3D Printed Interconnects on Bendable Substrates for 3D Circuits

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I. Summary And Motivation

3D printing systems are expanding to realising fully embedded, multi-purpose, out-of-plane circuits. It is possible to utilise the characteristics of 3D printing to produce customisable, complex and bendable 3D structures and sensors that go beyond the use of standard polymer materials used with the current technology. With multi-material 3D printing, the additive manufacturing could be advanced to produce fully embedded sensors and electronic systems that cannot be otherwise produced in a one-step automated process. Our goals are concentrated towards embedding sensing circuits into next generation prosthetics and robotic arms for more advanced and smoother operation. These devices, along with other similar interests such as healthcare wearable devices, will inevitably include moving parts. Therefore, the embedded printed connections and readout circuits should withstand the repeatable bending of the robotic phalanges or sensing devices without degrading in performance or showing any cracks.

In this work, a flexible substrate was developed using a flexible polymer, commercially known as NinjaFlex (TPU), employing 3D printing techniques. The bendable substrate was first fabricated with the 3D printer and then the conductive materials were printed in the designed grooves or tracks on the printed bendable substrate. Two different conductive materials (Electrifi conductive filament and an in-house formulated, graphite-based conductive ink) were employed for the printing of the flexible connections. The conductive filament was in solid state and was deposited using fused deposition modelling just like the substrate polymers. However, the ink was deposited in solution phase followed by drying. Both conductive materials experienced reasonable printability but did, however, show cracks in the tracks post printing. Both materials achieved the goal of maintaining electrical conductivity during bending. They also exhibited an increase in resistance in the bent state.

II. Advances over Previous Works

Many different wings of flexible and wearable electronics are expanding rapidly as this can provide solutions to many real-time monitoring applications. Flexible electronics are emerging in a variety of applications in the fields of wearable, flexible, and large area electronic systems providing sensors for healthcare, sports, and biomedical applications [1]. However, the basic need for all these devices to work is to develop flexible and wearable interconnects with a vision to implant them in wearable devices. Moreover, recent developments in prosthetic and robotic technologies, such as robotic arms, also require bendable electrodes and interconnects for smooth and reliable operation [2].

Electronic technological development is now moving towards wearable and flexible technologies [3]. Many researches have reported wearable and flexible sensors and devices in the past few decades [4]. In this line, flexible interconnects are currently one of the most interesting areas of research in the field of flexible electronics [1]. Flexible interconnects have been employed in many devices for a large variety of applications such as, sensing, neural interfacing, and healthcare using different techniques [5]–[7]. The reason for developing flexible interconnect is to reduce the exhibited thermo-mechanical stress and enhance the reliability of flexible electronic systems. Flexible interconnects provide the liberty to use them on the same substrate as the flexible sensors and circuits and provide benefit in terms of low energy consumption and lower cost [8]. However, it is important to understand the bending effects on printed flexible electrodes and interconnects with higher dimensions on bendable substrates.

Embedded 3D printed circuits, that cannot otherwise be produced in any other way, is an emerging next-generation topic in the fields of manufacturing and rapid prototyping [9]–[12]. However, it is still at its infancy and the examples produced by groups so far have generally focussed on planar, non-moving circuitry. This paper proposes to extend the functionality of 3D printed devices to include multi-material bendable structures [13]. With regards to the materials used, several filaments [14]–[17] and inks [18]–[20] have been developed to drive this fabrication method. This paper will build on that knowledge and suggest new solutions in this

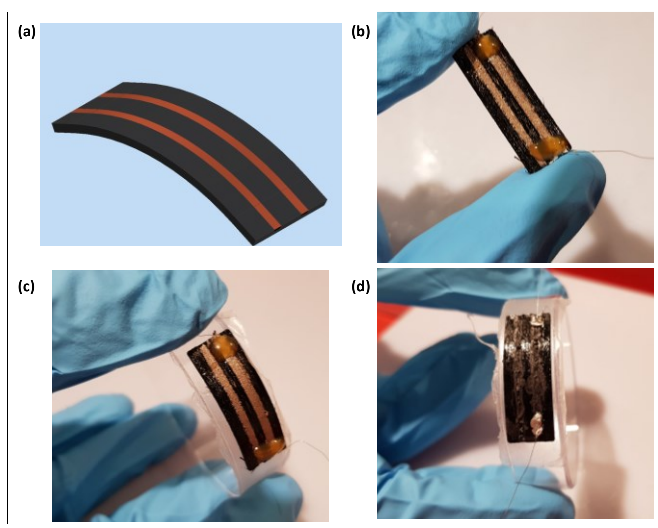

Fig. 1: (a) CAD design, and the images of the flexible interconnects; (b) planar Electrifi on NinjaFlex; (c) bent Electrifi on NinjaFlex; (d) bent graphite ink on NinjaFlex.

regard. In this direction, our recent work [13] demonstrated a 3D printed smart bendable structure for sensing applications. However, the present work illustrates an advancement towards the development of interconnects on more bendable substrates using a different ink and conductive filament.

