

Aerosol Jet Printed Tactile Sensor on Flexible Substrate

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Abstract— Inkjet printing for fabricating microstructures has gained popularity during the last decade, making it possible to realize complex electronic circuits, components, and devices previously manufactured using 2D lithographic processes. In this work, we use aerosol inkjet printing delivered from the NeXus, a custom-built microfabrication platform that can deposit silver ink on a flexible printed circuit (FPC) substrate. We present the fabrication method of a 10mm diameter circular strain gauge tactile sensor, which is annealed using oven curing or intense pulse light (IPL) process. The resulting sensor performance under varying curing schedules is evaluated by loading packaged sensors with increasing weight, reporting a measured resistance in the 300Ω-1.2kΩ range.

Keywords—Aerosol jet printing; Star shape strain gauge; Strain gauge; Tactile sensor; Intense Pulse Light (IPL)

I. INTRODUCTION

The advent of miniature electronic circuits on flexible substrates is enabling wearables, soft robots, and other emerging technologies. Flex circuit fabrication by additive manufacturing has been recently realized through new types of InkJet printing processes, such as Aerosol Jetting [1]. The flexibility of Aerosol jet printing in determining the sizes of components based on changing print recipes makes it easily adaptable, increasing its user operability in comparison to the extensive and delicate nature of lithographic processes [2].

The aerosol jet printing process works using the principles of aerodynamics to precisely align atomized ink droplets on substrates. In this work, an aerosol jet print head from Optomec® that is capable of depositing solvent or water-based ink droplets up to 30cp in viscosity is equipped with a piezoelectric diaphragm; upon activation by a pulsed voltage which deflects thereby generating ample amount of pressure wave required to push through a streaming jet of ink continuously through the nozzle tip [1]. These ink droplets are focused and carried along the deposition track with nitrogen gas acting as the controlled sheath gas. The formulated ink which could be either conductive metal, conductive polymers, semiconductors, or dielectrics, is first placed in the ultrasonic atomizer and then formed into a saturated mist that is parried along the track of deposition at a standoff position of 3 - 5 mm from the substrate.

The curing of flexible substrate follows immediately after the deposition of the ink to remove moisture, fusing the nanoparticles together and ensuring their compactness and smoothening. The curing process is mostly done in an oven and most recently, a sintering procedure with intense pulse light (IPL) has been developed and the results are examined in this paper.

In this publication, we presented the fabrication processes carried out in the NeXus, involving the use of an aerosol jet printer, the curing procedure of the sample both with oven and IPL, and the soft bedding encapsulation used for the testing procedure. We evaluated the performance of the printed sensors with the 4-point probe method. The baseline resistance of the printed sensors reduces with an increase in curing cycles in the IPL as does with an increase in the duration of the curing of the sample in the oven. But this thus seems to impact the sensitivity of the printed sensors as the oven-cured appears to be more sensitive with a longer curing time as compared to the IPL which has a faster curing time.

II. MATERIALS AND METHODS

In this study, the tactile sensors were printed with an aerosol jet printer from OPTOMECH®, which functions as a strain gauge. This means the structure upon deformation transforms applied strain to varying electrical resistance simultaneously [3]. Proposed in this study is a 10mm diameter star-shaped tactile sensor inspired by the conventional serpentine strain gauges, fabricated using NovaCentrix® JS-A426 silver ink and then cured by IPL [4]. The star shape tactile structure was designed with a trace width of 50μm; printable with the aerosol inkjet nozzle tip of 300μm with the process recipe listed in Table I. The NovaCentrix® silver ink has a conductivity of 7.05×10^6 S/m which is close to that of bulk silver at 6.3×10^6 S/m. This can be derived from Equation (1) below using the total length of the star gauge tactile structure which measures 173.11mm [1].

$$R = \frac{L}{\sigma \cdot W \cdot T} \quad (1)$$

From equation (1), W represents the width of the conductive silver line, T is the thickness of the deposited silver ink, σ is the conductivity of the silver ink, and L is the total length of the tactile structure. Fig. 1 shows the design of the tactile sensor.

