Time – strain monitoring system fabricated via offset lithographic printing

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Abstract: This paper reports progress in the development of strain sensors fabricated using the Conductive Lithographic Film (CLF) printing process. Strain sensitive structures printed via an unmodified offset lithographic printing press using a silver loaded conductive ink have been deposited concurrently with circuit interconnect, to form an electronic smart packaging system. A system populated with SMT components has proven successful in interpreting and logging deformation incidences subjected to a package during testing. It is proposed that with further development such a system could be printed in sync with packaging graphics using a single printing process to form an integrated time – strain monitoring system.

Key words: Conductive lithographic film (CLF), offset lithography, printed sensors, printed strain gauges.

1. Introduction

1.1. Electrically resistive strain gauges

Lord Kelvin discovered the principle of resistive type strain gauges in 1856 when he found the electrical resistance of metal wires changed when elongated by an applied load. He also established that the degree of resistance change differed from one metal to another [1].

Kelvin's discovery was not utilized for strain measurement until the 1930s when, Simmons and Ruge, working at the Californian Institute of Technology and the Massachusetts Institute of Technology respectively, independently applied his work to strain measurement [2]. Their work led to the first commercially available bonded resistance strain gauge, the SR-4, in 1938.

Since their introduction in the late 1930s, electrically resistive strain gauges have become the principal method of experimental strain analysis [1]. It is reported that during the early 1990s approximately 80% of strain measurements conducted in the United States were accomplished using this type of strain gauge [2]. The technique is highly adaptable, of low cost and possesses many criteria necessary for successful strain measurement. These include:

- easy adaptation compensation;
- ability to measure strain with an accuracy of ±1μm/m over a strain range of ±50,000μm/m;
- capable of being manufactured in small gauge lengths;
- minimal inertia, thereby permitting dynamic strain measurement;
- a linear response to strain;
- ability to be operated with reasonably inexpensive measuring equipment;
- easy installation and operation.

1.2. Conductive lithographic films (CLF)
The conductive lithographic film (CLF) printing process was originally developed as an alternative for etched resin-laminate circuit boards. The technique utilizes standard offset lithographic printing technology used in the mass production of books and magazines. The CLF process possesses a number of key advantages over more traditional forms of electronic circuit board fabrication [3]:

- high production speed (6,000 – 10,000 impressions/hour);
- good resolution of image (80 – 100μm track with 60μm gap easily achievable);
- low cost (low ink volume determining that substrate material proves the largest expense);
- ability to produce flexible electronic circuits and systems;
- reduced environmental impact [less energy, reduction in material use, easier disposal, and toxic heavy metals (e.g., lead) eliminated].

Electronic inks have been deposited on an array of flexible substrates including standard office paper and polymer films. In addition to circuit interconnect, a number of passive components and transducer structures have been developed and fabricated using the CLF process by exploiting the electrical properties of the printed ink films [4]–[8].

1.3. Previous Work
Screen printed polymer thick-film resistive (PTFR) strain gauges have been in existence for almost 30 years and primarily consist of solid, resistive ink layers deposited directly onto test beams which are loaded by an external force during analysis or onto thin metallic strips, subsequently attached to test beams. The dimensions of such structures are generally less than $10mm^2$ [9]–[14].

In addition to very specific substrates and small geometries of structures, and in common with other forms of PTF electronics, PTFR strain gauges require curing at elevated temperatures. These draw backs make the implementation of such structures in low cost, low environmental impact, disposable consumer goods problematic. In contrast, CLF deposited films are air curable and can be printing directly onto thin substrates via a standard printing press, enabling structures to be manufactured in bulk at high speed and low cost.

Resistive type strain sensors have previously been manufactured by the CLF process [15-17]. These studies concerned the development and characterisation of different structures when deposited on an array of substrate materials ranging from materials designed for graphics reproduction to engineering grade polymer films. Structures exhibit gauge factor (GF) values between 1 and 52 depending on structure design and substrate material. The work also details strong links between substrate material, structure design and linearity and hysteresis of response. For example, evidence has shown that CLF fabricated strain gauges are more sensitive to strain when deposited on porous substrate materials [15].

1.4. Development of consumer packaging
It is predicted that the role of packaging will change considerably beyond its principal operation of protecting goods during transit and (in the case of foodstuffs) helping to maintain freshness. Increasingly packaging is being used to make products "stand out from the crowd" through the implementation of novel forms and bold graphics. However, packaging is now being regarded as a means of enhancing the product [18], [19].

