Direct Write Fabrication of Platinum-Based Thick-Film Resistive Temperature Detectors

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***Abstract*— This paper investigates the feasibility and performance of platinum thick-film resistance temperature detectors (RTDs) fabricated using extrusion-based direct write (DW). A platinum (Pt) layer of micron-level thickness was directly deposited onto a planar alumina substrate and was physically and electrically characterized. A four-wire electrical configuration was used to eliminate the effects of contact resistance and increase measurement accuracy. The resistance-temperature behavior of printed Pt traces was consistent with that of bulk Pt wire. Durability testing indicated the printed Pt RTD was suitable for temperature measurements from room temperature to at least 350 °C, showing no degradation under long-term heating and lower signal noise than was observed in a Nickel-alloy type E thermocouple (TC). At 500 °C, the peak temperature variation of the Pt RTD was comparable to that of the type E TCs. To demonstrate the design freedom enabled by DW technology, an additional conformal RTD design was deposited onto a semi-cylinder glass–ceramic substrate and was subsequently characterized. This paper offers an alternative to current thick-film RTD fabrication techniques.**

***Index Terms*— Aerospace control, high-temperature techniques, platinum, temperature measurement.**

I. Introduction

THE ability to seamlessly integrate smart sensors into existing hardware offers great potential to enhance functionality and usability. Such sensors can be used to track temperature, pressure, vibration, light, pH, and many other phenomena that affect the short-term operation or long-term stability of the system. For temperature sensing in industrial applications, the use of resistance temperature detectors (RTDs), also known as resistance thermometers, is slowly gaining popularity over that of traditional thermocouples (TC), due to the increased accuracy and reliability of RTD [1].

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Traditional wire temperature detectors like birdcage or helix RTDs have difficulties for *in-situ* temperature measurement of operating parts such as rotary blades [2]. More recently additive manufacturing (AM) has been utilized in the RTD fabrication process, wherein a film of platinum or nickel-iron metal can be directly deposited onto a ceramic substrate [3]. Direct write (DW) is capable of depositing thin layers of the order of micron thickness. This decreases the amount of metal used, reduces cost, and increases resistance, which in turn increases sensor resolution. The custom nature of the process allows for sensors to be directly integrated into smaller or irregularly-shaped areas where off-the-shelf sensors cannot be integrated. Thin-film temperature detectors fabricated by inkjet or aerosol jet methods have lower reliability due to their sub-micron element layer thickness and lower metal solid loading, and are thus more vulnerable to contamination. Thick film (layer thickness > 1 μm) RTDs with a high temperature coefficient of resistivity (TCR) are of interest in microelectromechanical systems (MEMS) [4]. When comparing to other thick film technologies, screen printing is a popular thick film technique, which utilizes a squeegee to transfer ink onto a flat substrate through a stencil or a patterned mesh [5], but it lacks the ability to print on conformal substrates and design changes require a new stencil to be fabricated. Planar RTDs can also be fabricated through microelectronics lithographic processing techniques, but fabrication on non-planar substrates lacks industrial attention. In addition, these conventional techniques can be expensive, relatively complex, and impractical for fast-prototyping purposes.

This work reports the extrusion-based DW fabrication and device performance qualification of platinum RTDs that can be directly deposited onto conformal substrates. DW is an additive manufacturing technique that enables the direct deposition of electronic components and functional or structural patterns using different types of materials, without the need for masks or subsequent etching processes [6]–[8]. In extrusion-based DW, a software-guided machine extrudes continuous filaments onto a substrate through a nozzle [9]–[11]. The film thickness generated by micro-dispensing extrusion DW is typically between 1-100 μm, which could be considered as thick film. The extrusion-based DW technique enables direct fabrication of non-planar RTD elements onto non-planar, conformal substrates with a significantly improved layer thickness over thin film additive manufacturing technologies (inkjet and aerosol jet), producing accurate and durable temperature measurements.