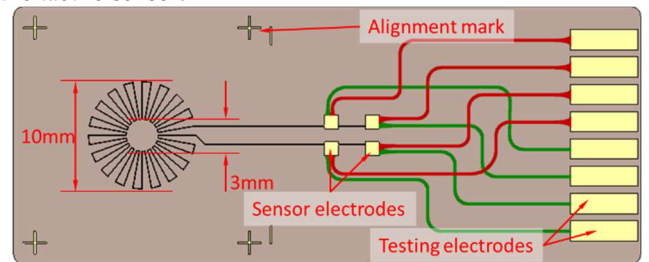


Fig 1. The star-shaped tactile sensor design with a customized FPC substrate.

A. Aerosol jet print system

The OPTOMECC® Aerosol inkjet print system is a subsystem of a novel robotic system used for multiscale additive manufacturing called NeXus [5]. The aerosol jet printing station, inspection station, and IPL are part of the inkjet printing system. The Aerosol jet printing station comprises a control cabinet for directing the ink streaming process through the print head, KEWA process control software, and a 6DOF positioner for aligning the substrate to the 300 μ m nozzle tip with a 3-5 mm standoff distance. Fig. 2a shows the substrate placed on the 6DOF positioner aligned for printing with the print head. Fig. 3a shows the printed line of 60 μ m width characterized for the printing based on the process recipe shown in Table I.

TABLE I. PARAMETERS FOR AEROSOL JET PRINTING

Sheath Flow Rate	132sccm	Print Speed	10mm/s
Atomizer Flow Rate	18sccm	Atomizer Bath Temperature	27°C
Atomizer Current	400mA	Stand-off Distance	3mm

B. Inkjet Printing Trajectory for Tactile Sensor

The trajectory path for the Inkjet printing of the tactile sensor is required to provide the 6DOF positioner accurate description in X and Y coordinates for the precise alignment of the fixed inkjet printer nozzle tip to the flexible printed circuit. This is created through an open-source computer-aided-Manufacturing (CAM) tool called Inkscape, which is a vector-based graphics editor with a G-code path generator extension. The design of the tactile sensor is uploaded in the workspace of the Inkscape interface, and the G-code file is generated into G-code paths present within the extension tab. The G-code files are uploaded into the Newport controller responsible for feeding the precise coordinates for the Inkjet printing of the silver ink [6].

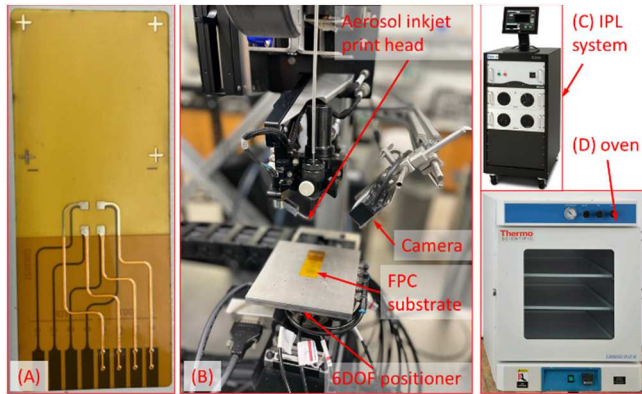


Fig 2. The fabrication process of tactile sensors with an FPC substrate. A) The customized FPC substrate. B) The OPTOMECC® Aerosol Inkjet printer system. C) The Xenon S-2210 IPL. (D) The Thermo Scientific Lindberg vacuum oven.

C. The Active Sensor Sintering Process

After the deposition of the silver ink, there is a need to cure the printed ink, removing the solvent allowing for compactness of the silver nanoparticles. The curing process ensures the fusion of these particles, thereby increasing their conductivity. For the curing process, Xenon® Intense pulsed light (IPL) S-2210 device and a thermal scientific Lindberg vacuum oven was used. The IPL which delivers peak energies and frequencies within a controlled experiment can successfully sinter metallic ink at precise control variables which prevent damage to the substrate[7]. Table II shows the

process recipe used for the IPL curing process while Fig. 3b shows the tactile sensor thermally cured with IPL. For oven curing, the fabricated tactile sensor was placed in the oven for approximately 20 hours at 200°C [1]. It is important to note that the duration of the thermal cure is dependent on the substrate. In this case, the substrate upon which the tactile sensor is fabricated is Kapton which is optimal for the intended purpose as regards the duration of the curing process within a specified number of cycles. Fig. 3c shows the tactile sensor cured in the oven. The color of the substrate has darkened after oven curing, and we believe this is due to the prolonged curing schedule that altered the properties of the adhesive used to assemble the customized FPC.

