

Direct Print Technology for Fabricating Mechanical Sensors

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Abstract

The emergence of printed electronics as an industry has been growing and recognized in application areas such as antennas, RFID, displays, and photovoltaic cells. In addition to these highly publicized areas, it also holds considerable promise for the sensor sector. Printing can reduce the cost of high volume manufacturing and is an ideal way for fabricating sensors even with multiple layers. The process of fabricating crack detection and strain sensor structures by the nScript direct printing technology has been developed. Compared to traditional photo-resist and acid etching processes as well as other jetting technology, the nScript direct printing technology gives a solution of laying down fine sensor geometries on flat or conformal surfaces and handling materials with a wide range of viscosities. One combination of conductor ink and dielectric ink was used to demonstrate the devices. The sensors were directly printed on a specified area of the structural component and a series of tests were carried out to evaluate their performance.

Keywords: direct-printing, micro-dispensing, high speed, high viscosity, low temperature, mechanical sensors

Introduction

Strain sensors are abundant in use, form factor and technological approach. One of the most common strain sensors known as a foil strain gauge is simple, rugged, inexpensive and effective. The most basic foil strain gauge is comprised of a dielectric substrate, typically a polyimide that is bonded to a surface, and a metallic pattern that is strategically designed to exemplify a change in resistance due to stretching, bending, cracking or any deformation on a given mechanical surface. As the strain of the surface changes, the resistance of the sensor is designed to vary linearly as a correlation of the strain. The foil strain gauge sensor has a number of advantages and including, reasonably stable over temperature ranges, physically small, simple in design, low cost and high sensitivity.

In standard strain gauge applications, the mechanical surface and the bond adhesive must correlate and translate the strain within the surface through the bonded portion and present this to the

conductive pattern. This direct coupling mechanism allows the metallic pattern to be linearly distorted thus presenting a mechanism for translating the change in resistance to strain.

There are a number of factors that influence the choice of strain gauge sensors, our focus is on applications in which conformal fitting is a benefit. Sometimes conformal implies curved surfaces and this can induce strain in the sensor before the surface has experienced any strain and thus induce an initial error. Sometimes conformal implies a more monolithic approach, which could be on a curved or a flat surface. In reality, flat surfaces are not truly flat and bonding a flat sensor and a semi-flat surface implies some mismatch. A truly conformal sensor will take the shape of the flattest, slightly flat or non flat surfaces and do so without initial strain on the sensor.

In this paper we will discuss methods of Directly Printing Sensors on various surfaces. Directly Printed Sensors have the advantage of taking the shape of the

surface that is being printed on. Two types of sensors were printed using a computer controlled micro-dispensing approach: 1) strain gauge sensor and 2) crack sensor. These sensors were printed on polyimide to evaluate their electrical consistency and then pulled to failure using a tensiometer to characterize the resistance versus distance of the sensors. In addition to this, a test of the sensitivity and consistency as both strain and crack sensors were demonstrated by directly printing these sensors on a stainless steel test fixture and then pulling the stainless steel test fixture to failure.

Foil Strain Gauge Functionality

Significant literature exists regarding the fabrication of strain gauges through printing or electro-deposition [1-7] and also about specific applications [8-11], however, these all describe the fabrication and use of circuits not originally fabricated in the shape of the final conformal destination. A foil strain gauge or crack sensor operates on the principle of changing resistance given the changes to stress or strain in the mechanical device under test. The resistance change will provide a Gauge Factor (GF) given by the following:

$$GF = \frac{\Delta R/R_G}{\epsilon}$$

where

R_G is the resistance of the gauge with stress, ΔR is the change in resistance resulting from strain, and ϵ is the strain.

For typical gauges, the gauge factor is around two, which is defined by the metal, the substrate and the bond being used. For a single active gauge in a Wheatstone configuration, the output v from a Wheatstone bridge is:

$$v = \frac{BV \cdot GF \cdot \epsilon}{4}$$

where

BV is the Wheatstone supply voltage.

Foil gauges typically have active areas of about 2-10mm² in size and strains of up to at least 10% can be measured under normal circumstances.