In terms of prior literature, Dziedzic *et al.* [1] reviewed the development of thick-film RTDs and concluded that RTDs made of alloys are used less often at elevated temperatures (800 °C) compared to one-component precious metal conductors because the resistance of pure metals at different temperatures are well documented. Platinum is a single-element conductor possessing high linear sheet resistance that is comparable to alloy-based conductors. As a result, platinum RTDs are listed as a key instrument in the definition of the International Practical Temperature Scale [12]. Wang *et al.* [13] have fabricated and characterized Indium-tin-oxide (ITO) thin film RTD using radiofrequency (RF) sputtering technique. The fabricated ITO RTDs have a larger temperature coefficient of resistance (TCR) than platinum RTDs above 600 °C. That implies larger change in resistance over the same temperature range, but were unstable below 600 °C due to reaction with oxygen. D'aleo *et al.* [14] designed and fabricated a thin film platinum RTD array on an alumina substrate using photolithography and observed significant variation in resistance among fabricated RTD traces, possibly due to nanometer-level layer thickness and defects in the photolithography and evaporation processes. Kim *et al.* [15] fabricated and studied platinum-based thin film RTDs by direct current (DC) sputtering and characterized the effect of annealing temperature on sheet resistance. To the authors' knowledge, there exists no published work on using extrusion-based DW to fabricate platinum-based RTDs on planar or curved substrates. This paper will present the extrusion-based DW fabrication, structure and composition analysis, and performance validation of platinum based RTDs on a planar ceramic substrate. In addition, the authors will demonstrate the printing of an RTD element on the lateral area of a semicircular cylinder alumina substrate.

II. Experimental Methods

A platinum ink formulation was chosen as the RTD material due to its reliable resistance to temperature relationship over a wide range of temperatures and its chemical stability. The ink used for printing was ESL 5545 fritted platinum paste, which contains platinum in a 2, 2, 4-Trimethyl-1, 3-Pentanediol Mono-isobutyrate (TXIB) binder. The ink contains approximately 50% platinum by weight. For sintering, the manufacturer recommended a peak sintering temperature of 850 - 1300 °C for 15 minutes with an initial ramp rate of 60 - 100 °C/min. The sintered platinum has a sheet resistance spec of 45-110 mΩ/sq. ESL 9595A silver palladium conductor ink was used for the metal contact pads. The silver ink manufacturer recommended a peak sintering temperature of 600 - 930 °C for 10 - 12 minutes with an initial ramp rate of 60 - 100 °C/min. The sintered silver has a sheet resistance spec of < 10 mΩ/sq. Moreover, the contact pads are designed thick and thus are not expected to change the resistance of the platinum trace. A 96% alumina sheet (McMaster 8462K21) was used as a planar substrate. DW printing was performed on an nScrypt tabletop series micro-dispensing system. This flow-based dispensing system supplies a continuous flow of ink through a nozzle. The nScrypt system integrates a novel smart pump into the direct-print dispensing tool (Figure 1a). First, a 3-cc syringe is loaded with the ink and connected to the assembly. When an air pressure command is sent through the software, ink fills the assembly and is stopped by a closed nozzle valve. The amount of ink extruded through the ceramic head nozzle is controlled by the degree of valve opening. A surface mapping of the substrate is performed before printing to account for any unevenness of the print surface through adjusting the height of the print head during printing. The integrated vertical valve system can dispense materials with a viscosity of up to 1000 Pa·s at room temperature under controlled air pressure, valve opening, and dispensing gap [16]. The printed trace line resolution can reach 20 μm, about twice of screen-printing resolution [17].

