International Journal of 3D Printing Technologies and Dijital Industry
Uluslararasi 3B Yazici Teknolojileri ve Dijital Endüstri Dergisi

EFFECT OF TEMPERATURE ON CONDUCTIVITY OF PLA-CARBON 3D PRINTED COMPONENTS

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ABSTRACT

There is continued growth in 3D print technology utilising thermoplastic materials that include polylactic acid (PLA) to print components of systems. The electrical properties of 3D printed thermoplastic components are critical because the product's conductivity is temperature dependent owing to the kinetics of breakage and reformation of their aggregated structure. This knowledge drives research to make 3D printed components more functional in terms of their electrical properties in addition to their mechanical properties. This research studies the effect of temperature on the conductivity of 3D printed components. The range of temperature T considered is $22\ ^{\circ}\mathrm{C} \leq T \leq 55^{\circ}\mathrm{C}$. A conductive 3D print filament made of PLA and filled with 4% carbon black is printed using Fused Deposition Modelling (FDM). The layer height and infill ratio are varied while the material resistivity ρ is measured as a function of temperature change. The measured magnitudes of resistivity lies in the range of $29.38\ \Omega \leq \rho \leq 6750\ \Omega$. The ρ is found to be a parabolic function of T – depicting an increase to a maximum and subsequent decrease. The parabolic nature of the ρ function is most visible in sample 1 which demonstrates an absolute change in ρ of 26%. The sample consisting of 50% infill ratio and 0.2 mm layer thickness (STDev 0.446) demonstrates least response to variations in temperature with the range investigated. This investigation reports on the significance of processing variables of FDM on the thermal sensitivity of conductive 3D printed Components.

Keywords: Temperature, PLA, Conductive

1. INTRODUCTION

Thermoplastics are usually electrical insulators however the addition of conductive fillers can make a conductive composite, used in electrical systems and electronic devices. These composites are highly flexible due to the ability to vary resistivity with conductive filler concentration.

Thermoplastics are generally soft (Shore A - Shore D) workable materials available at low cost. In order to exploit the workability of thermoplastics needed for 3D printing conductive fillers such as carbon can be added. As a result, their conductivity increases hence their electrical resistance decreases. Through this method the electrical volume resistivity of PE, for example, can be reduced from 10^{16} ohms to < 10^{6} ohms [1]. The addition of carbon however tends to significantly increase the hardness and inhibit elastic movement of polymer [2].

Significant work has been performed to develop functional conductive plastics using carbon fillers. Adjustment in matrix material, carbon type, carbon particle size, additives and wall thickness all vary the electrical properties of the final blend. Carbon black (CB) is the most commonly blended filler material (compared with other carbon additives e.g. graphite or carbon nanotubes). CB often has better compatibility with the thermoplastic matrix and is easier to process. The conductivity of a polymer filled with carbon black does not increase proportionally with the carbon black concentration. Up to a given filler level the resistance decreases only slightly until the percolation zone is reached. In this region the resistance falls strongly for only small increases in concentration. At concentrations above the percolation zone the resistance approaches that of the pure additive [1].

Most conductive materials change resistivity with changes in temperature, this is why figures of specific resistance are always specified at a standard temperature (usually 25˚C). The thermo-electric response of CB doped polymers has been well studied [3]. Resistivity of thermoplastic-carbon blends have also been shown to be sensitive to temperature. Zhang et.al. demonstrated the temperature sensitivity of UHMW Polyethylene and the effect filler percentage has on the measured results as shown in Figure 1 [5].

