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Characterization of Electrical Properties of Direct Ink Written Silver Ink

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Summary:
Direct-Ink Written Silver-ink traces on top of thermoplastic polyurethane substrates produced by Fused-Filament-Fabrication were characterized in terms of electrical - and piezo resistivity. Low resistivity in the order of 52.8 µΩ cm was achieved with piezoresistive strain response being limited to strains below 1 % as a result of crack formation. Silver-ink traces are therefore deemed most suitable for interconnects.
Keywords: 3D Printed Sensors, Fused Deposition Modelling, Direct-ink writing, Silver ink, Strain gauge

Introduction

Multi material (MM) fused filament fabrication (FFF), with electrically conductive materials has shown potential in fabricating and integrating sensing mechanisms within a given structure [1]. FFF compatible thermoplastics doped with conductive particles are known to result in relatively high electrical resistivity and high anisotropy across traxels (track-elements) [2]. In direct-ink writing (DIW), a liquid ink with specific rheological properties [3] is extruded through a nozzle. Post printing, traces are cured by either heat or a UV treatment. Due to the layers not being fully solidified during the printing of subsequent layers, the inter-layer resistance will be comparable to the in-layer resistance and low anisotropy can be achieved [4].

In this work, silver ink (CI-1036 [5]) was characterized for use as interconnect as well as a piezoresistive sensor. This was achieved through analysis of its resistivity and the dependance thereof upon strain.

Theory

The volumetric resistivity of a material measured from a prismatic structure is given by eq. (1). ρ is resistivity in Ω m, R resistance in Ω, A area in m^2, and l the sample length in m.

$$\rho = \frac{R \cdot A}{l} \tag{1}$$

To ensure the validity of this formulation contact resistances have to be accounted for during measurement. This will be achieved with the use of the transfer length method (TLM) [6].

Design & Fabrication

Figure 1 provides the design for characterization of the resistivity. The side pads are used for current injection, the three contract pads (red) at the top can be used for 4 point measurements. Three separate measurements were performed across varying lengths of; 8.5 mm, 12 mm and 20.5 mm. For the characterization of the piezoresistivity, only the two side pads were included in the samples to be used as contact.

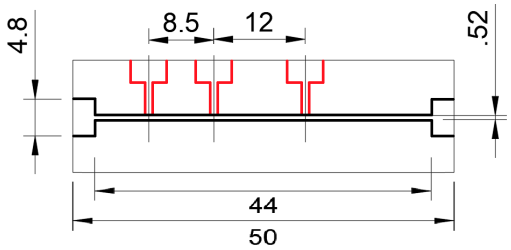

Fig. 1. Sample (black: strain, black&red: TLM)

Printing was performed on a Diabase H4 Pro MM 3D printer modified with an additional ViscoTec vipro-head 3 toolhead. This allows for both AM techniques to be performed intermittently, integrating silver-ink layers into the FFF structure. Post printing a thermal curing step was performed for 10 minutes at 120 °C in a convection oven (Memmert UF30) accelerating the evaporation of the ink solvent. All features were printed at a 100 % infill, with the substrate consisting of NinjaFlex TPU being printed at 220 °C and print speed of 25 mm s^{-1}. The silver-ink was deposited at a print speed of 4 mm s^{-1} at a layer height of 0.2 mm and a width of 0.514 mm.

Experimental Setup

Samples were clamped and mechanically loaded by a linear actuator (SMAC LCA25-050) operating under force control (figure 2). Piezore-

sistivity was evaluated by loading with a sine of 3 N amplitude at a frequency of 0.2 Hz. The resistance was measured through a micro-ohm meter (Keysight 34420A) at a sample frequency of 100 Hz.

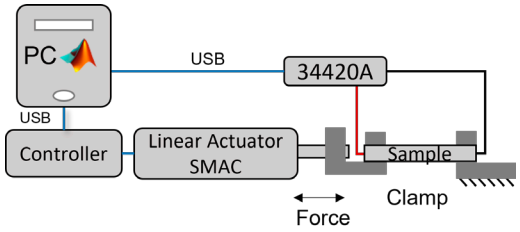

Fig. 2. Experimental measurement setup. (Blue: data transfer, red & black: 2-wire resistance measurement)

Results

Fabrication: Samples were manufactured by deposition of two layers of silver ink. Shrinkage was determined to be in the range of 70% after thermal curing, inline with the ink filler content of 66% [5].

Resistivity: Figure 3 shows the resistance as derived from the TLM method. Contact resistance was found to be in the order of 10.0 mΩ whilst providing a volume resistivity of 52.8 µΩ cm accounting for the volume shrinkage.

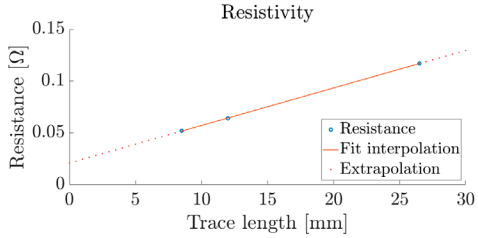

Fig. 3. Resistivity characterization

Piezoresistivity: Figure 5 and 4 show the response of the double ink layer sample to a sinusoidal force. Significant drift is observed in sensor resistance after repeated straining.

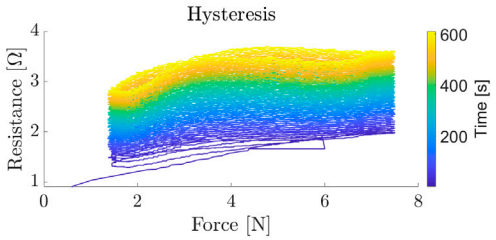

Fig. 4. Resistance vs force (2-layers)

A single cycle shows a reduction in sensitivity past ≈3.5 N, suggesting micro-crack formation in the silver ink. This crack formation was more

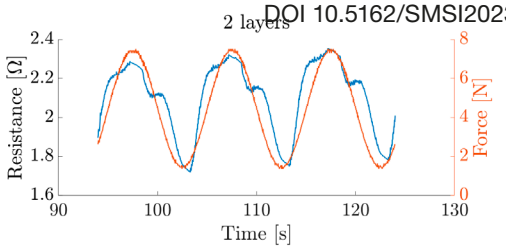

Fig. 5. Sinusoidal loading of (2-layer)

stongly observed for samples with a single layer of silver ink, as shown by figure 6.

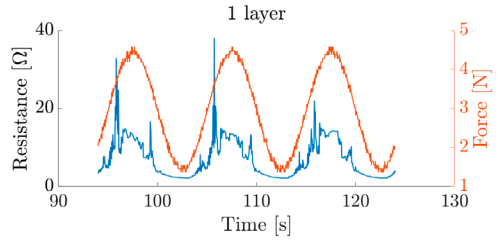

Fig. 6. Sinusoidal loading of (1-layer)

Discussion and Conclusions

In this work the application of printable silver-ink on top of a printed TPU substrate as a piezoelectric sensor was investigated. The silver-ink was shown to exhibit excellent electrical conductivity and a moderate resistance to strain, resulting from crack formation in the ink. Approximately linear strain sensing was found to be limited to 1%, resulting in a Gauge factor of 233. Modifying the design to only employ compressive strain of the silver ink might potentially extend this range.

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