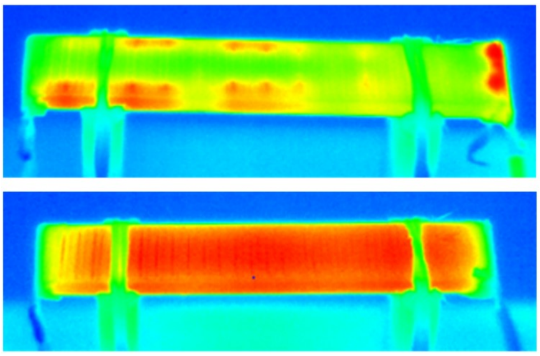

Figure 2: Temperature distribution in CP-PLA samples with high contact resistance (a) and low contact resistance (b)

2.4 Oven heating

The external heat source investigation was performed using a SciQuip oven-230HT. The specimens were initially heated to 50°C and afterwards temperature was progressively increased in steps of 5°C maintaining a constant temperature over a period of 5 minutes to ensure a homogeneous temperature distribution over the specimen. The temperature of the specimens was registered by thermo-couples, and the resistance was monitored with a TENMA 72-2540 generator set on 15 volts DC, low enough to avoid any self-heating Joule effect, see Fig 3.

Figure 3: Experimental disposition for oven heating investigation#

2.5 Data treatment

To analyse the evolution of electrical properties as function of the temperature, the parameter of Resistance Amplitude (RA) was introduced:

$$RA = \frac{R_i - R_0}{R_0} \times 100$$

where R_i stands to the registered resistance and R_0 stands for the initial resistance at room temperature (20°C). To ensure the statistical significance of the registered data, 5 repetitions of each experiment were conducted.

3. RESULTS & DISCUSSION

3.1 Baseline electrical properties

The initial resistance (R_0) of the samples as function of the printing direction and the layer height is shown in Fig. 4. The best electrical performance is achieved for the thicker layer height (0.2 mm), exhibiting an additional negligible influence of the printing direction. Decreasing the layer height results in a progressive increment of resistance and a printing direction sensitivity, with a drastic loss of electrical properties for architectures printed at 90°. The resistance of the samples printed at 0º presented a modest increment, between the layer height of 0.2 mm (234 Ω) to reach its maximum at 0.05 mm (293 Ω). On the other hand, the samples printed at 90° show a dramatic loss of electrical properties when decreasing the layer height, with large scattering in average resistances of 234 Ω, 283 Ω and 455 Ω for the layer heights of 0.2 mm, 0.1 mm and 0.05 mm respectively. The authors suspect interlayers are generally less conductive than core filaments, and more interlayers are present when the layer height is decreased.

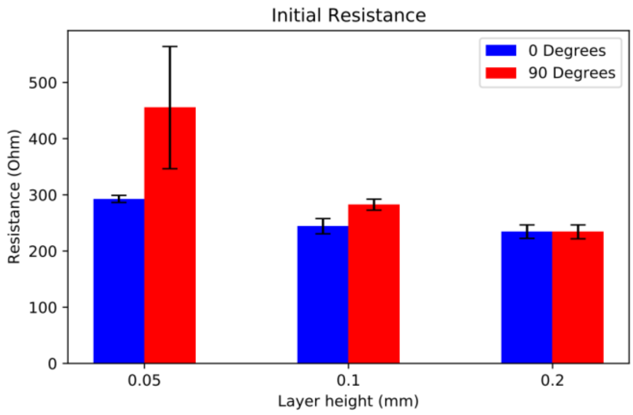

Figure 4: Initial resistance as function of the printing direction and the layer height.

3.2 Thermoelectric characterization

3.2.1 Influence of the layer height

Five samples for each layer heights were tested for self-heating behavior induced by the joule effect; all displayed a convergence after 5 minutes. Fig 5 (a). shows representative curves of the percentage of resistance amplitude for the samples printed at 90°. They present an almost linear behaviour up to 65°C and a noticeable offset between the 0.2 mm and the other layer heights. The samples printed at 0° (Fig.5. (b)) are much more reliable as every sample presented a similar evolution of resistance regardless of the layer height. The resistance is supposed to depend on the conductivity path which is less depending on the layer height in longitudinal direction (0°) than in transverse direction (90°).