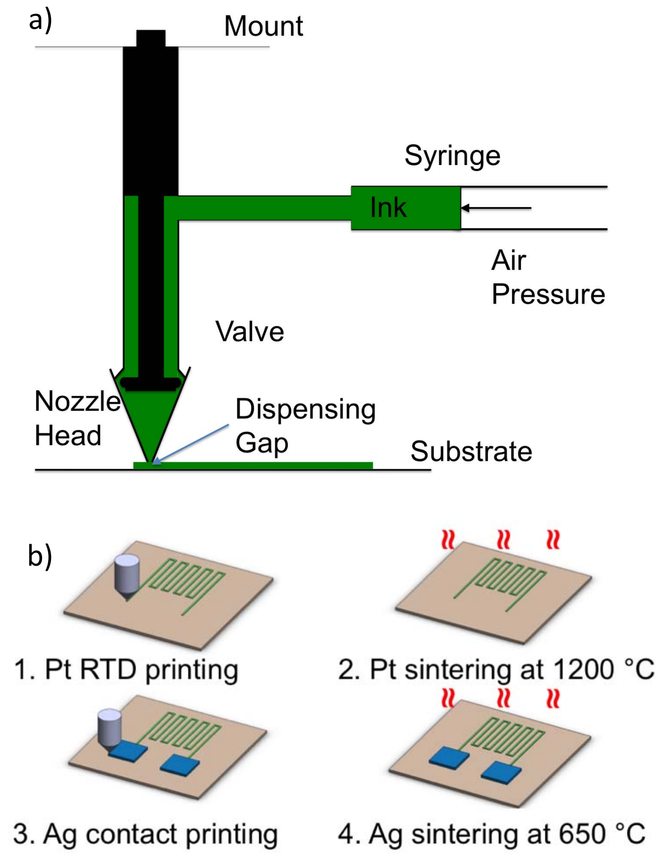

Fig. 1. a) Diagram of the nScrypt extrusion process. b) Stepwise procedure for DW printing and sintering of an RTD.

A typical RTDs resistance value is around 100 Ω for reliable temperature measurements, and since platinum has a relatively high conductivity, long, narrow, and thin traces are required to fabricate resistors in this range. Lewis *et al.* and Morissette *et al.* [18] investigated the influence of ink rheology on line resolution and surface topography of printed material for extrusion-based DW. Their studies suggest the apparent viscosities at low shear rates (< 1 s^{-1}) strongly influence the line width (resolution) and surface topography. For instance, inks with a higher viscosity at low shear rates would yield higher resolution patterns. Conversely, inks with a lower viscosity at low shear rates are prone to settling but tend

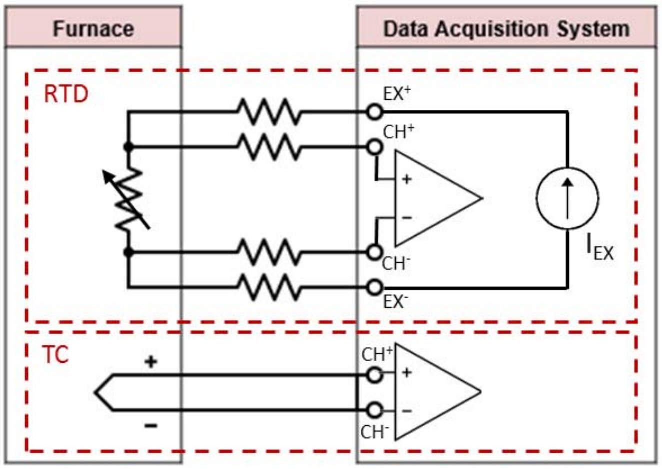

Fig. 2. RTD temperature testing apparatus, featuring 4-wire configuration of the RTD. A thermocouple (TC) is also presented for reference.

to produce smoother surfaces due to surface tension, which minimizes the surface area. The measured apparent viscosity of ESL 5545 platinum ink is around 1000 Pa·s at 0.1 s^{-1} shear rate using an AR-G2 rotational rheometer, which is high enough to minimize spread after ink is deposited onto the substrate. Other studies have shown that small dispensing gaps and high substrate speed are desirable for printing high-resolution lines in extrusion-based DW printing [8], [19].

Based on the authors' prior work [20], the following printing conditions were chosen for fabricating the platinum RTDs: a 100-μm diameter nozzle, a substrate moving speed of 20 mm/s, a dispensing gap of 75 μm, and an ink feed pressure of 30 psi. An alumina substrate was selected to withstand the high temperature involved in sintering. Figure 1b shows the stepwise RTD printing procedure for the planar RTD. The printed platinum RTD traces were sintered in air at 1,200 °C for 15 minutes. Before printing the silver pads, the substrate moving speed was reduced to 5 mm/s in order to increase thickness and improve definition. The pads were then printed and sintered in air at 650 °C for 15 minutes.