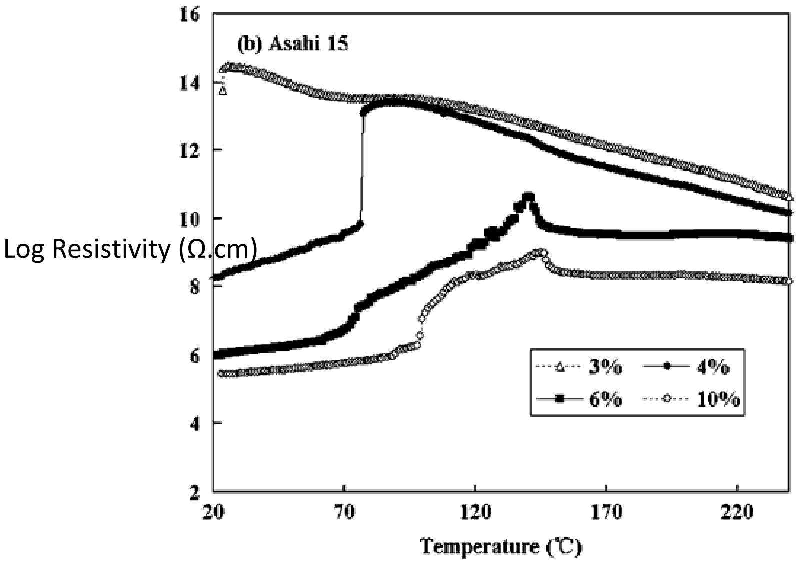

Figure 1. Response for UHMWPE with varying CB% (Zhang, 2005).

The resistive response to carbon filling and substrate is both complex and variable in nature. The variables selected can significantly alter the resistive response of a material with changing temperature as illustrated by Zhang [5]. Carbon black is non-ohmic and its response to thermal change can be highly variable. Lower temperatures have been explored by Poulaert [6] who shows that there is little change in and around room temperature but as samples are cooled more significantly resistivity can increase. Klason [7] shows positive thermal coefficient up to the melting point in Carbon Black filled LDPE and HDPE. Generally conductors increase their resistance with an increase in temperature. Insulators however are liable to decrease their resistance with an increase in temperature. The effect of temperature on electrical resistivity in carbon black doped thermoplastics gives a positive temperature coefficient due the kinetics of breaking and reformation of the carbon black aggregated structure [8].

The desire to manufacture functional 3D parts has led to the development of a number of thermoplastic-carbon blend conductive filaments. In this study, we use the Fused Deposition Modelling (FDM) 3D printing technique. FDM machines work by extruding a thermoplastic filament through a heated nozzle onto a build platform. The printed filament network cools and adheres to the previously deposited layers to build up a solid 3D object [9].

For many sensing applications temperature stability is vital, this study will therefore explore the impact FDM variables have on material resistivity.

2. MATERIALS & METHOD

2.1. Printing of conductive PLA

3D printed specimens were prepared on an IdeaWerk 06131 FDM printer. Figure 2 shows the 3D printer printing a tab used as samples in this study. 1.75mm carbon black filled (4%) PLA filament is used. The fixed parameters were honeycomb pattern, nozzle diameter 1mm and nozzle temperature 230˚C. Layer height is varied to explore the effect of the binding interface on thermal sensitivity. Table 1 shows the variable input parameters. Sample dimensions are 50x10x4mm rectangular tab samples. Sample surfaces are smoothed post printing to ensure a good contact is made when heating and monitoring resistivity.

Table 1. Test sample print conditions

Sample ID	Print variables
S1	100% infill, 0.2mm layer thickness
S2	50% infill, 0.2mm layer thickness
S3	50% infill, 0.4mm layer thickness
S4	100% infill, 0.4mm layer thickness

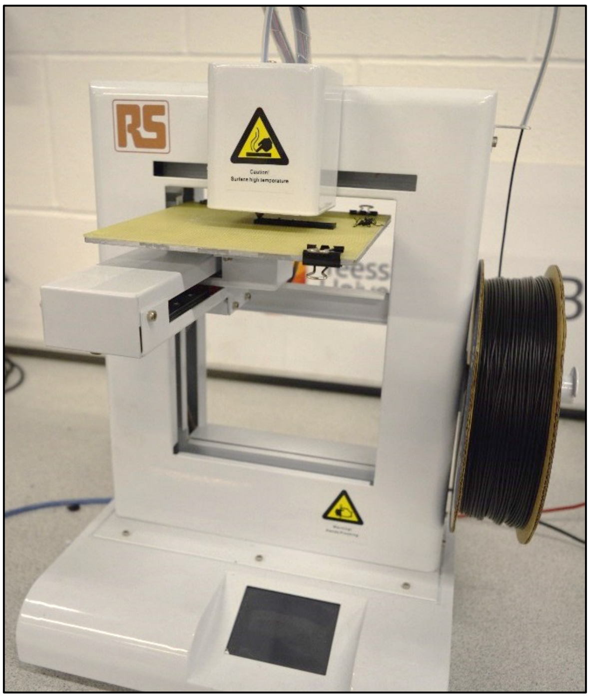

Figure 2. FDM build platform.

