

General

Process Optimization of Additively Manufactured Conformal Temperature and Humidity Sensor for High-Temperature Applications

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Additive Manufacturing (AM) and Printed Electronics (PE) have recently seen widespread implementation in numerous technological applications. The shift towards manufacturing AM PE is largely due to the numerous benefits that AM offers compared to traditional manufacturing. Some of these benefits include the ability to rapidly prototype and the reduction of waste material compared to traditional manufacturing methods, and the ability to realize conformal circuits onto existing structures and substrates with varying form factors. In this work, an AM analog temperature and humidity sensor for high temperature applications was designed and printed using a multi-axis tabletop nScript printer. Electrical, mechanical, and statistical testing was performed on the circuits to assess the performance and uniformity of the printed circuits.

I. INTRODUCTION

With the growing need for electronic circuits to fit unconventional form factors, Additive Manufacturing (AM) has become a popular method for creating conformal circuits. With benefits such as reduced material waste, reduced lead time for prototyping, and the ability to create substrates in nontraditional shapes and materials, AM has seen growth in its use. Despite this, AM has yet to be implemented on a large-scale. This is in part due to the lack of standards of manufacturing for handling AM materials. Similar work has explored the use of AM for creating wearable sensors (Patel et al. 2022). However, there has not been much work in developing these circuits for high-temperature applications. This work focuses on the design, manufacture, and optimization of a temperature and humidity sensor for use in high-temperature applications (200 C). The substrate, which is a carbon-nanotube impregnated Poly-Ether-Ketone-Ketone (CNT-PEKK) composite, is printed using a pellet-based FDM extruder. To combat the surface roughness inherent in FDM printing, and to provide shielding between the circuit and the substrate material conductivities, the surface of the substrate is coated with a commercially available, high-temperature dielectric material deposited using the tabletop nScript SmartPump syringe-dispense head. Once the dielectric base layer is printed, the silver traces are then printed using a commercially available silver ink and conductive epoxy hybrid using the nScript SmartPump. Due to issues with cold fusion of the silver nanoparticles, careful optimization of the material handling and process parameters was required to ensure consistent printing of

the silver ink. The components were then mounted to the silver traces and a layer of dielectric was printed onto the silver traces to prevent oxidation. Furthermore, statistical analysis of the reliability and repeatability of the sensors, along with rigorous analysis of printing processes were conducted. This work will provide details of the design implications, material and process optimization, and testing of an AM analog temperature and humidity sensor. This work provides details on the design implications, material and process optimization, and testing of an AM analog temperature and humidity sensor. [Figure 1](#) illustrates the flow-chart outlining the analog circuit manufacturing process.

II. CIRCUIT DESIGN

The sensor circuit was designed using a Sensiron SHT4X series analog sensor. This sensor was chosen for its ability to function and survive in high-temperature environments. The standard circuit schematic, which was outlined by the manufacturer's guidelines, is shown in [Fig. 2](#) ("Datasheet -SHT4x 4 Th Gen. Relative Humidity and Temperature Sensor Highlights," n.d.).

The print file for the circuit was designed using AutoCAD and is shown in [Fig. 3](#). The power and ground traces were designed to have a width of 1000 μm , and the signal-carrying traces were designed with a width of 500 μm .

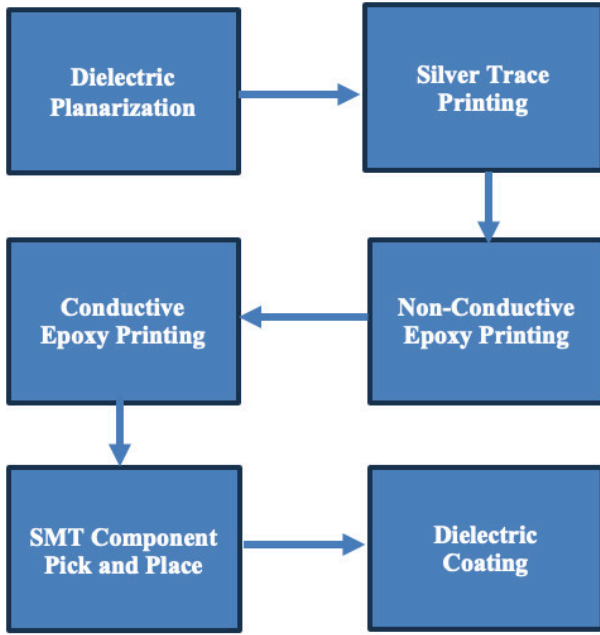


Figure 1. Flow chart outlining analog circuit manufacturing process.