When forces are applied to a stationary object, stress and strain are the result. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur as a result. For a uniform distribution of internal resisting forces, stress can be calculated by dividing the force (F) applied by the unit area (A).

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total change in the length (ΔL) by the original length (L):

$$\text{Strain } (\epsilon) = (\Delta L)/L$$

Typical values for strain are less than 0.005 inch/inch and are often expressed in micro-strain units:

$$\text{Micro-strain} = \text{Strain} \times 10^6$$

Direct Printing

There are a number of approaches that can be used for directly printing materials, each will have specific advantages given the nature of the technology. Micro-dispensing is one of the options and is particularly useful given the wide range of materials that can be dispensed with regards to viscosity. Micro-dispensing is typically done using a positive pressure on the material and pressing the material through a small orifice. The nScript technology uses a patented valve near the orifice to control the starts and stops of the material. In addition to this, a specialty designed pen tip is used to reduce the pressure when trying to press material out of very small openings, such as 100 microns or less. Fig. 1 below is a picture of an nScript pen tip printing lines on a substrate.

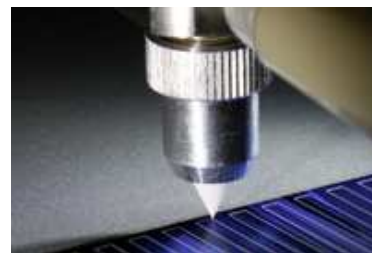


Figure 1 Pen tip printing fine lines on a solar cell.

The valve will open and close in a coordinated manner with the motion control. This allows any pattern to be printed in an X, Y plane and if necessary conformally in the Z plane also by doing Z tracking. The added benefit of Direct Printing is the computer control which implies any pattern that can be generated in a computer can now be printed on any curved surface. Therefore printing electrical devices on a wide variety of surfaces and making those devices functional is much more feasible.

Directly Printed Strain and Crack Sensors

Sensor structures, as shown schematically in Fig. 2, were formed by directly printing silver loaded conductive ink onto substrates, which include Kapton® and a stainless steel fatigue test fixture. For the metal substrates, a UV curable dielectric layer was printed prior the silver structure. A schematic process view is shown in Fig. 3. The step (b) was skipped for the sensor structures printed on Kapton®.

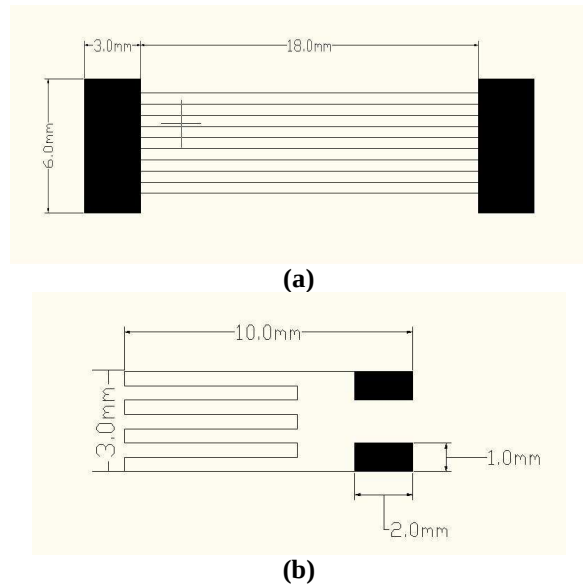


Figure 2 Schematic view of sensor structures (a) crack detection sensor, (b) strain gauge

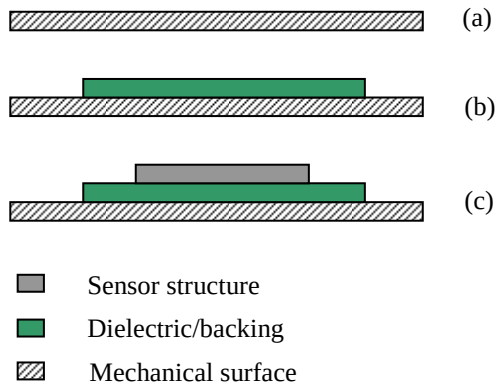


Figure 3 Process of Direct Printing Strain and Crack sensors: (a) substrate or test fixture, (b) print and cure dielectric layer, (c) print and cure sensor structure.