In addition to changes in the physical form of packaging containers, two key directions for growth and development of the "smart packaging" industry have been identified and termed as "*active"* or "*intelligent"* in nature [18].

"Active" packaging is designed to enhance the consumer's life through the incorporation of additional functionality, which is triggered on command and operates until the reaction started times out. Examples of such packaging are [20]:

- the widget, developed by Guinness, which produces a creamy head on stout beers;
- the self heating drinks container developed by Crown Cork and Thermotic Developments;
- the self cooling drinks container developed by Crown Cork in collaboration with Tempra Technology;
- the "SmartSeeker" insecticide aerosol can, developed by Mortein, which improves insect "kill" through electro-statically charging the mist produced by the nozzle.

The functionality of "*Intelligent"* packaging is triggered by changes in either external or internal conditions. A visual communication is generally used to communicate a change in situation to the consumer. As such, intelligent packaging can be defined as packaging which "senses and informs". Examples include:

- thermochromic inks used to sense a change in temperature and communicate the change to the consumer;
- "electronic tongues" capable of detecting pathogens in food packaging, indicating if food has started to spoil, subsequently causing a change in state of a visual display, which could work in collaboration with;
- breathable polymers used as fresh fruit wrapping, regulating the ingress of oxygen and the egress of carbon dioxide according to ambient temperature.

2. Proposal

Considering work presented in [15], [17], concerning the development of single-track, single-ink lithographically printed strain sensors, a study has been conducted to discover whether the CLF printing process could be applied to the development of an *"intelligent"* smart packaging system.

It is not anticipated that structures applied to packaging would be used for strain measuring applications, since the geometry of packaging does not usually permit this aspect of the design. Rather, it is considered lithographically printed strain sensors could be employed to indicate deformation of a package through instantaneous changes in structure resistance due to bending.

2.1. Preliminary study

The intended outcome of the preliminary study was an intelligent A4 size envelope capable of logging deformation caused during transit. It was proposed that an "intelligent label" incorporating a strain sensor element could be developed and subsequently adhered to A4 document envelopes. In future incarnations, it is envisaged that strain transducer elements could be printed directly onto the A4 envelope concurrently with manufacturer graphics.

System development was divided into three separate work packages, detailed as;

1. Investigation into whether thick or thin track structures offer the greatest sensitivity to deformation;
2. Development and characterisation of A4 sized sensors adhered to reinforced paper – cardboard document envelopes, and the;
3. Development of sensor incorporating a microcontroller, capable of interpreting deformation cycles used for the characterisation of structures in section 2.

3. Investigation into track thickness

Single track strain gauges detailed in [15], [17], possessed a gauge length of 22mm and a sensing area of 341mm^2. The single track had a width of 500μm. For packaging applications, it is envisaged that the sensing area for the strain structure should cover the entire surface of the package. Since structures of this size have not previously been studied and since changes in track thickness have not been investigated in terms of structure sensitivity, a decision was made to design and fabricate "oversized" structures specifically to investigate these areas.

Two sensor structures with active sensing areas of 15,000 mm^2, figure 1, were printed to investigate the effect track thickness has on structure sensitivity.

Structures were formed by lithographically depositing a silver-loaded conductive ink following the practice of over printing three times to ensure an even, approximately 3μm thick, ink film throughout. The ink employed has been described in previous work, [21], and consists of an electrically conductive silver metal particulate suspended in an organic resin. Ink was deposited using a sheet-fed offset lithographic printing press, model Heidelberg GTO46. Structures were deposited on the Teslin substrate, since linear straining results generated in [15], [17], for similar devices proved that this material would generate greatest sensitivity to deformation. Following printing, structures were permitted to air cure for 7 days before evaluation commenced.