2.2. Experimentation

The test method employed to measure dR/dT through the polymer samples is shown in Figure 3. The polymer samples are printed as 50x10x4mm rectangular tabs. These are connected to the two electrical probes to create a circuit and a K-Type thermocouple attached to the specimen centre (RS Pro -50 to +1100 °C 2000mm Cable K Type Thermocouple). Heating is achieved with a 28V film type heater (KHLV Series, Rectangular, 28 Volts KHLV-0502). A 300Ω resistor is placed into the circuit and millivolt readings taken across it. This allows for the direct measurement of voltage change in the material.

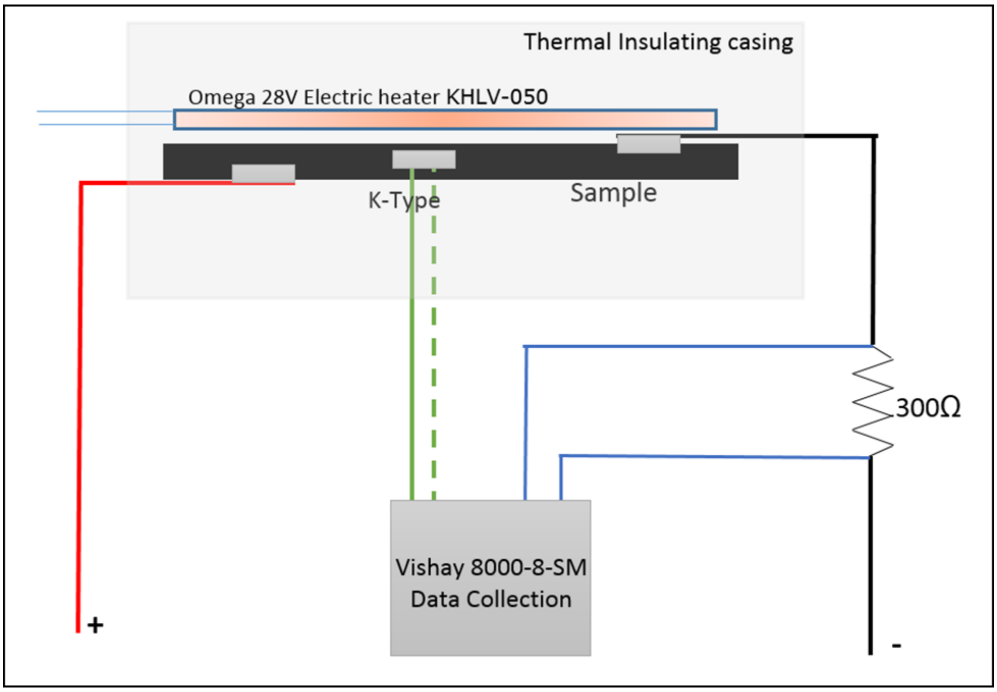

Figure 3. Test arrangement.

All data is collected with a MM 8000 data collection box (Micro measurements 8000-8-SM) running strain smart software at 1000Hz data collection. Power is supplied through a DC power supply (Diginess DC power supply SM5020).

3. EXPERIMENTAL RESULTS

Results for all samples tracking change in resistivity (Ohms) over change in temperature (˚C) (dr/dt) are show in Figures 2 and 3. All samples show a parabolic change resistivity as a function of temperature.