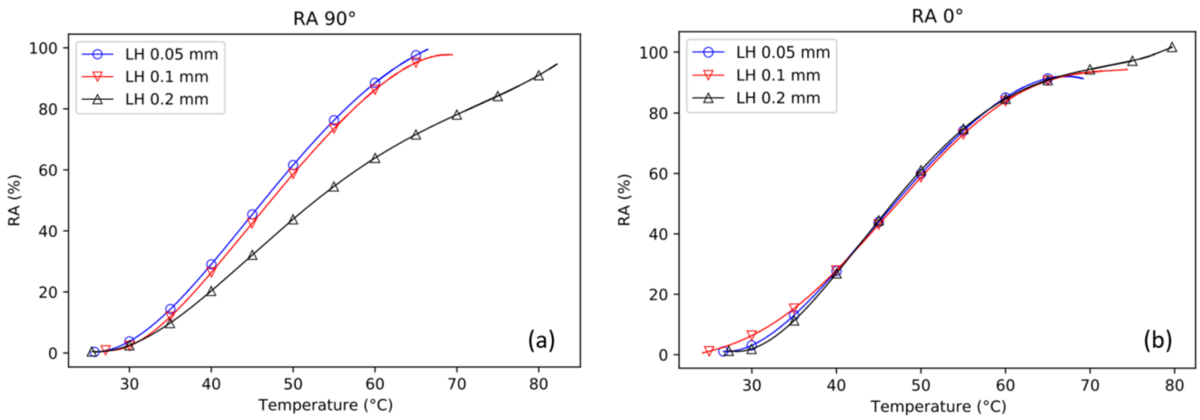

Figure 5: RA (%) of the samples printed at (a) 90° & (b) 0°

3.2.2 Influence of the printing direction

Fig. 6. (a) highlights the differences between the samples printed at 0° and the samples printed at 90° for the same layer height of 0.2 mm. The difference is remarkable especially after 50°C where a change in linearity can be guessed. Samples printed at 0.05 mm & 0.1 mm present a similar behavior up to 60°C. Once this temperature is reached, samples printed at 90 degrees take more time to stabilize at their maximum value (Figure 6, (b) & (c)). We could initially assume the samples manufactured on the longitudinal conductive direction are representative of the electrical response of the material, meanwhile the samples manufactured at the

perpendicular direction present the coupled effect of the material conductivity and the 3D architecture. In fact, the conductivity depends on electric paths formed in the sample: intrafilament and interfilament. The transverse sample has more interfilamentous connections resulting a more complex electric path. One hypothesis to understand the differences in trends is the evolution of the voids within the material. A decrement in void distribution might increase the contact area, compensating the loss of electrical properties at high temperatures.