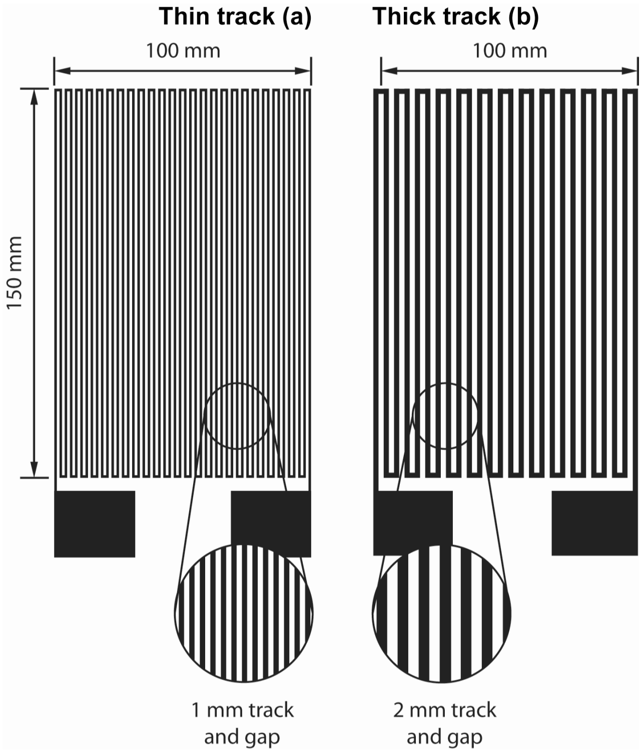

Figure 1. Differing track thickness structures.

The two structures, *a* and *b*, were designed to obtain track and gap measurements of 1 mm - 1 mm and 2 mm - 2 mm respectively. The differing track thickness results in each structure possessing noticeably different nominal resistance values. Mean nominal resistance calculated by measuring 10 samples of each design are detailed in table 1.

Table 1. Mean nominal resistance for each structure type.

Structure type	Nominal resistance (Ω)
Thick track	198.99
Thin track	668.72

3.1. Test method

Ten samples of each structure design were evaluated to attain resistance change sensitivity to deformation. Structures were adhered to reinforced paper – cardboard document envelopes using 3M Photo mount spray adhesive. Contact wires were subsequently attached to contact pads using a two part conductive epoxy, Circuitwork CW2400.

A test scheme to simulate "real world" situations was devised for the evaluation of structures. Reinforced paper – cardboard envelopes were filled with 50 sheets of standard 80 gsm A4 office paper and sealed.

Each envelope was subjected to repeated, three-point, linear bending deflections of 50 mm over a 10 minute period whilst changes in structure resistance were recorded at 1 second intervals using the data capture function on a Fluke 189 True RMS multimeter. Structures were subjected to an instantaneous displacement of 50 mm at mid span sustained for 10 seconds before relaxing, schematically represented in figure 2. A relaxation period of 30 seconds was observed before an additional instantaneous displacement was applied, followed by another 10 second period. This pattern of deformation continued until each structure had been subjected to 10 deformation cycles. After the final deformation incident, structures were permitted to rest for 200 seconds before testing concluded.

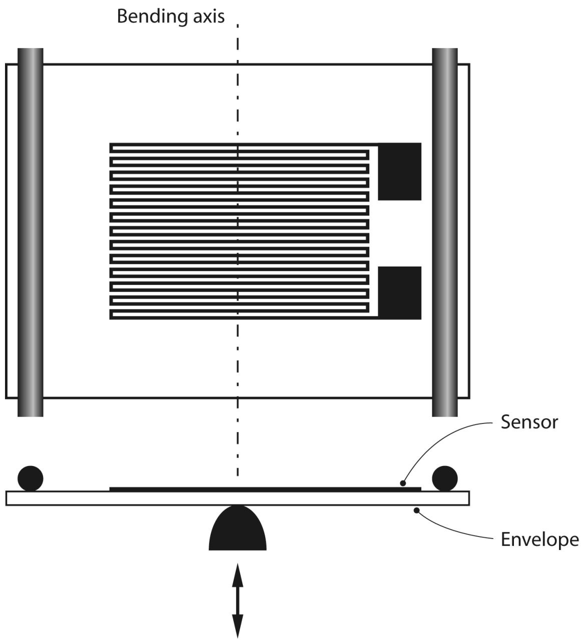

Figure 2. Deformation jig schematic.

3.2. Thick and thin track structure results

Mean responses were generated using the data gathered and are visually represented in figure 3, detailing fractional change in structure resistance (ΔR/R, defined as change in resistance/nominal resistance) against time.

Figure 3 clearly indicates that as structures are subjected to deformation, a sharp increase in resistance occurs. During each 10 second deformation period, resistance of both structure types fall slightly, which is attributed to relaxation of the deformed ink film. This is followed by a large decrease in resistance as deformation is removed. Both structure types also experience a large hysteresis effect following the first load application, followed by a constantly increasing hysteresis error during subsequent testing, which appears to be of the same magnitude after each deformation incident. This suggests that permanent deformation of the ink film occurs during each deformation incident.