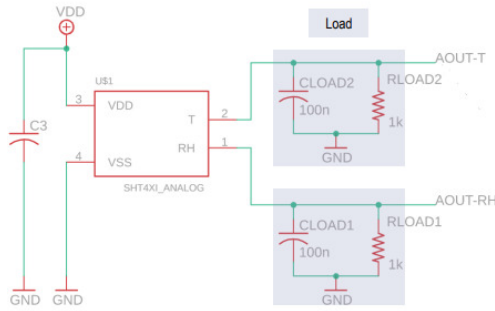


Figure 2. Analog circuit standard layout provided by the manufacturer.

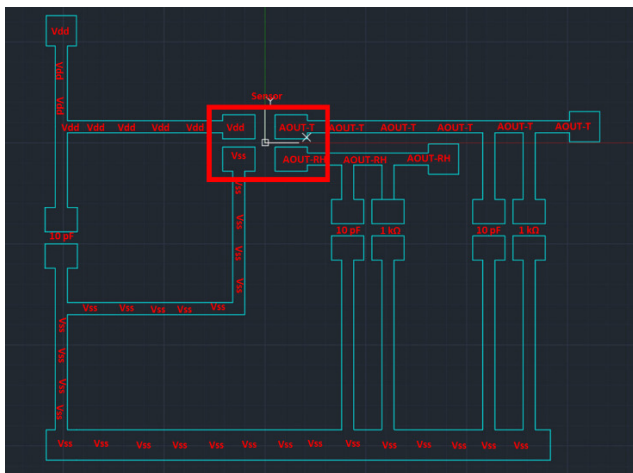


Figure 3. Analog circuit print file designed in AutoCad.

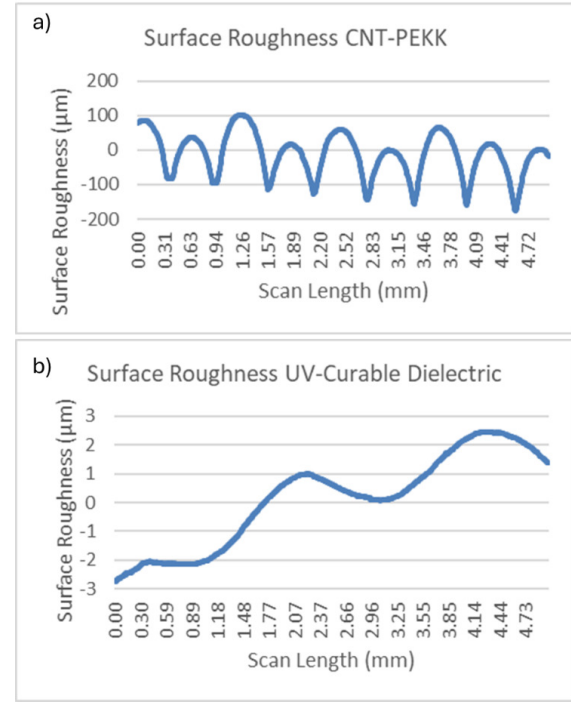


Figure 4. a) CNT-PEKK prior to planarization; b) CNT-PEKK post-planarization with UV-curable dielectric.