RTD calibration and testing: A Nickel-alloy type E thermocouple temperature was cemented onto the alumina substrate next to the RTD sensor using RESBOND 940 HT fast cure alumina adhesive and provided a reference temperature T. The TC and RTD were then connected to a National Instrument cDAQ-9174 signal transducer to convert resistance to digital values. A LabVIEW-based data acquisition system was used to measure and record changes in RTD resistance and TC temperature at a 1 min^{-1} sampling rate. A four-wire resistance configuration was employed to eliminate the effects of resistance between the lead wires and the silver contacts, increasing the accuracy of the RTD resistance measurement [21]. In this configuration, two of the wires are connected to an excitation current source to create a measurable voltage change across the RTD. The other two RTD wires are connected to measurement channels of the data acquisition system. These channels have high impedance, which results in a low current in the measurement circuit and a negligible voltage contribution from the lead wires and electrical interconnects (Figure 2). The resistance is calculated by dividing the measured RTD voltage by the supplied excitation source current. To generate temperature changes, a Neytech 9493308 three-stage programmable furnace was used to heat the RTD and TC from 50 °C to 350 and 500 °C at a rate of 2 °C/min, followed by a 3-hour hold at peak temperature, and a 2 °C/min cooling rate back down to 50 °C. A quadratic relationship between the resistance of the RTD (R) and temperature (T) was assumed (see equation 1 below).

$$R = R_0(1 + AT + BT^2), \tag{1}$$

where R is the resistance of the RTD trace, R_0 is the resistance of the RTD trace at 0 °C, T is the temperature in degrees Celsius, and A and B are temperature coefficients of resistance (TCRs). R_0, A, and B were acquired by fitting the RTD resistance readings with TC temperature readings for T up to 500 °C, according to equation 1. The fitted coefficients were: $R_0 = 72.33\ \Omega$, $A = 0.00380\ °C^{-1}$, and $B = -6.578 \times 10^{-7}\ °C^{-2}$. Following calibration, the same temperature profile was used to qualify the accuracy, repeatability, and long-term reliability of the RTD device.

To demonstrate conformal printing functionality, an additional RTD, comprising of Pt RTD traces and Pt contact pads on a glass-ceramic semi-cylindrical substrate, was printed and characterized.

III. Results and Discussions

Planar RTD physical analysis: Figure 3a shows a printed platinum RTD sensor with silver contact pads on a planar alumina substrate. Due to the nature of extrusion-based DW, variations in printing can arise from process parameters, material properties, substrate roughness, and other sources, resulting in resistance variations among individual samples. The average resistance of 12 sequentially printed platinum RTD traces was 69.5 Ω with a standard deviation of 10.2 Ω, measured at room temperature of 25 °C. The RTD selected for electrical characterization had a resistance of 76.5 Ω at room temperature. The average line width was measured to be 145 μm with a standard deviation of 9.32 μm based on micrographs taken at ten different locations. White-light interferometry imagery showed the RTD traces have an average post-sintering thickness of 3.5 μm. Using these values to calculate cross-sectional area yields a sheet resistance of 200 mΩ/sq or a resistivity of $7 \times 10^{-7}\ \Omega \cdot m$ for the printed traces, higher than the manufacturer's reported value of 45-110 mΩ/sq or the resistivity of $1.06 \times 10^{-7}\ \Omega \cdot m$ for pure platinum metal [22]. As the sintering process should already be accounted for in the manufacturing spec, the deviation may be attributed to the fast substrate moving speed during printing. To analyze the porosity of the traces printed in three dimensions, focused ion beam (FIB) microscopy was carried out to mill and collect a series of 2D images. These images were then used to reconstruct the 3D structure (Figure 3c). Non-unformity of the printed structures is noted. The larger (marco) pores are likely a result of sample inhomogeneity and/or process fluctuations during printing, for example due to fast substrate