The most interesting information noticeable from the data presented is that fractional changes in resistance for each structure appear to be very similar in magnitude, suggesting that track thickness does not have a significant effect on the sensitivity of structures to deformation.

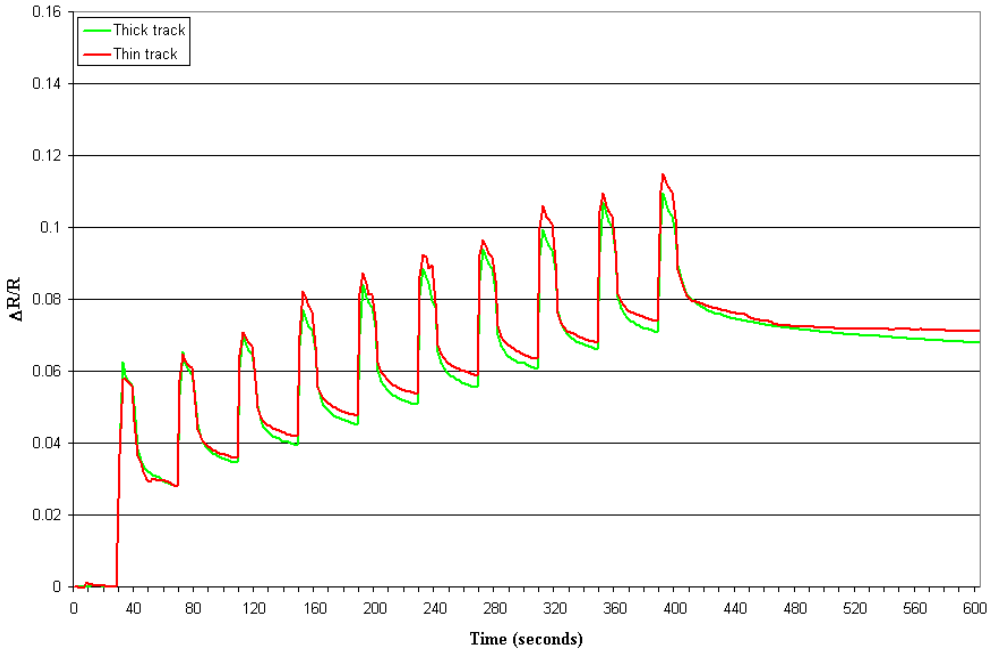

Figure 3. Mean fractional change in resistance plots for thick and thin track structures.

Mean instantaneous increases and decreases in fractional changes in resistance for each structure type when subjected to deformation are detailed in table 2. Whilst figure 3 suggests that the instantaneous fractional resistance increase for each structure is very similar, numerical confirmation suggests that thin track structures exhibit slightly greater changes in resistance compared to thick track structures. However, mean instantaneous fractional resistance changes due to the relaxation of the structures suggests that thin track devices suffer slightly more than thick track devices by exhibiting less resistance decrease when relaxed.

Table 2. Deformation response characteristics.

	Thick track	Thin track
Mean instantaneous ΔR/R increase	0.0383	0.0393
Mean instantaneous ΔR/R decrease	0.0331	0.0329
Mean ΔR/R high point hysteresis	0.0052	0.0064
Mean ΔR/R low point hysteresis	0.0053	0.0057

Values for mean high and low point hysteresis detailed in table 2 suggest, as illustrated in figure 3, that both structure types experience similar hysteresis, with thin track structures suffering slightly larger hysteresis than thick track equivalents.

Considering the last 200 seconds of figure 3, it is apparent that the resistance of thin track structures stabilize at a faster rate than that of thick track devices, the resistance of which is still noticeably falling towards the end of the test.

Analysis of data presented in this section suggests that thin track structures are more suitable for further development. Two key points have driven this decision:

1. Thin track structures possess a larger nominal resistance value, deeming preferable for inclusion in a microcontroller driven system from a power consumption perspective, and;
2. Structures stabilize at a more rapid rate when deformation is removed.

4. Multi direction deformation investigation

Following testing conducted in section 3, it was considered important to understand how CLF printed packaging structures respond to differing magnitudes and orientations of deformation.