III. MATERIAL AND PROCESS OPTIMIZATION

A. DIELECTRIC SUBSTRATE

Due to the conductive nature of the CNT-PEKK, a dielectric insulating layer was necessary to shield the conductive traces. This dielectric layer also served as a planarizing coating to decrease the effects of the surface roughness that are inherent in FDM printing. Initially, the CNT-PEKK was planarized using a custom UV-curable dielectric because of its ability to wet to PEEK, which has similar wetting characteristics to PEEK, as demonstrated in prior work (Lamport et al. 2023; Maiti et al. 2024). This UV curable ink was deposited onto the CNT-PEKK using a Nordson Pro4. In this work, to streamline manufacturing, and to meet the criteria for high-temperature applications, a commercially available, high-temperature laminating adhesive from Creative Materials (CM124-07) was used. To ensure proper coating of the CNT-PEKK, surface roughness measurements were taken before and after the deposition of the dielectric. The surface roughness of the dielectrics was measured using a Bruker ContourGT Optical profilometer, and the surface roughness measurements of the CNT-PEKK were performed using a KLA-Tencor stylus profilometer, due to the optical absorption of the CNT-PEKK. Fig. 4 shows the average surface roughness before and after planarization using the UV-curable dielectric, and Fig. 5 shows the average surface roughness before and after planarization using the commercially available printed dielectric.

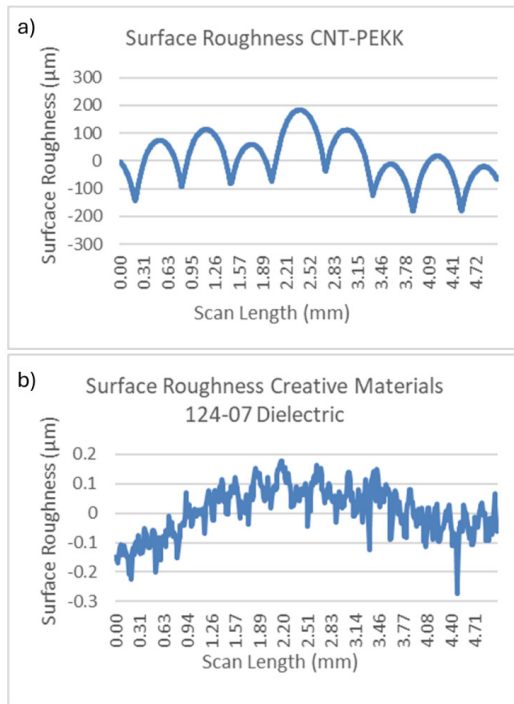


Figure 5. a) CNT-PEKK prior to planarization; b) CNT-PEKK post-planarization with Creative Materials 124-07 dielectric.

B. SILVER INK

To print the conducting traces of the sensor, a commercially available silver ink and conductive epoxy hybrid ink for high-temperature applications, from Creative Materials (CM126-40) was used. Since this ink was used for both the traces and the conductive epoxy for the component attachment, fewer materials were used, which increased material compatibility. During extrusion, the force inside the flow path caused cold fusion of the silver nanoparticles in the tip, leading to inconsistent printing and clogging. Hence, careful optimization was required to determine which parameters resulted in the most consistent printing.

Regarding the uniformity of the printed silver traces, the infill angle was found to be a significant factor. To determine this, the analog silver traces were printed using three different infill angle orientations: 0° , 45° , and 90° . The linewidth was measured at least five times in different locations, which are labeled in Fig. 6. From these measurements, the standard deviation was calculated for each group, as shown in Fig. 7.

From the above figure, the samples printed with a 90° infill angle had consistently lower standard deviation values than samples printed with either 0° or 45° infill angles. Hence, for the remaining of the prints, the 90° infill angle was used.

