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Abstract

This study presents a novel electrical connection strategy for additive manufactured electronics and sensors. The conductive polymer layer was printed directly on a metal surface using fused filament fabrication. This eliminating intermediate bonding steps and post processing effort for electrical connecting printed structures. Contact resistance was characterized through electrical measurement of different 3-D-printed samples. This direct deposition strategy establishes robust interfacial connections between conductive polymers and metal substrates while eliminating printing process interruptions and post-processing complexity. The approach demonstrates significant potential for advancing additively manufactured electronics, printed sensor systems, and integrated electronic devices.

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Direct 3-D Printing of Conductive Polymers on Metal Sheets: A Novel Electrical Connection Strategy

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Summary: This study presents a novel electrical connection strategy for additive manufactured electronics and sensors. The conductive polymer layer was printed directly on a metal surface using fused filament fabrication. This eliminating intermediate bonding steps and post processing effort for electrical connecting printed structures. Contact resistance was characterized through electrical measurement of different 3-D-printed samples. This direct deposition strategy establishes robust interfacial connections between conductive polymers and metal substrates while eliminating printing process interruptions and post-processing complexity. The approach demonstrates significant potential for advancing additively manufactured electronics, printed sensor systems, and integrated electronic devices.

Keywords: Additive manufacturing, electrical connection, printed electronics, conductive polymers, contact resistance.

Motivation

The integration of 3-D-printed conductive elements with conventional electronics raises significant challenges. The bulk resistance is typically low enough to be neglected under low-current conditions for metals. However, the contact between a conducting polymer and a metal is expected to be significantly more resistive [1]. Current methods for establishing electrical connections between additive manufactured parts and traditional electronic components vary widely in their approaches.

One approach is to rely on mechanical pressure to establish contact between the polymer and a metal component, such as a screw or an alligator clip. A stainless steel screw has been used in [1], but such contacts can suffer from mechanical instabilities that cause variations in electrical contact resistance, leading to increased noise or irreproducible measurements. Surface roughness further compromises mechanical electrical contact. Conductive silver ink can be applied to the printed structures to establish a better electrical contact surface [2]. Another method with silver ink is to glue copper pads next to the printed conductive polymer. Connecting wires to the copper pads. Then, the copper and polymer pads are coated with conductive silver ink creating the electrical connection [3], [4], [5]. The manual application causes variability in thickness and coverage, which compromises reproducibility. Furthermore, application to intricate geometries remains challenging.

The surface roughness can also be improved using an ironing. This involves a hot nozzle going over the printed surface with finer line spacing to melt the surface and fill in the gaps [6]. Also manual surface heat treatment creating a smoother finish [7]. This still depends on post printing connections.

Melting the polymer to connect it with the metal increases the effective contact area and lowers the electrical contact resistance. Embedding a copper wire into the electrode body during 3-D printing represents an implementation of this approach [8], [9]. This method necessitates manual wire insertion during printing interruption, introducing assembly variability that affects reproducibility. Post-printing soldering of components onto 3-D-printed conductive substrates is feasible as shown in [10]. This technique exhibits low reproducibility and is recommended exclusively for rapid prototyping of individual structures.

Electrical connection Strategy

In this study, we introduce a novel electrical connection strategy that leverages direct deposition of conductive polymer onto metal substrates during fused filament fabrication (FFF), eliminating additional connecting methods.

The conductive polymer layer is printed directly on a metal surface using FFF. The process is automated by the 3-D printer and no manual intervention is necessary. This eliminates intermediate bonding steps and post processing effort for electrical connecting printed structures. Only a previous adjustment to the printing bed is necessary. The metal plates must be secured to the printing bed. This was done using magnets, but other detachable connection are viable. The resulting offset in z-direction due to the metal thickness can be corrected by the 3-D printer, through print bed calibration before each print. Otherwise, a manual correction is needed before printing.

The first layer has the smoothest surface, resulting in a larger contact area. Molten polymer fills substrate surface irregularities. In addition, preheating of the print bed further enhances interfacial adhesion compared to mid-process plate insertion.

Material and Methods

Test samples were designed to validate the concept (see Fig. 1). The shape consists of two inclined legs forming an A-frame, connected by a horizontal top bar. The 60 ° angle enables production without support structures. Each leg ends on a flat rectangular base plate at the bottom, for improved surface area and better bonding to the print bed. The geometric dimensions of the base plates are 7 mm in width, 7 mm in length, and 0.4 mm in thickness, respectively. The cross-section of the inclined legs is rectangular with 9 mm^2 area size. The samples are printed with conductive PLA (Proto-pasta). They were manufactured using a Prusa MK4S printer with 0.2 mm layer height and 100 % infill. The print bed was covered by two copper plates. The z-direction offset resulting from metal thickness was automatically compensated via print bed leveling prior to each print job. This eliminates potential print bed calibration errors associated with manual processing. A small gap between the plates provides electrical isolation between them.