TABLE II. PARAMETER FOR ONE IPL CURING CYCLE

Duration (μ s)	Delay(ms)	Pulses	Voltage (V)
100	100	50	1500
250	100	50	1500

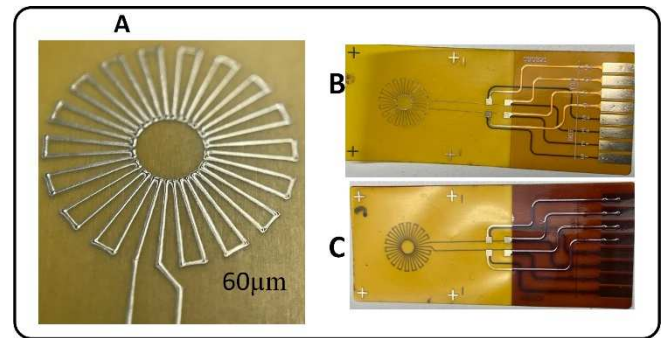


Fig 3. A) 60 μ m measured width of the silver printed lines. B) printed tactile sensors cured with IPL. C) printed tactile sensors cured in an oven

D. Tactile Sensor Encapsulation

The proposed tactile sensor design detects strain rather than force; thus, compliant bedding is necessary [8]. On top of the printed sensor, we also include a cover piece to 1) protect the printed traces, and 2) to help concentrate strain by converting external force with an integrated dimple. As shown in Fig. 4. A piece of hard acrylic plastic with dimensions of 40mm width, 70mm length, and 5mm thickness is chosen as the sensor's testing bed. A cylindrical cut-out is machined towards the sensing end, and Sylgard® 184 Polydimethylsiloxane (PDMS) is poured and cured to serve as the compliant surface, with a thickness of 4.5mm. The diameter of the bedding is 25.4mm and it is large enough to cover the entire sensor area, to provide deformation across the surface as even as possible. The printed sensor sheet is placed directly on the testing bed, with the circular sensor portion visually aligned concentrically with the bedding, and the testing electrodes land on the hard acrylic surface. Spring-loaded testing pins are fixed on top of the sensor testing electrodes to allow resistance measurements to be conducted with the 4-point probe method.

E. Experimental Test Setup

Resistance measurements are made using an Agilent 34461A 6.5-digit multimeter with a 4-wire Kelvin connection to the printed sensor, which eliminates resistance across the testing probes and the testing pads. A 2-wire measurement is compared to the Kelvin measurement to determine that high contact resistance is not present. A difference of less than 2 Ω between the two measurements was observed, which suggests

the silver ink print to the copper contact on the FPC is insignificant. The meter was set to the $1k\Omega$ range and sources 1mA constant current to the sensor. According to specific resistance on each sensor, roughly 60 to $400\mu W$ is dissipated by the sensor. We do not observe noticeable self-heating effect that would significantly alter the reading of the resistance [8]. The experimental test setup is shown in Fig. 4b. Force is applied to the sensor by placing the acrylic plate fixture onto a stand that holds a weighted rod that is centered over the sensor pattern. A plastic guide ensures the rod is free to move and is stable. Metal weights are placed on the rod to provide force and the sensor resistance is noted.

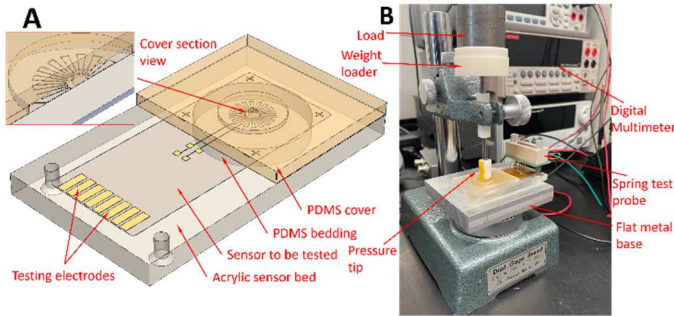


Fig 4. A) illustration of the tactile sensor setup. B) shows the experimental test setup