Another factor that affected the quality of the printed silver was the piston used in the dispensing syringe. The piston is designed to create an even pressure differential and fluid flow inside of the piston when pneumatically activated. In most ink applications, the white piston from Nordson is sufficient to use. In high-viscosity applications,

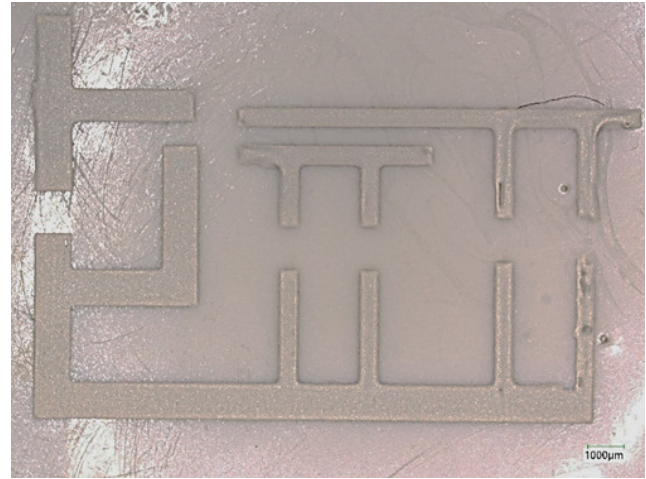


Figure 6. Measurement regions of printed silver traces. Each number represents a different region of the print file, and the letters V and H denote, respectively, vertical and horizontal in-plane orientation.

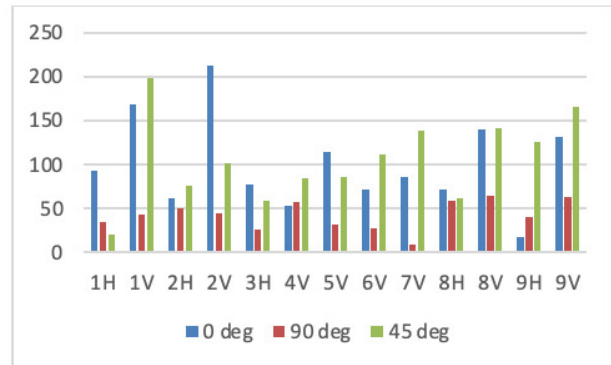


Figure 7. Graph of standard deviations for varying infill angles for the different traces of the analog sensor.

however, the piston does not provide the right pressure differential to sufficiently move the ink. The piston moves up and down in the syringe—a phenomenon known as “piston bouncing.” The force that the piston exerts on the ink when it is bounced leads to cold fusion of the nanoparticles in the silver ink. This leads to an increase in the occurrence of clogging in the tip, which slows manufacturing time and can reduce the overall quality of the printed traces. To combat this, a flexible clear piston from Nordson was used inside of the dispensing syringe. The flexibility of the piston allows for dynamic change in the pressure differential to allow the ink to flow more smoothly and to prevent piston bouncing from occurring. Once the conducting traces were printed, the conductive epoxy (CM 126-40) was printed to connect the SMT component leads to the silver traces, and then the nonconductive epoxy (CM 124-07) was deposited where the center of the chips would be placed to increase the mechanical robustness of the printed sensor. Both epoxies were printed using a Tabletop nScript SmartPump. Once the epoxies were printed, the compo-

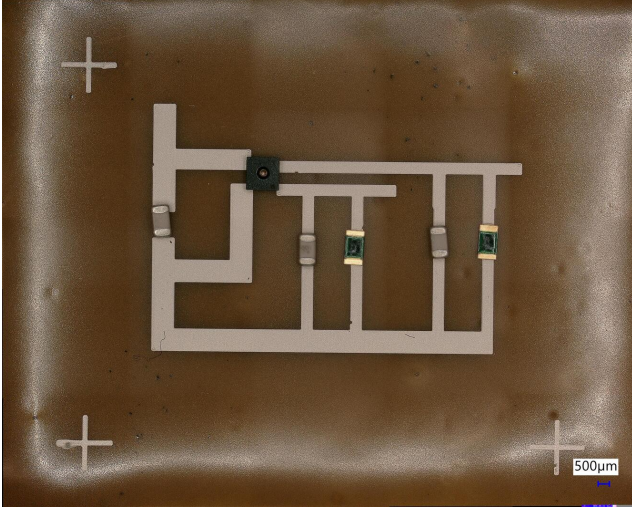


Figure 8. Finished printed circuit for the analog sensor.

nents were placed using an nScript 3Dn-300 Pick-n-Place head. [Fig. 8](#) shows a finished printed circuit.