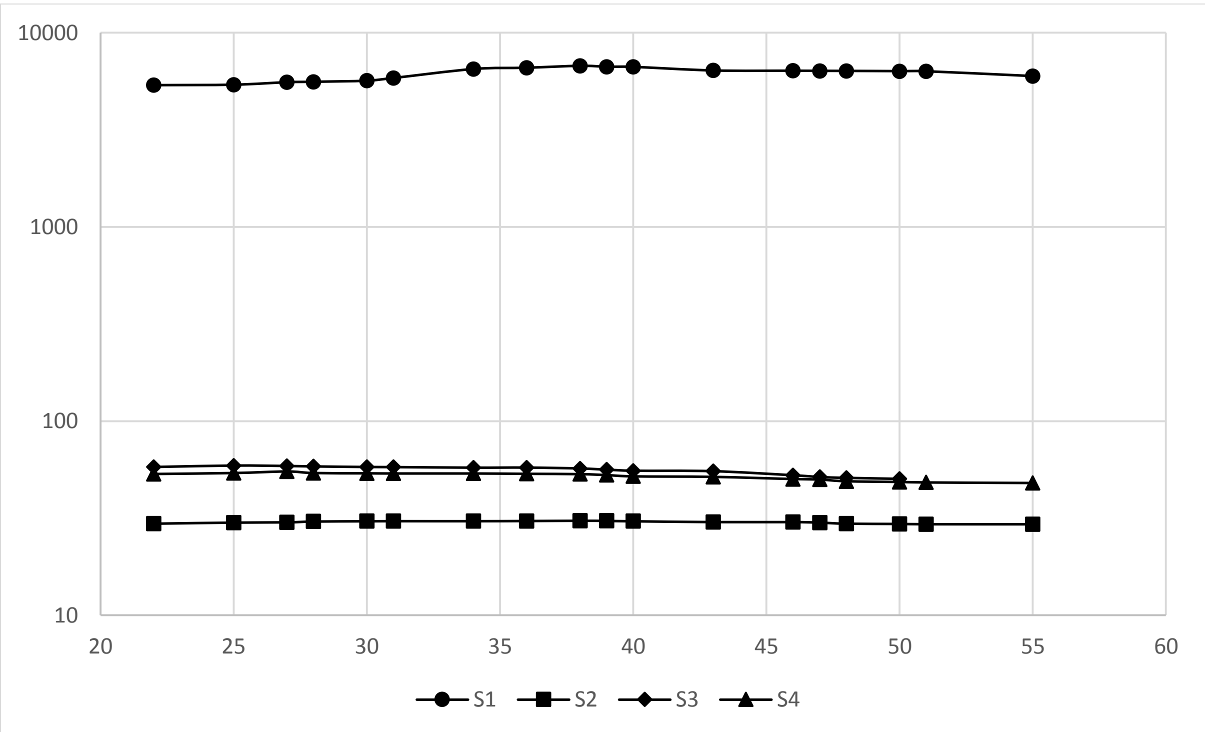

Figure 4. dr/dt for samples 1 to 4.

4. DISCUSSION AND CONCLUSIONS

Three-dimensional (3D) printing of functional components using conductive fillers presents significant opportunities to the development of novel sensors. This study shows that filled PLA conductive FDM 3D printed components demonstrates resistivity that is a function of temperature. A method is developed and employed to measure dr/dt for a range of FDM print variables. All samples investigated produce resistivity magnitudes that increase from 22°C to a maximum at the range of 30 °C to 40 °C and subsequently decrease. The parabolic nature of the resistivity function is most visible in test vehicle 1 which demonstrates an absolute change in resistivity of 26%. The kinetics of breakage and reformation of the carbon black aggregated structure causes the initial positive coefficient. The observation is reported by Wack [8]. The influence of infill ratio is difficult to determine from the current study. Therefore, further investigation is required to map clear trends. Layer height in samples 2 & 3 shows inverse behaviour to samples 1 & 4. The combination of layer height and infill ratio combine to contribute to conductive sensitivity of filled FDM prototypes. A 50% infill ratio with 0.2mm layer thickness provides the most stable conductive material across a range of temperatures (STDev 0.446). Further work is required to define fully the relationship between FDM processing properties and the thermal sensitivity of printed prototypes. The accurate definition and prediction of these variables will be critical to the future of thermoplastic 3D printed conductive sensors.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Steven Dearlove for his contributions to characterisation and qualification of the material.

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