Fabrication and mechanical characterisation of inkjet printed strain gauges

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Abstract

The present study focuses on printing strain sensors directly on tensile test specimens using inkjet printing technology. This type of strain gauges has the advantage over conventional strain gauges that no glue or carrying platelet is present between the sensor and the surface that should be measured. Therefore, strains in thin foils can possibly be measured with printed strain gauges. First, proof of principle is given in this paper by successfully printing strain gauges on FR4. The printed strain gauges prove to behave linearly up to strains of 0.2% and can measure the strains within 3.5% accuracy.

1. Introduction

Printed smart objects that are fabricated using conventional or digital printing technologies have generated enormous interest in industries as far afield as healthcare, retailing and packaging. These smart objects can, among other functions, fulfil one or more of these functionalities: sensing and perception, actuation and activation, communication, information storage and user interaction. The combination of conductive polymers and inorganic materials with printing technologies enables thin, lightweight and extremely cost-effective systems such as flexible batteries, displays, logic and memory components [1], along with basic electronic building blocks.

Smart objects can be prefabricated and embedded into/onto another carrier. An example for this approach is a radio frequency identification (RFID) device printed on a plastic substrate and subsequently mounted on a retail product such as clothing. On the other hand, they can also be fabricated directly on the entity that needs to be tracked, monitored or measured. An example for this approach is discussed in this paper, wherein a strain gauge is inkjet printed on tensile test specimens. These printed smart strain gauges eliminate the need for an additional carrier substrate as well as the need to glue them onto the test specimen, both of which are integral steps of the hitherto widely used conventional approach.

Inkjet printing is a versatile fabrication technology that is especially suited to product development and production prototype up to intermediate lot sizes [2]. It is a non-contact process that can selectively deposit a wide range of materials onto a wide range of substrates in a drop-by-drop manner, and results in minimal material consumption and wastage [3]. In addition to these characteristics, inkjet printing is a mask-less, master-less direct writing method offering a great deal of flexibility within a process chain. This technology was deployed during the course of the present research to fabricate strain gauges on three tensile test specimens made of FR4, an E-glass fibre reinforced epoxy material. The dimensions of these tensile test specimens conformed to ASTM D3039/D3039M standard, and measured 200 mm × 25 mm × 0.8 mm. Subsequent to their fabrication, the performance characteristics of printed strain gauges, especially reliability, repeatability and linearity of the measurement dataset, were established and the findings are reported in this paper.

2. Fabrication of strain gauges

A piezoelectric drop-on-demand inkjet printer (Jetlab-4 from MicroFab Technologies, Inc., USA) was used for the printing trials relevant to this paper. The nozzle used had an internal diameter of 80 µm. A silver nanoparticle-based dispersion (NPS-J from Harima Chemicals, Inc., Japan) was used to print the strain gauges. The sequence of strain gauge fabrication on FR4 (Park Electrochemical Corp., USA) is as follows:

1. Designing the strain gauge using a CAD software program and converting the resulting design into printer-readable bitmap image with sufficient resolution
2. Optimisation of inkjet printing parameters for the given nozzle diameter, ink and substrate material. The important parameters are the waveform that actuates the piezoelectric transducer (PZT), which, in turn, generates acoustic waves within the nozzle, the droplet pitch, the frequency of droplet formation, and the nozzle as well as substrate temperature settings
3. Inkjet printing of the strain gauge
4. Sintering of the printed strain gauge to impart continuity and hence render it electrically conductive

The optimised printing and post-print-processing parameters used for strain gauge fabrication are listed in table 1.

Table 1. Printing and post-print-processing parameters

Parameter	Setting
Waveform	Unipolar, voltage = 51 V
Droplet frequency	650 Hz
Droplet pitch	X = 90 µm; Y = 120 µm

Temperature settings	Nozzle: room temperature; Substrate holder: 70 °C
Sintering method	Convection oven-assisted thermal sintering
Sintering parameters	Temperature: 210 °C; Duration: 60 minutes

Figure 1 depicts a printed strain gauge on FR4. The droplet pitch in X and Y directions are different, as in the X-direction, continuity of the printed strain gauge is of prime importance, whereas in the Y-direction, the individual line segments of the strain gauge should not contact each other to avoid short circuiting. By heating the substrate holder during printing, the spreading of the ink on the substrate is minimised, as the solvent present in the ink evaporates rapidly. This approach resulted in well-defined line segments that form the strain gauge. The sintering parameters were specified by the ink supplier for good electrical conductivity.