IV. RESULTS

A. ELECTRICAL TESTING

Once the sensor printing was completed, electrical testing was performed to assess the performance of the circuit. The circuit was powered to 5V and the output voltage at pin #1 (Relative Humidity (RH)) and pin #2 (Temperature) were measured. The measured voltage at pin #1 was inserted into Equation 1 to calculate RH, and the measured voltage at pin #2 was inserted into Equation 3 to calculate temperature in degrees Fahrenheit.

$$\begin{aligned} RH &= \left(-12.5 + 125 * \frac{V_{RH}}{V_{DD}} \right) \%RH \\ &= -\frac{10}{0.8} + \frac{100}{0.8} \left(\frac{V_{RH}}{V_{DD}} \right) \%RH \end{aligned} \quad (1)$$

$$\begin{aligned} T &= \left(-66.875 + 218.755 * \frac{V_T}{V_{DD}} \right) ^\circ C \\ &= -45 - \frac{17.5}{0.8} + \frac{175}{0.8} \left(\frac{V_T}{V_{DD}} \right) ^\circ C \end{aligned} \quad (2)$$

$$\begin{aligned} T &= \left(-88.875 + 393.75 * \frac{V_T}{V_{DD}} \right) ^\circ F \\ &= -49 - \frac{31.5}{0.8} + \frac{315}{0.8} \left(\frac{V_T}{V_{DD}} \right) ^\circ F \end{aligned} \quad (3)$$

The relationships between the output and source voltage ratio compared to RH and temperature are shown in [Fig. 9](#) (“Datasheet -SHT4x 4 Th Gen. Relative Humidity and Temperature Sensor Highlights,” n.d.).

These measurements were taken on three different days to monitor the variability of the measured values. The voltage output measurements are shown in [Table 1](#), and the calculated RH and temperature values are shown in [Table 2](#). The values obtained from the sensor were compared to RH and temperature values obtained from a Govee H5074 Bluetooth RH and temperature sensor.

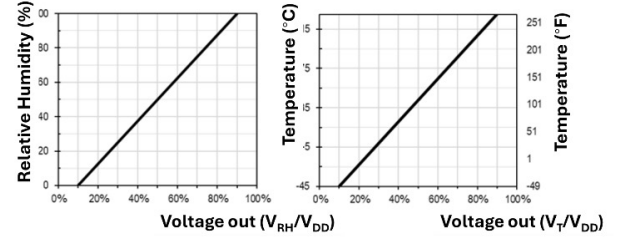


Figure 9. Graphs of relationships between output and source voltage ratio with RH (Left) and Temperature (Right)

Table 1. Measured output voltages

	V _{out} RH	V _{out} Temperature
Day 1	1	2.2
Day 2	1.2	2.2
Day 3	1.1	2.2

To test the performance over multiple temperature and humidity ranges, the analog circuits were subjected to temperature cycling over multiple relative humidities. This was done in an ESPEC environmental chamber. The results are shown in [Fig. 10](#).