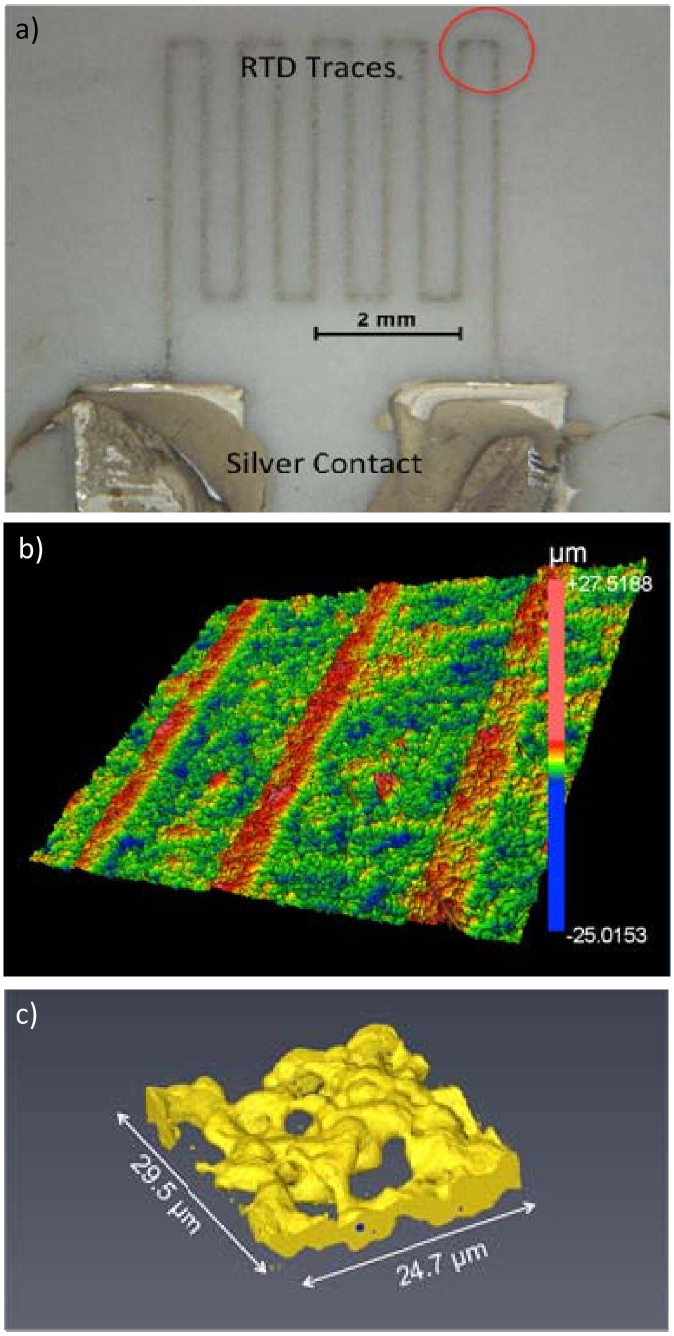

Fig. 3. a) Printed RTD device including platinum traces and silver pads on a planar alumina substrate post sintering. b) White light interferometry analysis of a Pt trace on the flat substrate post sintering. c) 3D printed platinum trace image by assembly of discrete cross-sectional FIB images.

moving speed and insufficient material dispensing; whereas the smaller pores are probably created as solvents evaporated during sintering. Similar observations have been reported in previous studies [18], [20]. This non-uniformity affects the sheet resistance of printed traces compared to a conventional screen-printed pattern (Figure 4a). The process variability could be reduced by increasing the extrusion amount or the cross-sectional area of printed traces, at the expense of a longer printing pattern for achieving the same resistance.

Planar RTD microstructure and component analysis: Figure 4b shows the microstructure of sintered RTD traces.