III. RESULTS AND DISCUSSION

The tactile sensor fabrication procedure developed in this paper printed a patterned star shape tactile structure successfully onto an FPC substrate, using the aerosol jet printer and the samples are cured by the IPL and oven, which are all part of a custom-built NeXus microfabrication platform. The entire process requires the characterization of printing resolution giving a precisely measured width of the printed silver lines to be 60 microns and the evaluation of the silver ink conductivity during the sintering process. Fig.3 shows the complete tactile sensor fabrication after the curing process. The one cured in the oven has shown to be darker, depicting the long duration in the oven heats the adhesive used for the lamination of the customized FPC substrate. However, this doesn't seem to affect the eventual responses of the tactile sensors. After the fabrication process is carried out and the sintering process is concluded, the resistance values of the tactile sensors under the influence of measure weights are taken.

TABLE III. TACTILE SENSORS LOAD – RESISTANCE VALUES

Load (g)	3-IPL Cycles(Ω)	4-IPL Cycles(Ω)	Oven cure (6hrs)	Oven cure (20hrs)
0	400.501	65.651	441.74	188.39
28	400.684	65.656	441.806	188.444
44	400.694	65.664	441.855	188.5
72	400.712	65.67	441.93	188.564
84	400.717	65.675	442.004	188.624
112	400.735	65.681	442.065	188.69
128	400.74	65.689	442.153	188.75
156	400.755	65.698	442.208	188.821

As shown in Table III, it is observed that the resistance measurement varies based on the curing duration of the tactile sensor in the oven and the number of impulse cycles ran on the tactile sensor with the IPL. With an increase in the number

of impulse cycles, the resistances of the tactile sensors decrease, showing significant differences between the measured resistance between different cycles and the length of time the tactile sensor spends in the oven.

The graphs shown in Fig. 5 show the relationship between the load profile and resistance measured. It shows the near-linear characteristics as the resistance increases with respect to the varying load. This depicts the effectiveness of the aerosol jet printed tactile sensors irrespective of the curing technique. The solid lines are fitted with least squares method (lsline) in MATLAB.

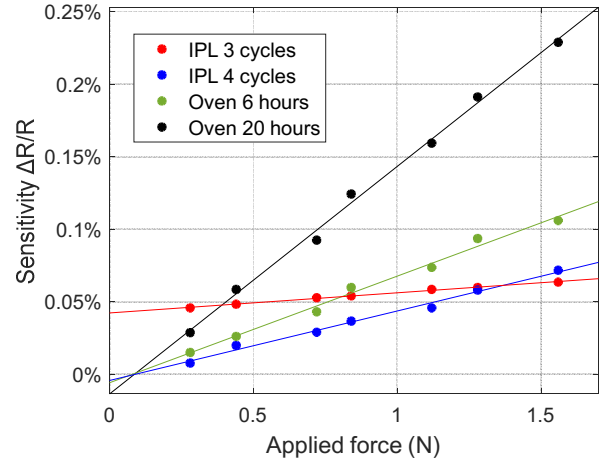


Fig 5. Graphic relationship between the applied load on the sensors (Newton) vs. the change in resistance.

IV. CONCLUSION AND FUTURE WORK

In this publication, we made certain the possibility of fabricating tactile sensors with the use of aerosol jet printing, providing the recipe for achieving the printed width of $60\mu m$. To ensure the fusion of the nanoparticles, the silver ink is cured with the Xenon S-2210 IPL (intense pulse light) and the Thermo scientific Lindberg vacuum oven. The sintering process showed it is possible to vary the resistance of the tactile sensor for relevant applications based on the length of the curing time in the oven or the number of impulse cycles carried out with the IPL. The experiment results show the linearity in the variation of load applied to the tactile sensor and corresponding resistance measured. Longer curing leads to steeper slope of the plot for both oven-cured and IPL-cured samples, this observation may imply stronger fusion would increase sensitivity of the sensor.

The possibility the future holds with this method of fabricating tactile sensors is the potential expansion of this tactile sensor over a large surface, and the size reduction of an individual sensor. We will also conduct a more extensive study to examine the effect of different curing procedures, such as the number of IPL curing cycles and oven curing duration, on the sensitivity of the printed sensors.

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