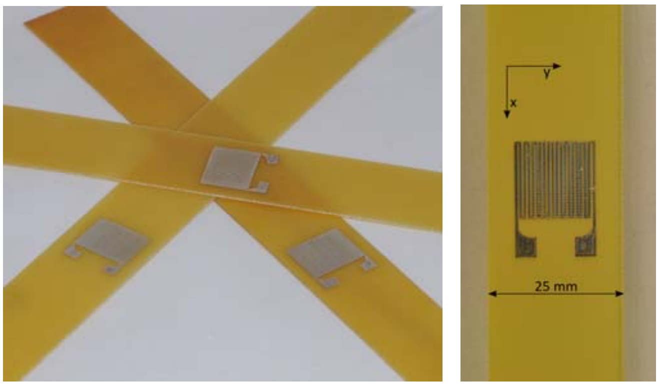

Figure 1. Three printed strain gauges on FR4 with a close-up of the strain gauge design on the right.

3. Experimental

For the mechanical characterization a Zwick Z5.0 universal mechanical testing machine equipped with two tensile fixtures and a 2.5 kN force cell was used. The strain was measured using an Instron clip-on strain sensor. Both the clip-on strain sensor and the printed strain gauge were connected to a National Instruments 9237 half/full bridge connector. National Instruments Labview was used for the data acquisition.

A quarter bridge type II setup was used, meaning that one active strain gauge and one inactive element with an equal electrical resistance is used. If a strain gauge is used as an inactive element, the measurement will be compensated for temperature effects. As the resistance of the printed strain gauges is not equal to one another, a variable resistance is used as inactive element to properly balance the bridge before each measurement.

4. Strain Gauge Performance

The performance of the printed strain gauges was characterised by subjecting the substrate to a uni-axial, cyclic tensile load. Were it would be easier to reach high strain levels in a three point bending setup, the tensile direction was selected as it is more straightforward to measure the tensile strain with an additional clip-on strain gauge and moreover the tensile modulus is known, which can be used as a cross-check of the results obtained. After clamping the specimen it deformed in a cyclic manner. The resulting strain (as measured with the clip-on strain gauge) is shown in Figure 2 (bottom). The strain increases linearly up to 0.18% kept constant for 10 seconds and subsequently decreases linearly to 0.04%, where it is kept constant again for 10 seconds. This cycle is repeated three times to validate whether the printed strain gauge gives repeatable results after being strained. The measured force is converted into the (tensile) stress in the specimen and also shown in Figure 2 (top). At maximum strain a maximum stress of 44.2 MPa is measured, resulting in a Young modulus of 24.5 GPa which is close to the 25.1 GPa given by the manufacturer.

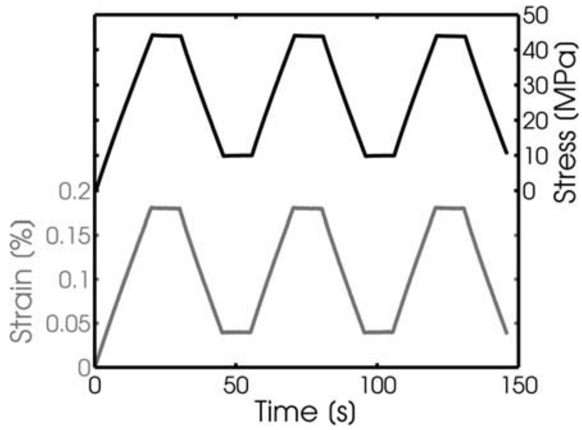

Figure 2. The measured strain signal from the clip-on strain sensor (bottom, grey) and stress signal (top black) resulting from the crosshead displacement.

4.1. Gauge Factor

The gauge factor of the printed strain gauge can be determined from the measured voltage on the Wheatstone bridge (V_{ch}). The relation between the gauge factor and a quarter bridge type II is given by (if the influence of the resistance of the wiring is neglected):

$$\text{gauge factor} = \frac{4 \cdot V_{ch}}{\varepsilon\left(V_{ex} + 2 \cdot V_{ch}\right)}, \quad (1)$$

where ε is the strain as measured by the clip-on strain sensor and V_{ex} is the excitation voltage which was equal to 2.5 V for all measurements. The resulting gauge factor of one of the printed strain gauge as measured during the cyclic tensile test is shown in Figure 3. The gauge factor shows to be nearly