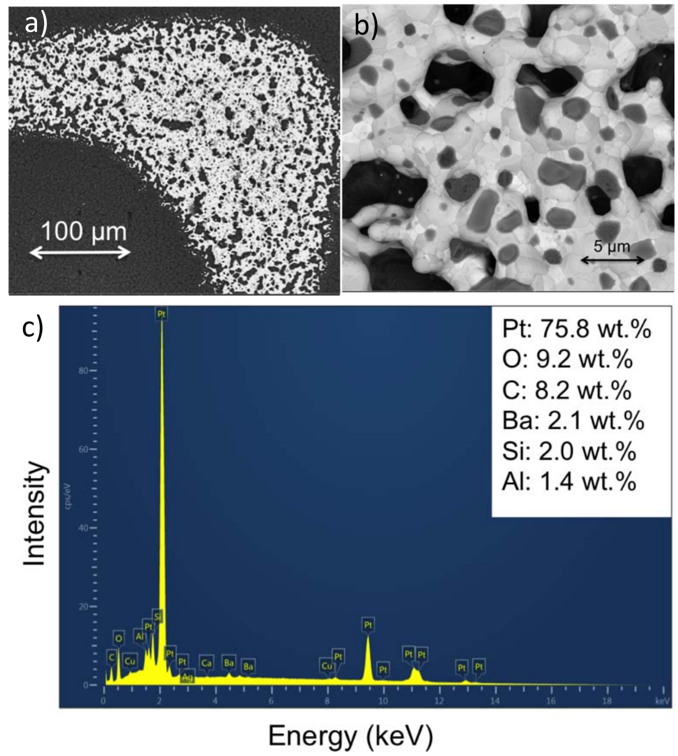

Fig. 4. a) High magnification SEM image of a platinum trace post sintering. b) High magnification SEM image of platinum trace. c) EDS spectrum: analysis of particles in the thick-film RTD trace.

The EDS spectrum (Figure 4c) listed the elements present with concentrations at or above 1 wt%. The results indicate the particles are predominately Platinum with some underlying alumina elements present, as a result of the porosity of the Pt trace. In this application, the increased resistance caused by the porosity is desirable to create sufficiently high resistance for RTD functionality.

Planar RTD electrical analysis: Figure 5a shows the repeatability performance of the RTD during temperature ramping tests at 350 °C. An excellent match can be seen from the three experiments, with a peak temperature variation of less than 0.2 °C. In comparison, type E TCs have a peak temperature variation of around 3 °C. At 500 °C (Figure 5b), the peak temperature variation between three temperature ramping experiments increased to around 3 °C for the RTD, similar to the variation of 3.5 °C for type E TCs. One possibility of the deviation is the oxidation of the silver contact pads. Since the silver pads were sintered at 650 °C, exposure of the pads to 500 °C for a long period of time might make the silver unstable and possibly contaminate the platinum traces. Following the 500 °C endurance test, some darkening of the Pt traces was observed near the silver contact pads and the resistance of the RTD had drifted slightly. While the RTD was still able to achieve high temperature reproducibility that is comparable to a type E TC, applications with more precise high temperature requirements should utilize a more stable high-temperature contact material or an encapsulation methodology.

From Figure 6a, it can be seen that the RTD responds slightly slower (about 10 seconds slower) to temperature