In this paper, the fabrication of a flexible substrate having flexible interconnects deposited on top of it during the same 3D printing process is suggested. The design and fabrication of the flexible substrate are discussed along with the characteristics of the printed conductive ink and filament. A comparative study was performed to understand the optimised printing settings and material properties along with the effect of bending providing an initial study and baseline for this work. This study will help develop flexible electrodes and interconnects for a variety of sensors and devices. The work also illustrates a possible 3D printing system to realise fully embedded, multi-purpose out-of-plane circuits with a vison of developing sensing circuits for robotic and wearable applications.

III. Results and Discussion

A. Materials: The polymer used as the substrates was NinjaFlex (NinjaTek, USA) which is made from thermoplastic polyurethane (TPU). The flexible conductive polymer Electrifi (Multi 3D, USA) is a metal-polymer composite consisting primarily of a biodegradable polyester and copper. The graphite-based conductive ink was formulated in-house.

B. Preparation of conductive ink: The graphite-based conductive, 3D printable ink was formulated in an organic solvent-based formulation technique. Based on previous knowledge regarding the effect of the solvent on the printability of the ink, isopropyl alcohol was used for the formulation. In a typical process, 35% of graphite powder was dispersed in the solvent with continuous stirring. To achieve a better dispersion of the graphite powder in the solvent, 10% of Triton X-100 was used as a dispersant. The binder used for the present formulation was ethyl cellulose (10%). The whole mixture is stirred continuously overnight to get a well deflocculated ink.

C. Preparation of flexible substrates: The polymer substrate was heated in an oven at 70°C for 45 minutes prior to printing. This is to rid the filament of the moisture it absorbs from the air

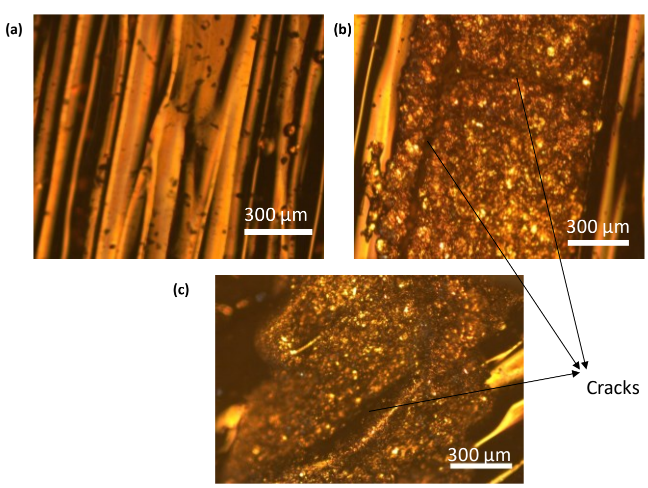

Fig. 2: Optical microscope images of the (a) flexible substrate, and the conductive tracks on the printed flexible substrates: (b) Electrifi on NinjaFlex, (c) graphite-IPA on NinjaFlex.

Table 1 Variation of the resistance of the conductive materials with bending on NinjaFlex

Material	Resistance (Ω)	Resistance while bending (radius of curvature 27mm) (Ω)
Electrifi filament on NinjaFlex	2.5M	4.5M
Graphite ink on NinjaFlex	4.3k	5.8k

and allow for a higher quality print. Fig. 1 shows the CAD design and images of fabricated interconnects on the substrate.

D. Printing methodology: To print these materials, a standard desktop FDM printer was used (RepRap Pro Ormerod 2) which was also fitted with an extension (Discov3ry Paste Extruder) for the printing of the conductive inks. For the prints that involved the copper filament, a different dual-head FDM printer was used (Ultimaker S5). All of the conductive tracks were printed in the same dimensions (30mm x 1mm x 0.4mm) and all flexible substrates were printed at 1mm thickness.

E. Results: Fig. 2 shows optical microscope images of the printed conductive materials on the substrates before any bending as well as the substrate itself. There is evident cracking in the printed copper filament tracks which lead to a much higher resistivity measurement than expected. The viscoelastic properties of the formulated inks are shown by their lack of spreading on the substrate and a more continuous flow with minimal cracks even after drying.

Table 1 shows how the resistance of the conductive tracks varies with bending. A small amount of silver paste was placed at either end of the tracks to ensure a secure electrical connection with the digital multimeter.

All the conductive materials experienced a reasonable and repeatable level of printability as well as showing good adhesion to both substrates. The electrical properties of the materials, however, could further be improved to allow for their use as circuit interconnects. Moreover, more optimal settings are required for the consistent printing of the conductive polymer to avoid the emergence of cracks which substantially increase its resistivity. Future work will involve the integration of electronic components as well as 3D printed circuits to compliment further study on the 3D printed conductive materials performing as bendable interconnects.

IV. Conclusions

A flexible substrate was developed using a flexible polymer, commercially known as NinjaFlex (TPU) employing 3D printing techniques. Two different conductive materials (Electrifi conductive filament and an in-house formulated, graphite-based conductive ink) were employed for the printing of the flexible connections.

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