The apparatus used for direct printing was the nScript 3D-450 fast speed direct printing/micro-dispensing system equipped with the SmartPump™. A UV curable dielectric ink (Acheson ElectroDAG 452SS) and a low temperature curing silver ink (DuPont CB028) were used for the dielectric layer

and conductive sensor structures. After printing, the dielectric layer was cured under UV light (125wpi) and has a thickness of ~50um. The conductive sensor structures were cured at 160°C and ~15um thick.

The crack sensor includes tens of paralleled conductive lines and two connecting pads. The strain gauge sensor is a serpentine line with connecting pads at both ends. The smallest line width can reach 60um and the spacing between lines is usually a few hundred micrometers.

Tensile Testing of Strain and Crack Sensors

Tests were performed on two basic strain gauge designs: a parallel line design; and a serpentine design. Gauges of each type were printed on polyimide film. The printed gauges were tested using an Instron Model 5866 test station with a 500N load cell for tensile load and extension measurements. Fig. 4 shows the testing setup. A Keithley Model 2000 multi-meter was used to measure resistance. A one hundred-point moving average filter was enabled for measuring low resistances (several hundred milliohms to a few ohms), while a ten-point moving average filter was enabled for higher resistances.

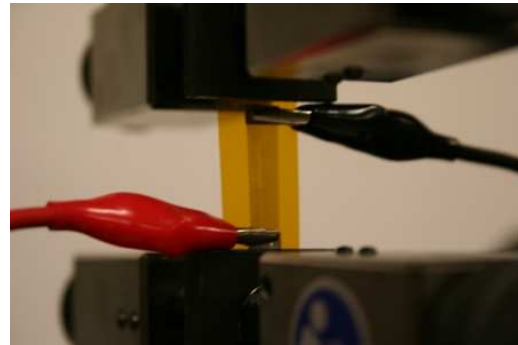


Figure 4 Gauge under characterization test.

For each type of gauge, five samples were tested with three being used for gauge characterization and two for gauge repeatability. Characterization involved preloading the samples with tension to a point where a detectable change in resistance was observed. The displacement meter on the Instron machine was then reset to zero to mark the beginning of the characterization. Displacement (or extension) was then increased in increments of 0.1mm with the load and resistance being captured at each increment. This process was continued for each sample until either the gauge or the substrate exhibited catastrophic failure. Greater than 100 data points were observed resulting in gauge-to-gauge comparison plots for resistance versus strain such as that shown in Fig. 5, and for Load versus Extension as in Fig. 6.

The divergence of the characteristic curves shown in Fig. 5 can be attributed to variations in the

thickness of conductive ink lines from the printing process or possibly to the ink curing process. Fig. 6 shows data collected up to gauge and substrate failure. A point of interest is the near linear performance of the gauge far beyond the elastic range of the substrate material, reaching 9mm in extension before failure. This implies potential use in macro-strain applications.

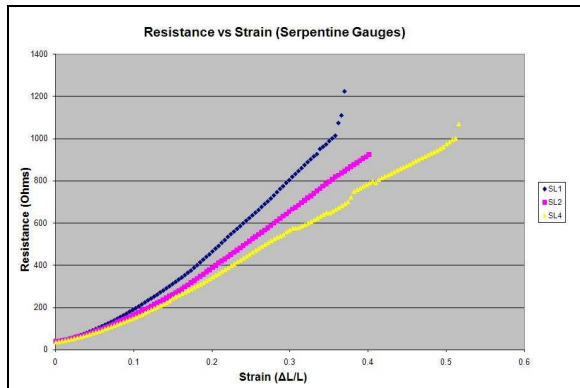


Figure 5 Gauge-to-Gauge Comparison (Serpentine Gauges)