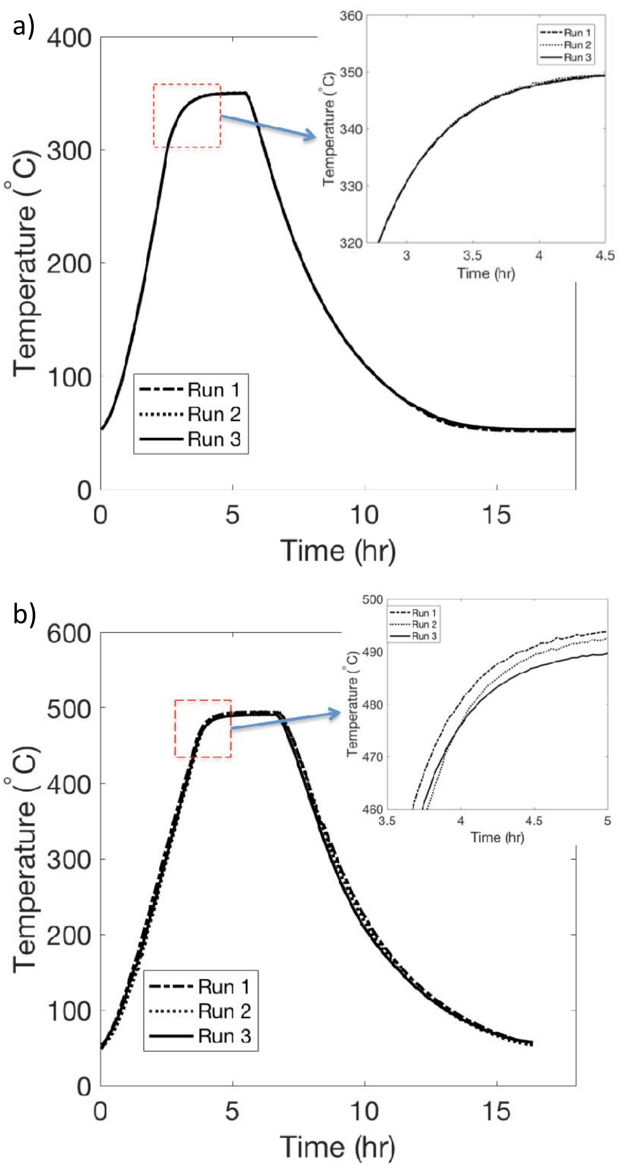

Fig. 5. a) 350 °C repeatability evaluation based on three runs on the same RTD device. b) 500 °C repeatability evaluation based on three runs on the same RTD device.

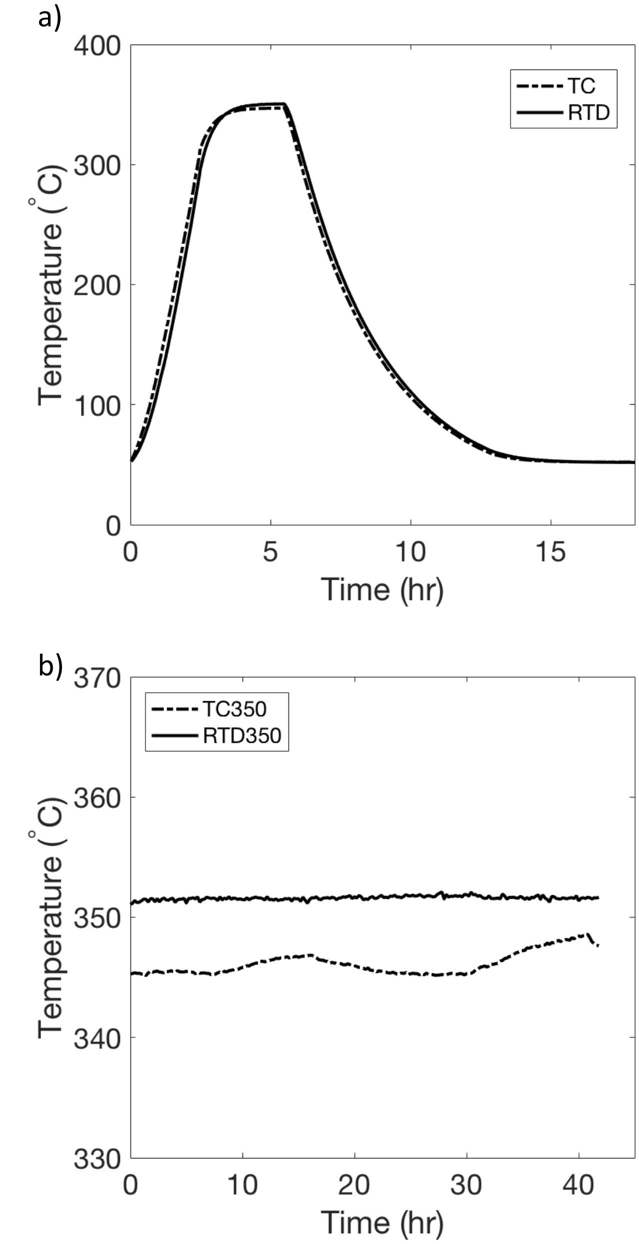

Fig. 6. a) Temperature testing: RTD compared to TC. b) 40 hours at 350 °C endurance test of RTD compared to TC.

changes than the TC. This is because RTDs cannot be grounded and their sizes and thermal inertia are slightly larger than a TC. During a 42-hour air stability test comparison at 350 °C (Figure 6b), the printed RTD showed a temperature variation of 1.03 °C, which is 70% smaller than the TC's 3.45 °C variation. TC readings were consistently 3-4 °C lower than the RTD readings and 2-3 °C lower than the furnace's set temperature of 350 °C.