A sensor structure was designed to fit an A4 sheet, attaining an active measuring grid of 37,400 mm^2 with linear and transverse measuring grid dimensions of 220 mm and 170 mm respectively. Track and gap dimensions identical to that of thin track structures detailed in section 3 were employed. The mean nominal resistance of the A4 size structures, as determined by analysis of 25 identical devices, was 2403.42Ω. Samples were fabricated following the printing methods described in section 3 and prepared for testing following the technique outlined previously.

4.1. Testing method

To determine structure resistance change to differing deformation magnitudes and differing orientations of deformation, two separate test situations were developed. Testing was conducted using a three-point bending jig as previously discussed.

1. The first test was conducted to gauge the magnitude of structure resistance change to differing degrees of envelope deflection. Systems were subjected to bending about the *linear* axis of 25 mm and 50 mm as illustrated in figure 4. Deformation periods lasted for 10 seconds and were followed by 30 seconds of structure relaxation before a further deformation period was applied. In total, 10 deformation incidents were created over each 10 minute test and followed the order of: - 2 x 25 mm, 2 x 50 mm, 2 x 25 mm, 2 x 50 mm and finally 2 x 25 mm. A 200 second relaxation period was observed before testing was concluded.

2. The second test was designed to understand in greater detail how systems would respond to bending about the linear, transverse and diagonal axes. For the purpose of this testing, structures were subjected to differing orientations of 50 mm deflections. Testing comprised of deforming structures for 10 second periods followed by 30 seconds of relaxation. The pattern of deformation followed: - 2 x linear, 2 x transverse, 2 x diagonal, 1 x linear, 1 x transverse, 1 x diagonal and finally 1 x linear followed by 200 seconds of relaxation.

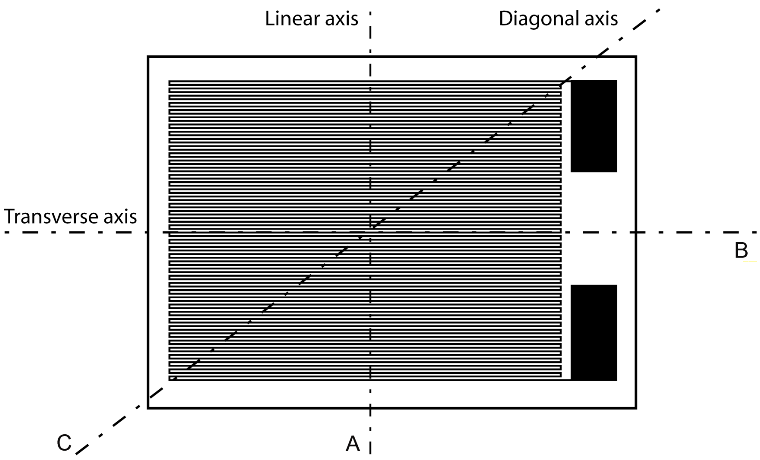

Figure 4. Deformation orientations.

4.2. Differing magnitude deformation results

Data generated from each of the ten structures analysed for differing magnitude deformation testing were compiled to generate a mean response plot, figure 5. The plot indicates a similar response between this test and that previously conducted, figure 3, such that instantaneous straining is indicated by sharp increases in structure resistance, generally a small decrease in structure resistance is observed during the deformation period, and a large decrease in structure resistance as deformation is removed.

By analysing mean fractional change in resistance against time chart, figure 5, it is apparent that structures experience a larger change in resistance when deformed by 50 mm compared to resistance changes induced by 25 mm deformation, with a ratio of approximately 3:1.

As observed in previous testing, structures subjected to deformations of varying magnitude experience a positive shift in hysteresis following each deformation incident. However, unlike previous testing, the direction and magnitude of hysteresis varies noticeably between deformation incidents. Whilst hysteresis is generally increasing in nature, it can occasionally be noticed to fall. It can be visually noted from figure 5, that a large degree of hysteresis occurs after the first of each 50 mm deformation cluster, suggesting significant permanent deformation of the ink film occurs. This was also evident in the tests described in section 3.2.