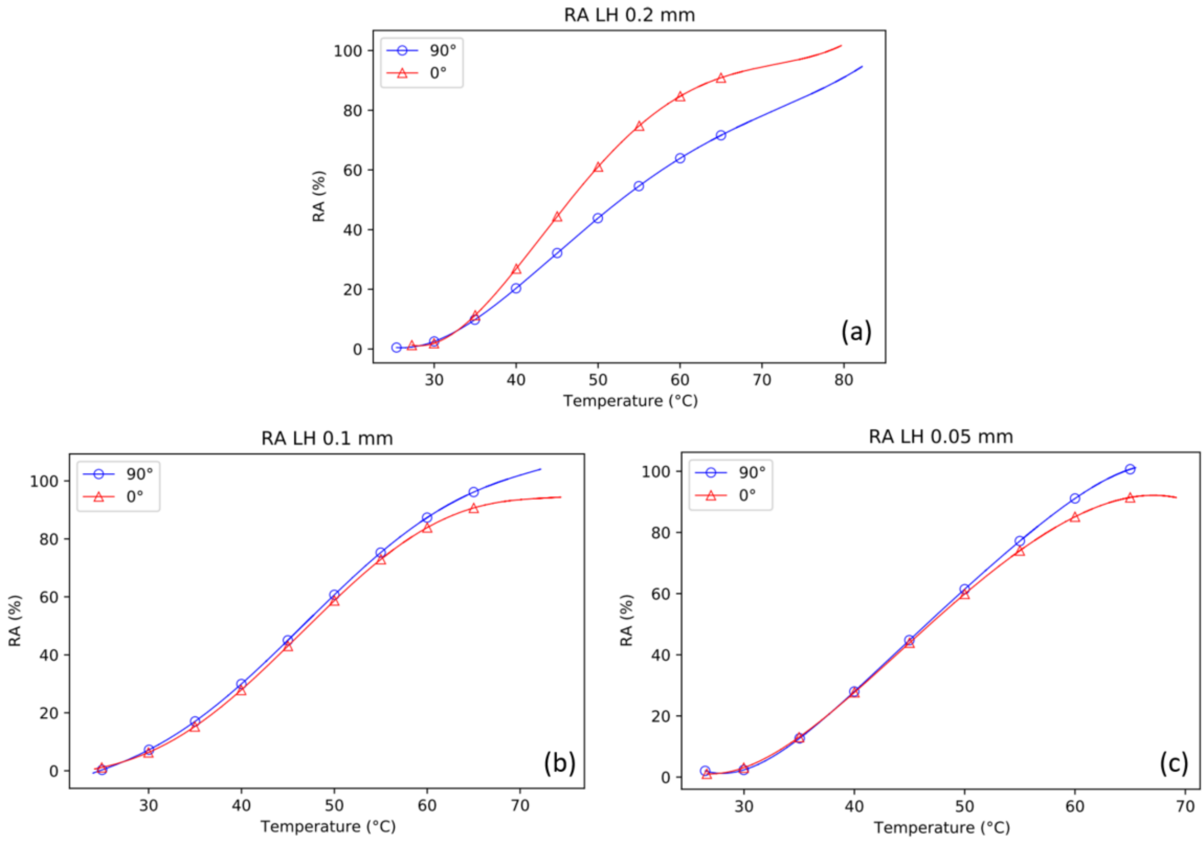

Figure 6: RA (%) of the samples printed at a layer height of (a) 0.2 mm, (b) 0.1 mm & (c) 0.05 mm

3.3 Oven heating

The oven heating experiment shows that samples printed at 90° have the same offset as the samples heated by joule effect, especially after 50°C as show in fig. 7 (a). In an other hand, AR of 0° the samples (Fig. 7 (b)) are the same between 0.1mm and 0.2 mm layer height while the 0.05 mm layer height behaves differently once 50°C is reached.