When comparing the performance of printed RTDs against commercial TCs, RTDs provide more accurate and repeatable readings than TCs, but are slower in response time. TCs are typically made of thin wire to minimize thermal shunting and reduce response times. The thin wire could cause TCs to have a high resistance that can cause errors due to the input impedance of the measuring instrument [23], [24]. The accuracy of a thermocouple can also be compromised by electrical interference and the impurity of the metals used. Printed RTDs can be smaller than their coil counter-parts, using less material and providing faster response time.

Conformal RTD physical analysis: Figure 7a shows the surface mapping of a curved glass-ceramic substrate, as evaluated by the nScrypt machine's laser displacement sensor. During printing of a layer, the print head adjusts vertically according to local substrate height to enable DW printing on curved surfaces. This functionality of extrusion DW provides increased application flexibility over screen printing and unleashes the possibility of directly printing electronic components onto existing components with non-planar geometries. Figure 7b demonstrates DW printing of an RTD element with contact pads on the substrate, with post-sintering surface topology analyzed by white light interferometry showing a trace height of $\sim 5\ \mu$m (Figure 7c).

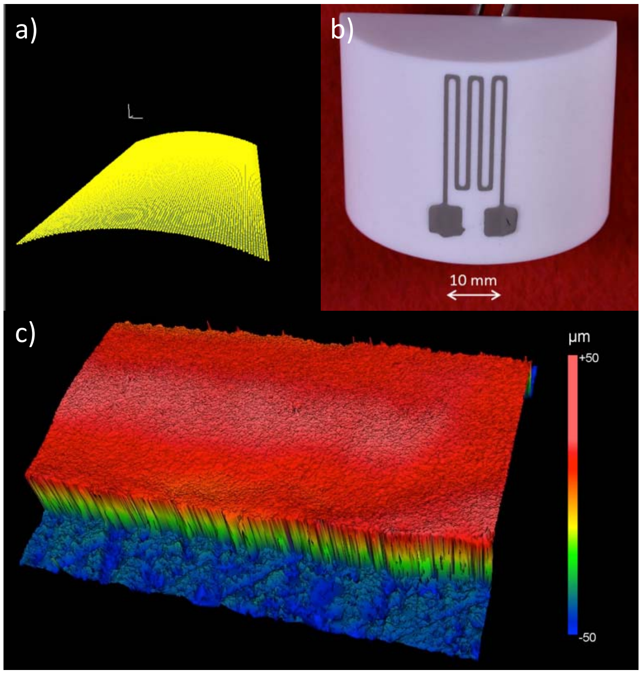

Fig. 7. a) Surface mapping of a curved glass-ceramic substrate before printing. b) Printed Pt RTD element with Pt contact pads on the curved substrate before sintering. c) White light interferometry analysis of a Pt trace on the curved substrate post sintering, indicating a trace height of $\sim 5\ \mu$m.

IV. Conclusions

Thick film RTDs comprising of Pt traces and silver contact pads were fabricated by extrusion-based DW. The platinum ink was sintered at 1200 °C and the silver ink was sintered at 650 °C. A printed RTD was fully characterized to determine the microstructure, chemical composition, and electrical characteristics of the printed platinum traces. A four-wire resistance configuration was utilized to eliminate the effects of contact resistance and increase the accuracy of the RTD resistance measurement. The printed RTD showed good repeatability in temperature ramping tests and a slightly slower response time compared to a commercial thermocouple. In the endurance tests, the printed RTD sensor showed less variation than the thermocouple. The printed RTD resistor showed linear response to temperature up to 350 °C. The small deviation in linearity from a typical bulk-Pt wire could be attributed to the Pt impurity related to ink-formulation additives. Encapsulation will be required to protect the platinum RTD for industrial applications at higher temperatures.

With extrusion-based DW's potential to print on conformal substrates, this work offers methods for depositing RTDs onto 3D structures. Additionally, this construction produces a very stable RTD element with a strong thermal contact between the platinum and the measurement point. This results in a more accurate temperature reading and a fast thermal response time. Future work will focus on encapsulating printed RTDs and testing at elevated temperatures.

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