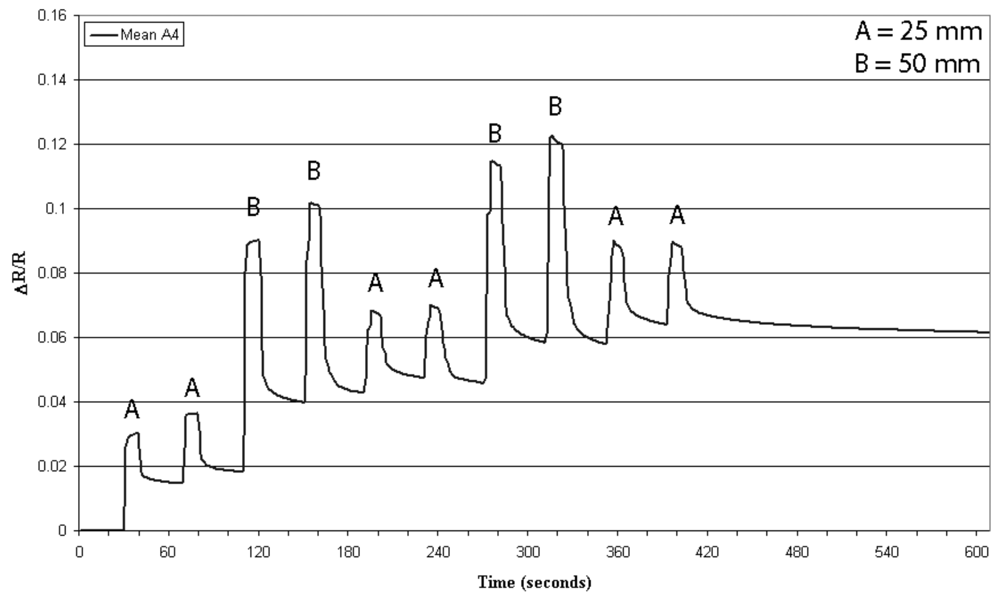

Figure 5. Differing magnitude deformation.

4.3. Differing orientation deformation results

Resistance responses gained from ten A4 structures subjected to differing orientations of 50 mm deformation have been processed to form a mean response, presented in figure 6. Peaks on the plot detailed as "A" represent linear deformations, "B" as transverse and "C" as diagonal deformations.

It is clearly visible that each deformation incident causes a sharp positive change in structure resistance. Analysis of figure 6 indicates that structures experience a much greater increase in resistance due to bending about the linear axis deformation compared to bending about the transverse axis. This observation is in keeping previous work comparing linear and transverse strain sensitivity in CLF printed strain gauges.

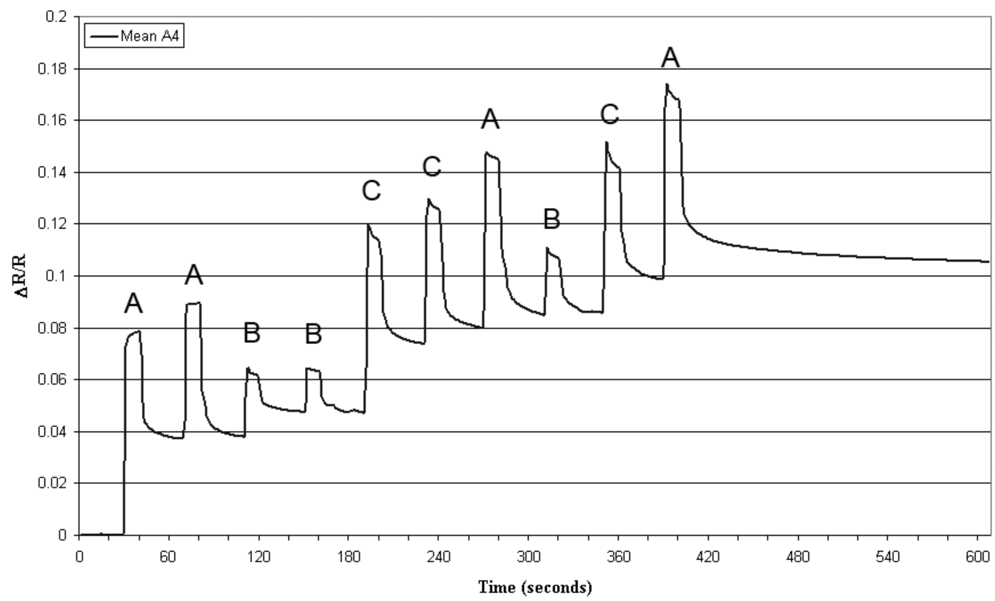

Figure 6. Multi direction deformation.

It is apparent that resistance increases due to bending about the diagonal axis are similar in magnitude to those noticed during bending about the linear axis. This observation was expected since all parallel sensing tracks are subjected to longitudinal elongation, as in the case of linear deformation.