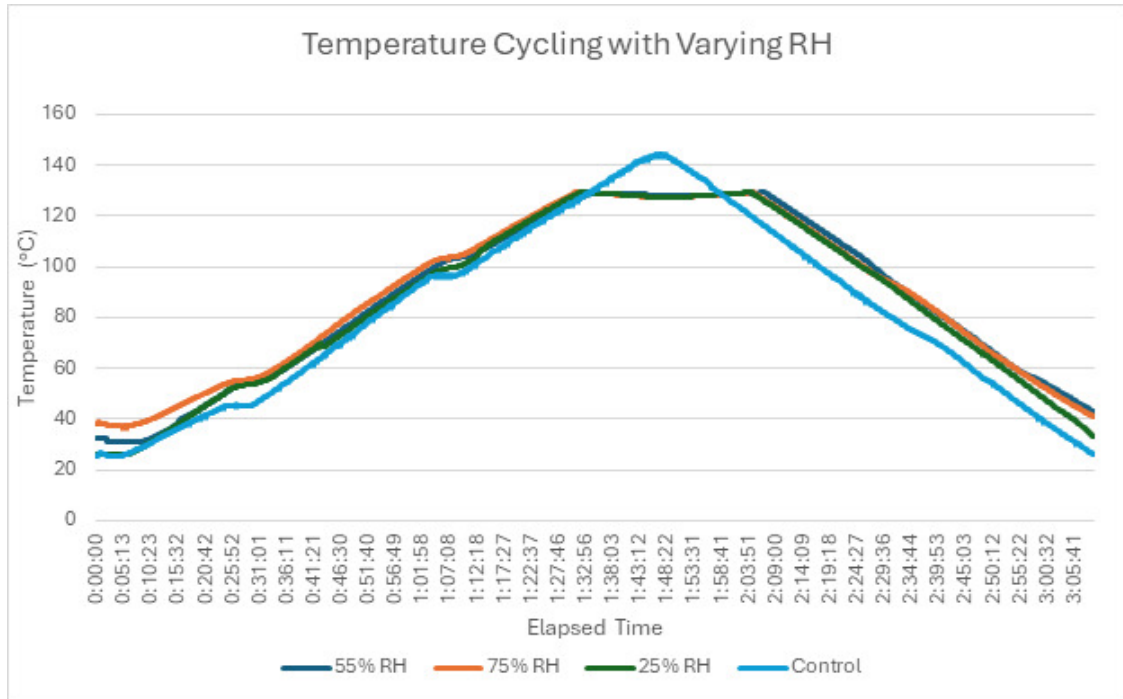
The temperature and RH cycling of the sensor circuit through varying RH levels shows good agreement of the control measurements in the chamber, which is measured by a thermocouple. The plateau seen in the temperature graph can be attributed to the temperature of the chamber exceeding that of the operating temperature of the sensor, which is 125°C. Differences in the measurements of temperature can be attributed to two main causes: (1) increased resistance on the printed traces providing less current to the sensor, and (2) lack of calibration for the resistance when measuring the voltages required to extract the temperature and RH data.

B. MECHANICAL TESTING

To quantify the strength of the bond of the epoxies between the SMT components and the silver traces, die-shear testing was performed. It was hypothesized that the SMT components would be most robust when nonconductive and conductive epoxies were used to bond the chips to the silver traces and the substrate to increase the mechanical robustness and the quality of the electrical connection, respectively. The non-conductive epoxy is used to bond the chips to the substrate, and its purpose is to add mechanical robustness to the mounting of the chips. The conductive epoxy is mounted between the terminals of the SMT components and the silver traces and provides the electrical connection between them. Three samples were prepared with three chips, each used in the analog sensing circuit, to optimize the surface mount process of the components. The details of the sample fabrication area are shown in [Fig. 11 \(a\)-\(c\)](#).

Table 2. Calculated RH and temperature values compared with measurements from commercial RH and temperature sensor.

	RH Printed Sensor (%)	RH Govee (%)	Temperature Printed Sensor (°F)	Temperature Govee (°F)
Day 1	12.7	10.8	82.1	72.6
Day 2	17.9	21.4	82.3	75.7
Day 3	15.6	11.6	82.3	75.2

**Figure 10. Graph of temperature cycling over different relative humidities**

The die shear testing was performed on each chip on each sample using a Chatillon KMP model 1750. A load force was applied laterally to each chip until it was removed. The load force at which the chip was dislodged was then used to calculate the maximum lateral stress of each chip. The results of the die shear testing are shown in [Figure 12](#), for the three samples shown in [Fig. 11 \(a\)-\(c\)](#), respectively (Pan et al. 2006).

The cured silver traces and the conducting epoxy led to better mechanical results. The maximum stress values of traditional solder materials SAC305 and SnPb for similarly sized SMT packages is 65 MPa and 75 MPa, respectively, and the maximum load force is 30 N and 35 N, respectively. The maximum stress and maximum load force is much greater in the solder materials than the results obtained during the die shear testing due to the epoxy chemistry being significantly more brittle than the chemical makeup of the traditional solder materials. To increase the robustness of the sensor, the components will be encapsulated for future work.