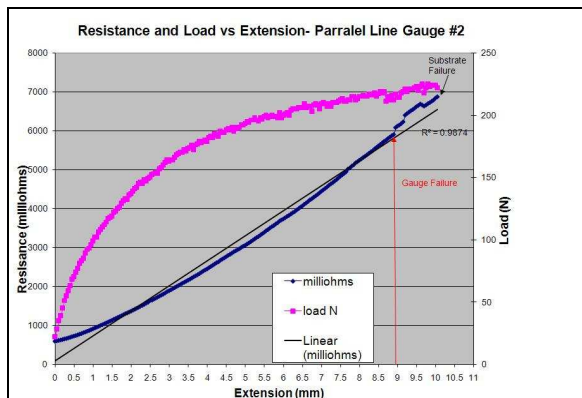


Figure 6 Resistance and Load vs. Extension

Repeatability testing involved a review of the gauge characterization data to establish an appropriate range for repeated tension/relaxation cycles. The desired range is one in which the gauge substrate material (polyimide) will experience temporary deformation in its elastic phase and not suffer permanent damage during strain. For determination of this range, the load versus extension plot was examined. Referring to these plots (see Fig. 6), a decrease in the slope of the load curve near 0.2mm extension for the parallel line gauge (1.0mm for the serpentine type) indicates the edge of the elasticity range of the substrate and the beginning of its plasticity range. These values were used as the maximum extension values during the

tension/relaxation cycles. Several data points were monitored during the cycling ranging from the relaxed state, determined with a preload as with the characterization tests, to the maximum extension discussed above. Resistance and load were captured at each point in the test. The process was repeated a total of five times per gauge resulting in plots such as those shown in Figs. 7 and 8.

Although resistance versus strain appears to be drifting with each cycle performed, the load versus strain is relatively unchanged. This confirms that the substrate material did not experience permanent damage, but the printed gauge itself may have experienced physical change with each cycle. It is possible that this is related to the nature of the cured conductive ink and the elastic properties of the binding material used therein. Another possibility is thermal influence on the test.

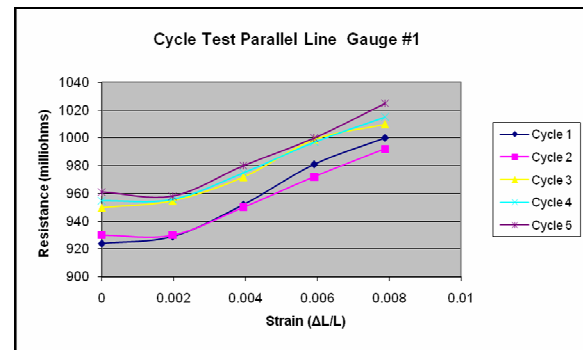


Figure 7 Repeatability – (Resistance versus Strain).

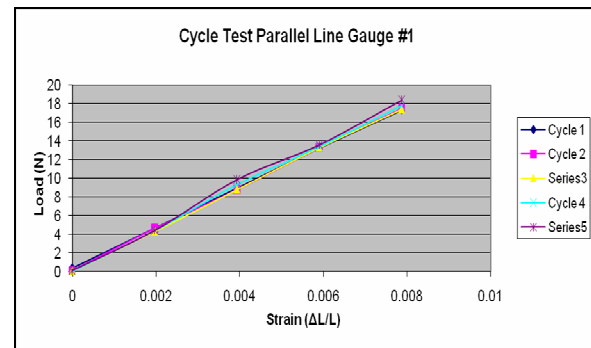


Figure 8 Repeatability – (Load versus Strain).

Application of Direct Print Crack Detection Sensors

The crack sensors were fabricated by Direct Printing technique on CT-samples (size 62.5 × 60 × 10 mm) made of structural steel (St52). The surface of the samples was ground to plain and slightly polished. The crack detection sensors were formed on

two CT-samples (CT-16 and CT-17) within a 10×30 mm large area of the substrate surface by printing first the dielectric layer to insulate the conductive substrate. On the dielectric layer a series of conductive lines connected on both ends forming the contact pads, were printed to form the crack detection sensor as shown in Fig. 9. The line width, spacing, and thickness values of the crack sensors are described in Table 1. Fig. 10 shows an optical microscopy image of the conductive lines. The overall appearance of the sensor materials was smooth and the adhesion of the materials to the steel surface was good enough to withstand the fatigue type testing. The controlled fatigue tests were carried out for the CT-samples according to ASTM E647 standard by using a hydraulic MTS810 material testing equipment. The CT-sample mounted in the test set-up is shown in Fig. 11. The test load was varied following a sinusoidal form with a frequency of 10 Hz. The crack growth rate was kept constant during the tests and the load was adjusted to provide the test duration of about 6 hours as described in Table 2. The opening of the crack was also measured by a conventional crack opening sensor mounted in the notch.