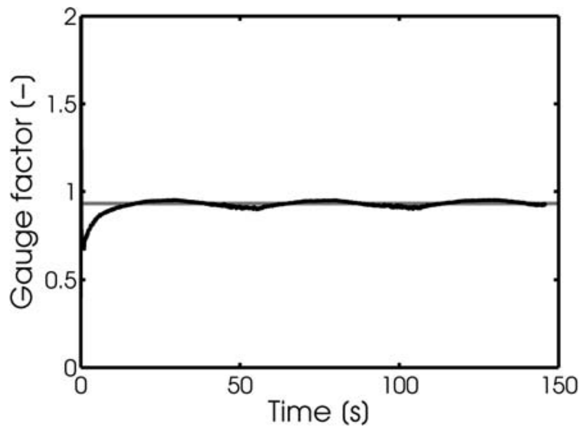

Figure 3. The gauge factor as calculated from the measured voltage over the Wheatstone bridge using equation (1), with the strain from the clip-on strain sensor as a reference.

constant after some non-linearity at low strains (mostly at the start of the test). Neglecting the first 20 seconds of the test, the average gauge factor value is determined to be 0.93.

With this value of the gauge factor the measured voltage on the bridge can be converted into a strain. A new tensile test was carried out (and shown in Figure 4) to verify whether the strain as determined with the printed strain gauge (black line) is comparable to the strain measured by the clip-on strain sensor (grey line). The strain from the printed strain gauge proves to behave linearly and quantitatively agrees with the strain as measured from the clip-on strain sensor. The relative error of the printed strain gauge signal is lower than 3.5% throughout the cyclic tensile test. The two other printed strain gauges show a similar linearity and relative error. The gauge factor of the other two strain gauges do, however, differ significantly, which will be briefly discussed in section 5.2.

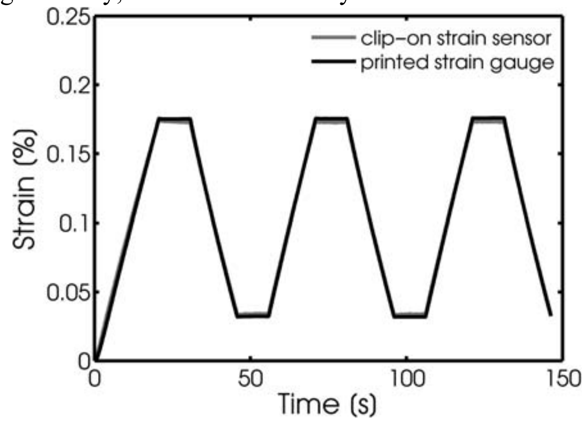

Figure 4. The measured strain signal from the clip-on strain sensor versus the strain as measured with the printed strain gauge, using gauge factor of 0.93.

4.2. Robustness

After multiple cyclic tensile tests the gauge factor of the printed strain gauges remains fairly constant, so it is possible to reuse the gauges when strained to low deformations. One of the gauges was strained up to 1% without permanent damage or a change in gauge factor. The same was found for all three printed strain gauges.

5. Discussion

Two notable effects were found during the characterization of three printed strain gauges. Firstly, the strain gauges appeared to be very sensitive for temperature changes. Secondly, although the resistance of the three printed strain gauges are similar, their gauge factor is not. These two outcomes will be discussed briefly in this section.

5.1. Temperature Dependence

Temperature fluctuations have a distinct influence on the printed strain gauge signal. Blowing upon the gauge surface can result in a measured strain of up to 0.05% strain, which was very significant in the tests carried out in the present study. Therefore, the tensile bar was wrapped during the cyclic tensile tests to protect the gauge surface from drafts. The sensitivity of the printed strain gauges to temperature changes is directly related to the high surface to volume ration of the sensors when compared to conventional strain gauges. In the future it would be sensible to print an additional gauge upon the specimen surface to compensate for temperature effects with the use of a half bridge Wheatstone configuration.

5.2. Variation in gauge factor

Although the unstrained resistance of the three printed gauges do not differ too much from one another (36.1 Ω, 34.7 Ω and 35.2 Ω) the gauge factor does (0.93, 1.82, 1.90). The reason for this difference in gauge factor is not yet known, but has to be resolved in the future. Until the origin is known, all of the printed gauges have to be characterised before they can be used for strain measurements.

6. Conclusions and Outlook

As a first step towards strain gauge printing, three stain gauges have been printed on FR4. The strain gauges prove to be able to measure the strain with a precision within 3.5%. Drawbacks of the strain gauges are that they very sensitive for temperature changes and the strain gauges printed so far differ in the gauge factor. Future work focuses on reducing the temperature dependence by printing a second strain gauge on the substrate and on reducing the variation the strain gauge properties.

7. Acknowledgements

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8. References

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