C. STATISTICAL ANALYSIS

To ensure print uniformity of the silver lines over continuous printing intervals, a gauge repeatability and reliability (Gage R&R) analysis was performed (Hessing, Pv, and Naomi 2024). The two methods of this analysis include the Mean-Range method and the Analysis of Variance (ANOVA) method, both of which were utilized to assess the print uniformity. Three samples were printed over three days, each with three prints per sample. These samples are shown in [Fig. 13](#).

The results from both the Mean-Range method and the ANOVA method for gage R&R are shown in [Table 3](#).

Table 3. Statistical analysis of linewidth and thickness of printed silver lines.

Trace Property	Mean-Range Method (%)	ANOVA Method (%)
Linewidth of 1000 μm Traces	8.76	0.26
Linewidth of 500 μm Traces	6.19	0.39

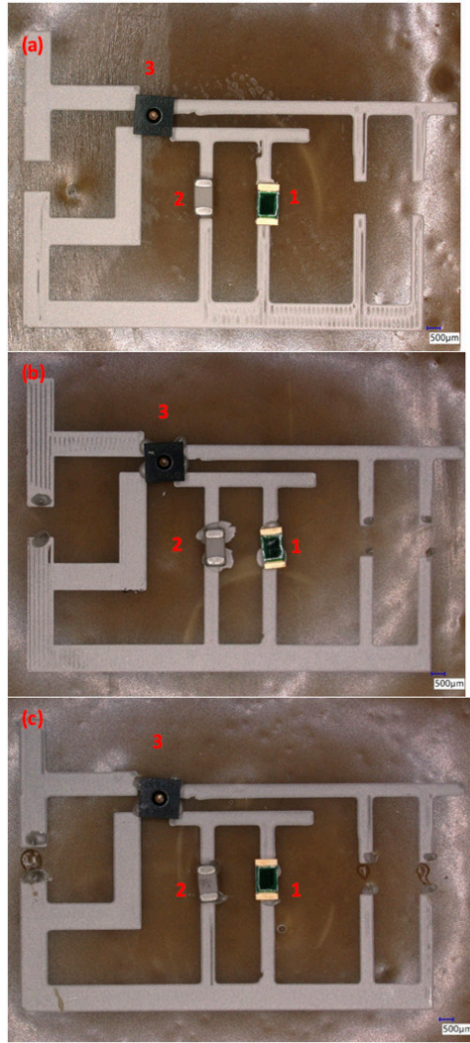


Figure 11. Pictures and descriptions of each mechanical testbed. (a) chips 1 (1k Ω resistor), 2 (100 nF SMT capacitor), and 3 (analog temperature-humidity sensor) are placed directly onto the uncured CM126-40 traces, no additional epoxy support. (b), chips 1, 2, and 3 are placed onto the cured 126-40 silver traces and the CM126-40 Conductive epoxy pads. (c) chips 1, 2, and 3 are placed onto the cured CM 126-40 silver traces, CM126-40 conductive epoxy pads, and CM124-07 Nonconductive epoxy pad between the two conductive epoxy pads.

Trace Property	Mean-Range Method (%)	ANOVA Method (%)
Thickness of Lines	2.05	.03

According to the specification of this analysis, the acceptable range is <10% and <1% for the Mean-Range Method and ANOVA method, respectively. The results for the measured linewidths of the 1000 and 500 μ m lines and the thicknesses were all within these acceptable ranges (Hessing, Pv, and Naomi 2024).

V. CONCLUSION

This work has demonstrated not only the successful completion of a printed temperature and humidity sensor for use at high temperatures, but it has also demonstrated optimizations in both print processes and material handling to increase the efficiency and quality of the manufactured sensors. These optimizations are vital to allowing the widespread adoption of AM as an independent manufacturing technique. With the growing need for nontraditional circuit designs, these optimizations are vital for future innovations in a variety of technologies.