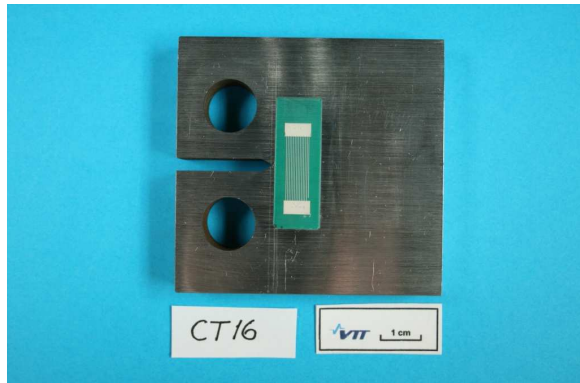


Figure 9 Crack detection sensor on the CT-sample surface consisting of conductive lines printed on the insulating layer.

Table 1 The line width, spacing and thickness values of the crack sensor structures.

Test sample	Conductive lines no	Line		
		width μm	spacing μm	thickness μm
CT16	13	75-110	400	15
CT17	26	100-110	200	11

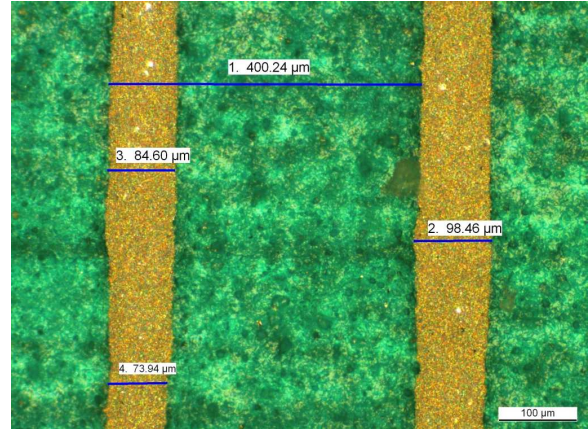


Figure 10 Conductive lines on dielectric layer.

Table 2 The test parameters used in fatigue tests.

Test sample	Load [kN]		Frequency [Hz]	Crack growth rate [mm/h]
	min	max.		
CT16	1.86-0.74	18.3-7.40	10	5.2
CT17	1.50-0.91	14.7-8.90	10	2.5

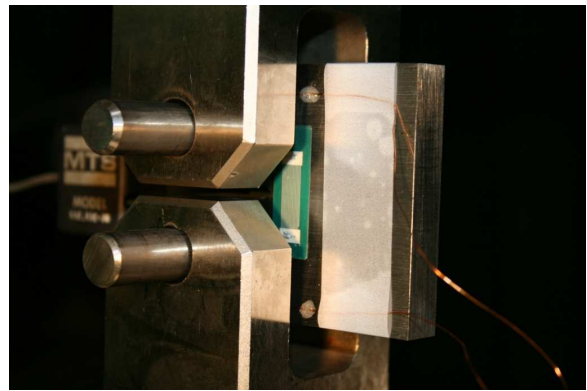


Figure 11 The CT-samples mounted in the hydraulic material testing equipment.

In the fatigue tests the crack initiated from the notch on the side face of the CT-sample and propagated through the sample. The conductivity of the crack sensor structure was measured during the fatigue tests and as the crack propagated through the conductive lines, an increase in the resistivity was observed. For the other CT sample, the resistance was measured by using a simple ohmmeter. Fig. 12 describes the change in resistance as the crack was propagating through the sample. In this case, the change in resistance was delayed compared to actual crack propagation. The sensor consisted of 13 conductive lines and the clear change in resistance was visible after the crack was passed through more than half of the lines.