The print bed temperature for the first layer was increased from 60 °C to 100 °C. At 60 °C, the material exhibited poor adhesion to the metal substrate, whereas 100 °C ensured robust bonding.

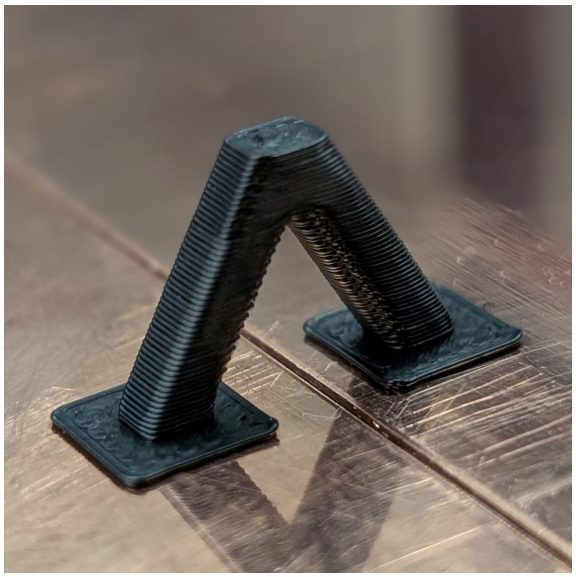

Fig. 1: Direct 3-D-printed resistor sample: conductive polymer deposited directly onto a metal substrate to form an electrically connected structure.

Experimental setup

We used a four-wire measurement setup to determine the samples resistance. In this configuration two force wires deliver a constant current trough the samples. The other two wires measure the voltage alongside the sample. This separation eliminates errors from the wire and contact resistance of the voltage sensing wires. For a statistically significant result, 500 measurements were taken with an Keithley 2450 SourceMeter, and the mean values were calculated. Three different measurements were conducted were the sensing wires had various measuring positions. The measuring positions are shown in Fig. 2. The force wires were connected to the copper plates at position 0 and 5. The total resistance of a sample were measured at position 1 and 4, further referred to as R_{14}. To calculate the contact resistance R_{12} and R_{34} between the copper and the 3-D-printed part the resistance R_{13} and R_{24} were measured and subtracted from R_{14}.

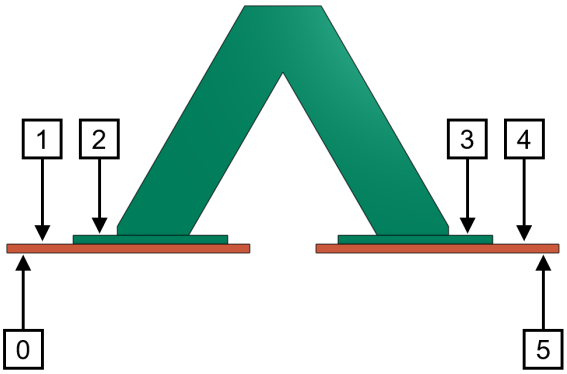

Fig. 2: Sample showing marked positions for electrical measurements.

Results and Discussion

We tested the samples in an experimental setup. The standard deviation of the measured values ranges from 5 mΩ to 17 mΩ. The electrical resistance among the five samples is similar but not the same, as Fig. 3 shows. The five samples R_{14} value exhibits a range 23.09 Ω with a mean resistance of 487.96 Ω. The resistance range compared to the mean resistance is 4.73 %. This behavior could depend on a not uniform electrical resistance in the raw filament before being melted together. The inhomogeneity of the conductive particle in the filament creating irregular conductive paths. This is also reported in other literature [3], [11].

Figure 4 shows the contact resistance R_{12} for the five samples. The values span from 0.21 Ω (Sample 3) to 1.19 Ω (Sample 2), with a mean of 0.76 Ω. The range of 0.98 Ω reflects consistent contact quality, comparable to R_{34} measurements despite slightly higher variability.

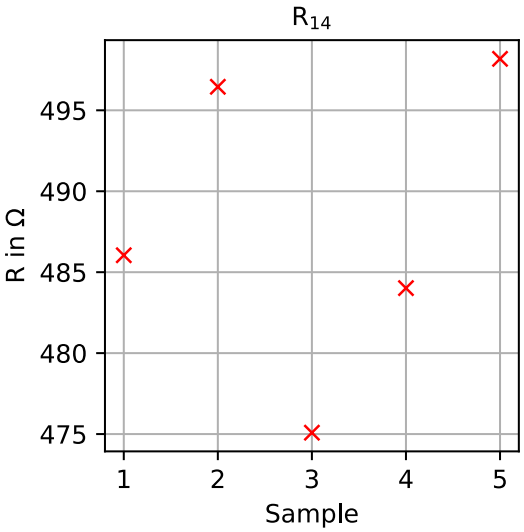

Fig. 3: Measured total mean resistance R_{14} of five samples.