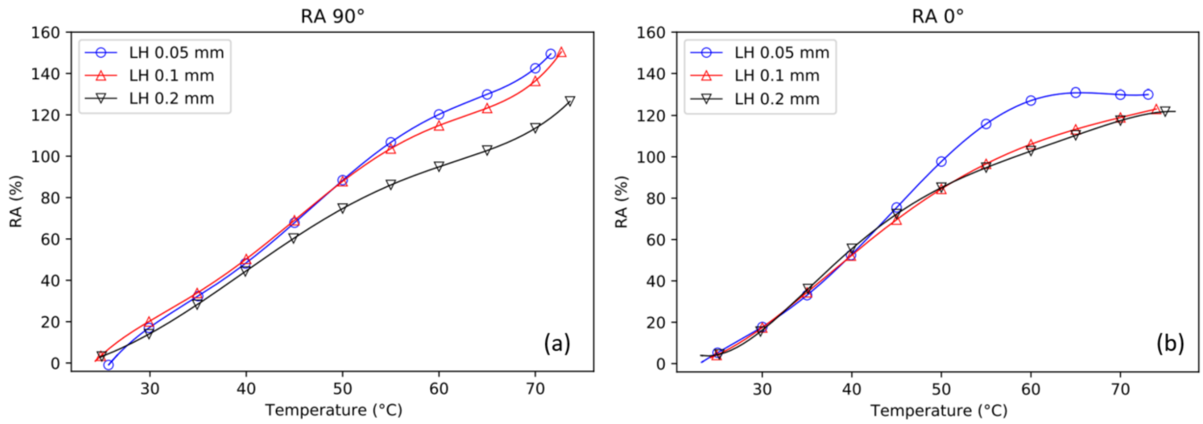

Figure 7: RA (%) oven heating sample printed at (a) 90° & (b) 0°

Globally the samples heated in the oven have a bigger increase of resistance. The comparison of Joule heating and oven heating for the samples printed at 90° illustrates the fact that samples with this printing angle configuration have an offset and behave differently depending on the heating technique (Fig. 8 (a)). Fig. 8 (b) shows how reliable samples printed at 0° are. AR is higher when samples are heated in the oven, and apart from the 0.05 mm layer height samples, the result are quite similar. For the same temperature, an external source of heat has a more influence on theresistance (electrical sensitivity). The self-heating behaviour due to joule effect allows for an homogenised source of heat, whereas an external heat source such as convection oven create a temperature gradient, locally allowing for more micro-displacements of conductive particles when compared to joule heating.

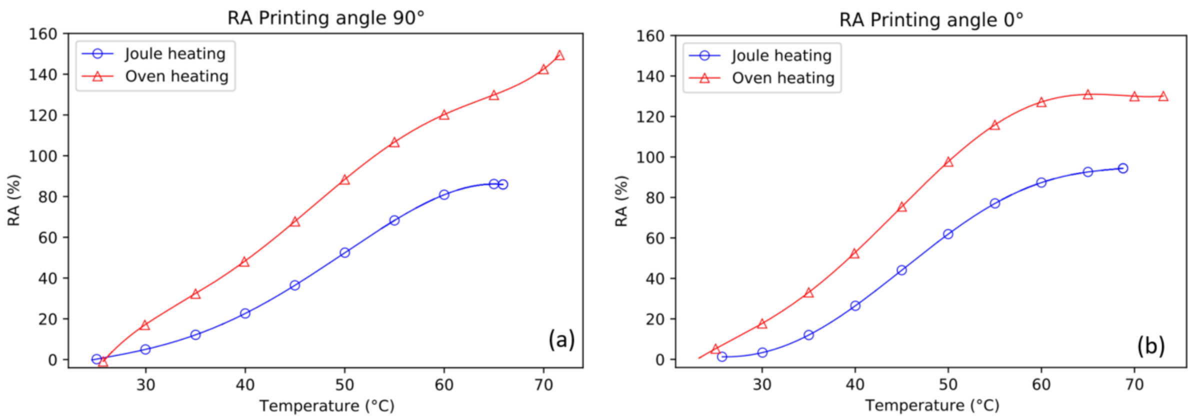

Figure 8: oven heating & Joule heating samples printed at (a) 90° & (b) 0°

4. CONCLUSIONS

In this study the dependency of electrical properties of a 3D printed PLA component with different processing parameters (printing orientation and layer height) have been analysed. The layer height parameter has an effect on the resistance evolution. Indeed when samples are printed at 0 degrees the resistance evolves the same regardless of the layer heights. Nevertheless samples printed at 90 degrees present an offset between the layer height of 0.2mm and the others. In addition when samples are heated by an external source, the same behavior is observed between the different layer heights.

The printing angle parameter has also an influence on the evolution of the resistance as large differences between the longitudinal and the transverse direction for the 0.2 mm layer height samples have been found. However, similar behavior between the two directions are found in 0.05 mm and 0.1 mm layer height up to 60°C The results should be further analyzed especiallyregarding the porosity and electric paths. Further experiments need to be carried on to determine how they affect the electrical properties.

The heating technique analysis illustrates that an external source is increasing the resistance faster than the self-heating. The first hypothesis is the particles move differently when a current go through them and modify the percolation of the particles.

5. ACKNOWLEDGEMENTS

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