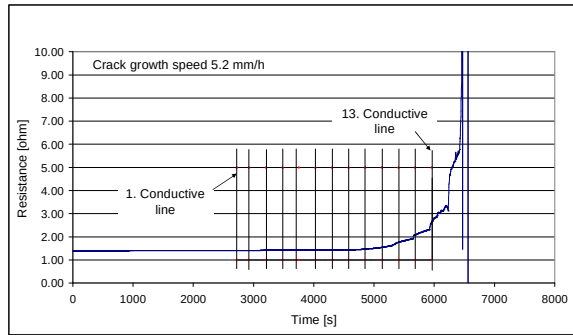


Figure 12 The change of resistance as the crack was propagating through the sensor for the sample CT-16.

In the test carried out with the sample CT-17 the Wheatstone bridge circuit was used for resistance measurement which provided more accurate determination of the resistance and thus offered the possibility to distinguish the difference in resistance for the minimum and maximum load during cyclic loading. As the maximum load was applied, the crack was opened and the resistance of the crack sensor showed high resistance value. However, when the test load was on the minimum level, the crack was closing and the measured resistance decreased on a lower level simultaneously as represented in Fig. 13.

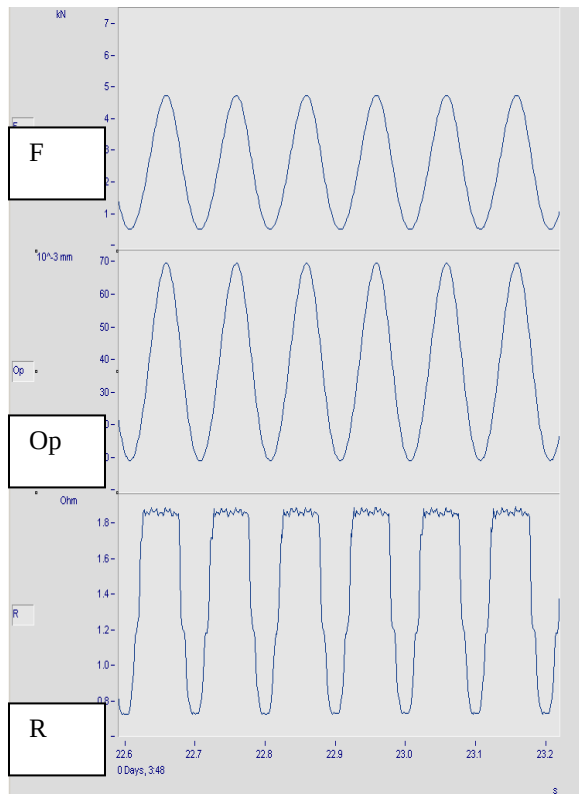


Figure 13 The opening of the crack (Op) and the change in resistance of the crack sensor (R) as the cycling load (F) was applied.

During the test the resistance was measured for the minimum and maximum load during cyclic loading. The signal measured during maximum load opening and the fatigue crack indicated the crack propagation well as shown in Fig. 14. Thus an indication of the crack propagation with a shorter time delay compared to the previous test was observed.

The tests results showed that Direct Printing is a viable technique to manufacture sensors, such as crack detection sensors, for mechanical applications. The adhesion of materials is good enough to withstand the conditions of cyclic loading and the sensors provide good indication of the crack propagating in the mechanical structure.