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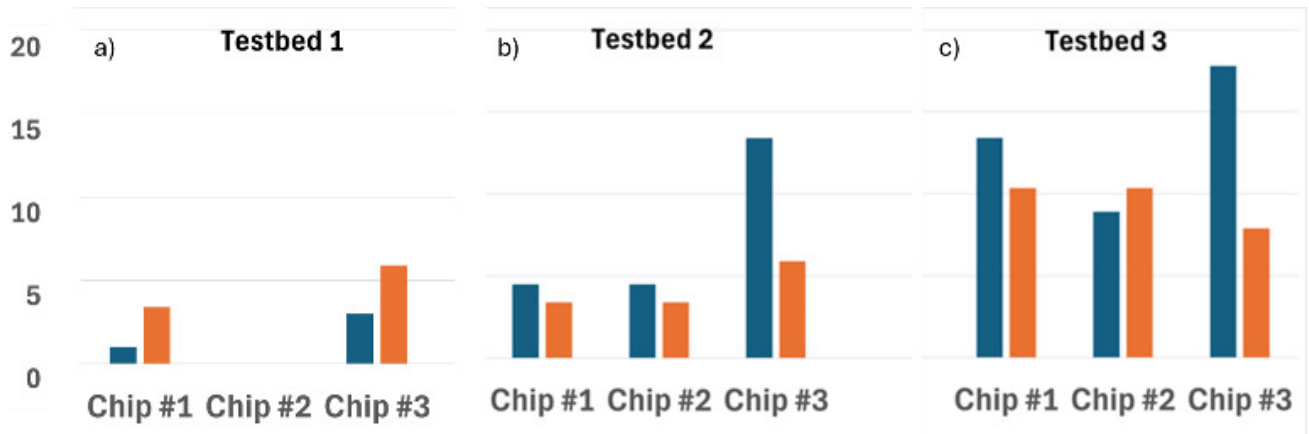


Figure 12. a) – c) Results of the mechanical shear testing in Max Load Force (N) and Max Stress (MPa) for the three chips on the three samples.

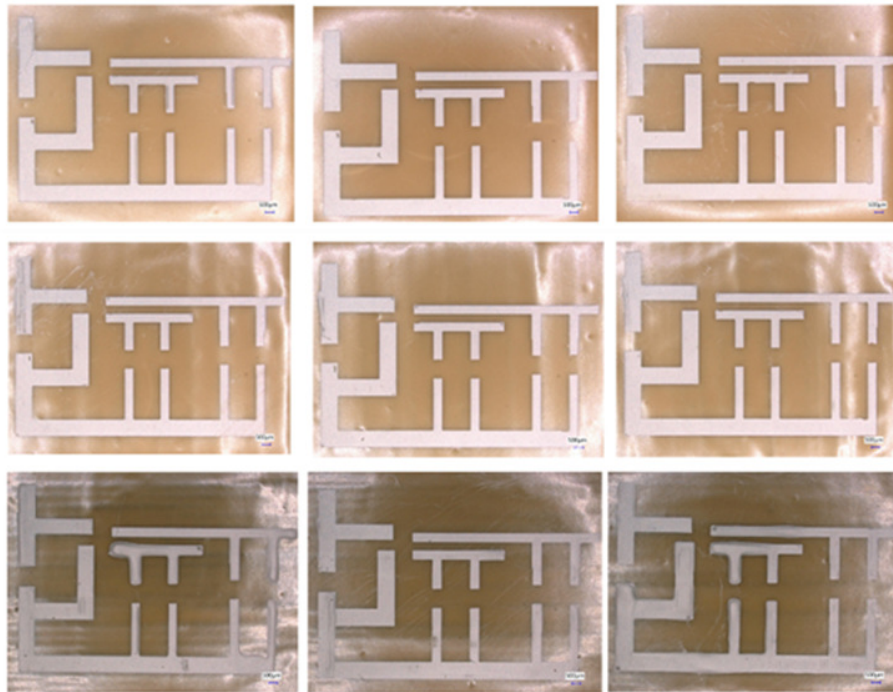


Figure 13. Samples 1 (Top Row), 2 (Middle Row), and 3 (Bottom Row) for Gage R&R studies.



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