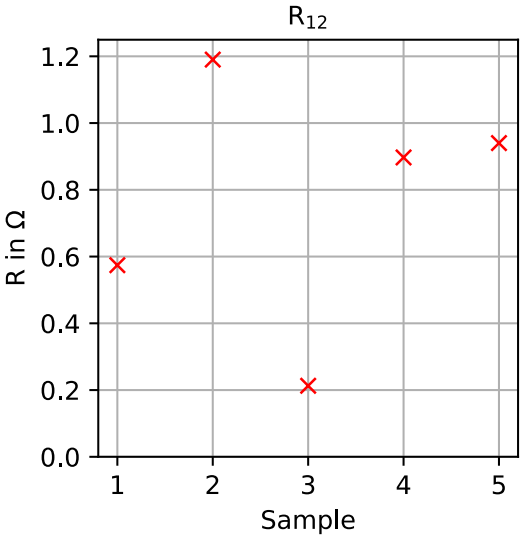

Fig. 4: Mean resistance R_{12} of five samples.

Figure 5 presents the resistance R_{34} for the five samples. The values span from 0.13 Ω (Sample 3) to 0.71 Ω (Sample 4), with a mean of 0.54 Ω. The majority of samples cluster tightly between 0.57 Ω to 0.71 Ω, while Sample 3 exhibits notably lower resistance, potentially attributable to superior electrode-surface bonding or printing uniformity.

The resistance R_{12} and R_{34} consists of the contact resistance between copper and polymer as well as the resistance of the 3-D-printed base plate part. It is not possible to determine the contact resistance exactly, but it should be lower than 1.19 Ω. The low range of 0.98 Ω for R_{12} and 0.59 Ω for R_{34} across the samples indicates reproducibility of the 3-D-printed electrode contacts, consistent with the overall resistance measurement. The difference may due to the two copper plates geometrical variation or surface quality.

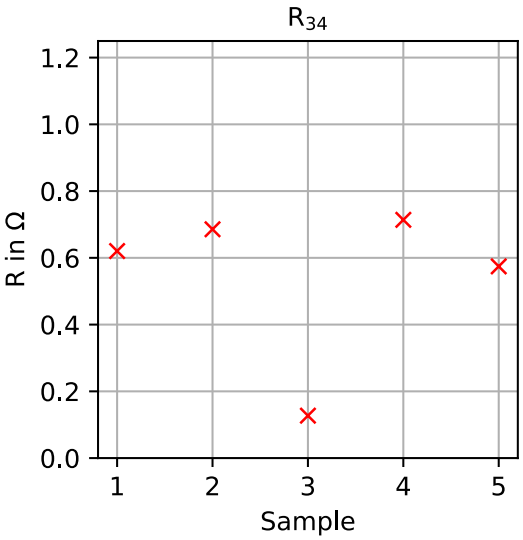

Fig. 5: Mean resistance R_{34} of five samples.

Conclusion

We demonstrated a novel connection strategy for 3-D-printed electronics. Fully 3-D-printed resistors have been fabricated using this new approach and evaluated. This method, using a conductive metal sheet as print beds in combination with printed conductive polymers, opens up new design possibilities and enables fully additive one-shot electronics manufacturing, without mid- or post-process connection. The concept can be easily scaled and adapted for a wide range of printed electronics. The measurement results indicate a reproductive contact resistance lower than 1.19 Ω.

Future work

The influence of printing parameters on the electrical connection quality, along with the thermal behavior of various print bed materials, could be investigated in future research. The full integration of the proposed connection strategy into the FFF-printing process represents a key direction. Specifically, a modified print bed configuration, featuring cut-outs to securely position the copper plates is anticipated (see Fig. 6). This adaptation enables seamless process integration and supports the scalability of the approach for industrial additive manufacturing applications. Such enhancements are expected to yield a fully practical connection methodology compatible with standard FFF workflows.

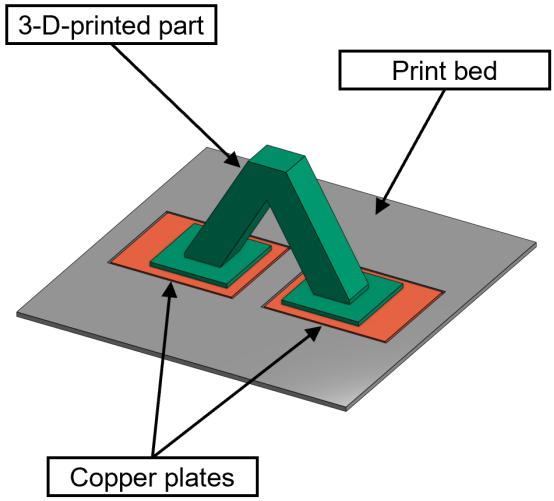

Fig. 6: Future integration in FFF-printing process with modified print bed.

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