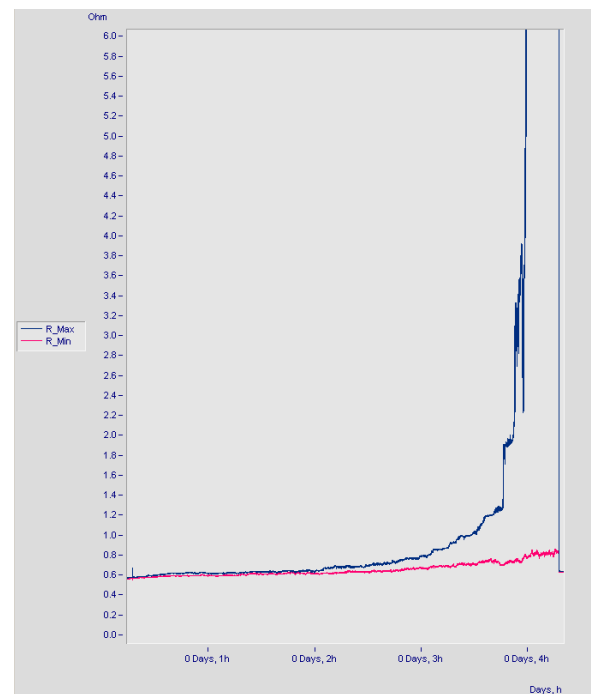


Figure 14 The change of resistance as the crack was propagating through the sensor for sample CT-17. The red line represents the resistance signal during the minimum load and the blue line during the maximum load.

Summary

Characterization and repeatability testing of a small number of Direct-Printed strain gauges of two different designs were performed. Two CT-samples with Direct-Printed crack detection sensor were prepared for fatigue tests. Data from these tests provide an initial indication of the capability of such devices in regards to linearity and dynamic range, while also showing areas requiring further investigation. A comprehensive study involving a more statistically valid sample quantity would be enhanced by investigation and quantification of gauge hysteresis and thermal effects. The relationship

between the printing process and sensor performance must be better understood and controlled. Finally a review of ink/binder properties in terms of elasticity is necessary to obtain the full potential of Direct-Printed mechanical sensors including crack detection sensors and strain gauges.

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References

- [1] Y. Nagase and T. Yoshizaki, "A basic study on the fatigue gauge made of electroplated copper foil (effects of under stress), *International Journal of Fatigue*, vol. 14, no. 1, pp. 65, Jan. 1999.
- [2] G.I. Hay, D.J. Southee, P.S.A. Evans, D.J. Harrison, G. Simpson, and B.J. Ramsey, "Examination of silver-graphite lithographically printed resistive strain sensors," *Sensors and Actuators A: Physical*, vol. 135, no. 2, pp. 534-546, April, 2007.
- [3] G.I. Hay, P.S.A. Evans, D.J. Harrison, D. Southee, G. Simpson, and P. M. Harrey, "Characterization of lithographically printed resistive strain gauges," *IEEE Sensors J.*, vol. 5, no. 5, pp. 864-871, Oct. 2005.
- [4] A. Agrawal, P.K. Patra, and P.D. Calvert, "Printed soft structured piezoresistive strain sensor," *NSTI Nanotech 2007, Nanotechnology Conference and Trade Show*, vol. 2, pp. 32-35, May 2007.
- [5] R.J. Crawford and M. Braniff, "The printing of strain gauges on to plastics," *Plastics and Rubber Processing and Applications*, vol. 8, no. 2, pp. 105-114, 1987.
- [6] G.I. Hay, D.J. Southee, P.S.A. Evans, D.J. Harrison, G. Simpson, and B.J. Ramsey, "Conductive lithographic film fabricated resistive strain gauges," *Proc. of IEEE Sensors*, 2003, vol. 1, pp. 248-252, Oct. 2003.
- [7] M. Seika and K. Hosono, "Fundamental Study on a Foil Strain Gage of Electrodeposited Nickel," *Bul. JSME*, vol. 25, no. 206, pp.1240-1246, 1982.
- [8] Z. Wisniewski, R. Wisniewski, and J. L. Nowinski, "Application of foil strain gauges in high pressure research," *Review of Scientific Instruments*, vol. 72, no. 6, pp. 2829-2831, 2001.
- [9] H.S. Freynik Jr., D. R. Roach, D. W. Deis, and D. G. Hirzel, "Evaluation of metal- foil strain gauges for cryogenic application in magnetic fields," *Advances in Cryogenic Engineering*, vol. 24, pp. 473-479, 1978.
- [10] W. H. Huber, L. M. Hernandez, and A. M. Goldman, "Improved calibrator for the evaluation of batch produced strain gauges in cryogenic environments," *Review of Scientific Instruments*, vol. 70, no. 6, pp. 2872-2874, 1999.
- [11] U. Nolten and W. Mokwa, "Strain gauge foil for the measurement of elastic deformations in orthopedic milling tools," *2008 IEEE Sensors Conf.*, pp. 1476-1479, Oct. 2008.