The pattern of hysteresis noted for multi-orientation deformation is similar to that present during differing magnitude deformation testing. It is apparent that a positive trend of hysteresis is present and that the magnitude of hysteresis increases due to either linear or diagonal deformation, which cause much larger increases in structure resistance compared to transverse deformations.

5. Microcontroller based system

To develop structures previously discussed into an intelligent packaging system it was necessary to incorporate sensor structures with a microcontroller centred circuit capable of converting deformation data into a digital signal, and storing such data for subsequent analysis.

Figure 7 schematically represents a circuit containing a Microchip PIC16F876SO microcontroller. This peripheral interface controller (PIC™) has five inputs (AN0 - 4) multiplexed to an analogue to digital converter (ADC). Such a feature is required to convert the analogue change in resistance of a printed sensor into a 10-bit binary equivalent.

The circuit was designed such that the sensing structure (Strain_Gauge) is included in a potential divider configuration with a pull up resistor (R1) of similar resistance value (~ 1.9 kΩ). The configuration causes approximately half the circuit voltage (+5V) to be dropped across the pull up resistor, leaving a potential between the mid-point and ground of ~ 2.5V. As the sensing structure is deformed, the resistance of the element increases, causing the ratio between it and the pull up resistor to change, resulting in a mid-point voltage increase.

The mid-point voltage is channelled into an ADC through pin 2 (RA0/AN0) of the PIC™, where it is converted to a 10 bit binary value (between 0 – 1023). In an unstrained state, the 10-bit value is approximately 511, and when deformed the value rises.

The PIC™ microcontroller is serially programmed using the CLK, DAT and VPP pads where VPP supplies a high voltage signal to the master-clear pin on the PIC™, holding the device in a programming state. The CLK (clock) pad is connected to the program clock pin (PGC/RB6) and synchronizes data flow to the device. The DAT pad is connected to the program data pin (PGD/RB7) and transmits the program data to the PIC™.

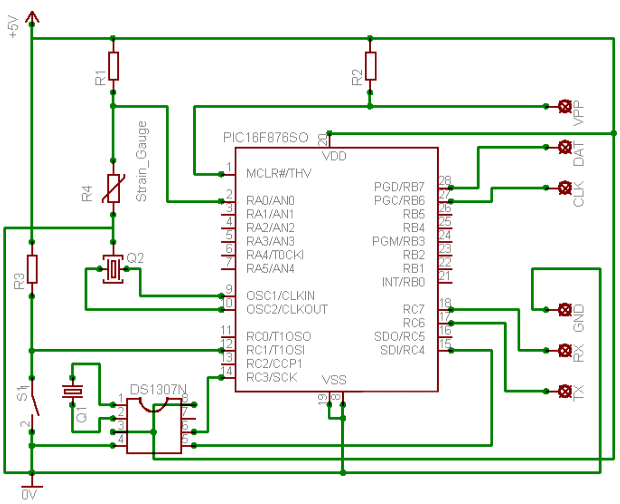

Figure 7. Schematic of microcontroller circuitry.

During operation the analogue voltage appearing on RA0/AN0 is converted into a two byte digital value where the lower order byte contains the first 8-bits of the 10-bit value and the lower two bits of the higher order byte contains the remaining two bits. In application situations, the two bytes containing the 10-bit conversion would be transmitted from the PIC™ through pin 17 (RC6 or TX) to an electronically programmable read only memory (EEPROM) module, for retrieval at a later time. However, for this prototype design, the two bytes containing the 10-bit conversion are transmitted through the TX pad to a PC running software to convert and store the 10-bit conversion as a decimal value in a comma separated variable format (CSV). The PIC™ begins running after receiving a signal from the PC through the RX pad (connected to pin 18, RC7), and converts the analogue value before transmitting to the PC. The PIC™ program then loops until it receives a further transmission from the PC, at which point it converts a further analogue value and transmits that to the computer. The PC software is configured to transmit to the PIC™ 5 times per second, resulting in the same number of data transmissions from the PIC™.

A circuit diagram of the prototype is detailed in figure 8. The external components (PIC™, crystal, oscillator, RTCC and resistors) are attached to the printed circuit using previously described methods.

The circuit detailed in figure 8 includes a real time clock chip (RTCC), model MAXIM DS1307ZN, which produces time and date information during testing. When in use, the data produced by the RTCC is transmitted at the same time as each analogue conversion. This associates every analogue conversion transmitted by the PIC™ with a unique time and date stamp.

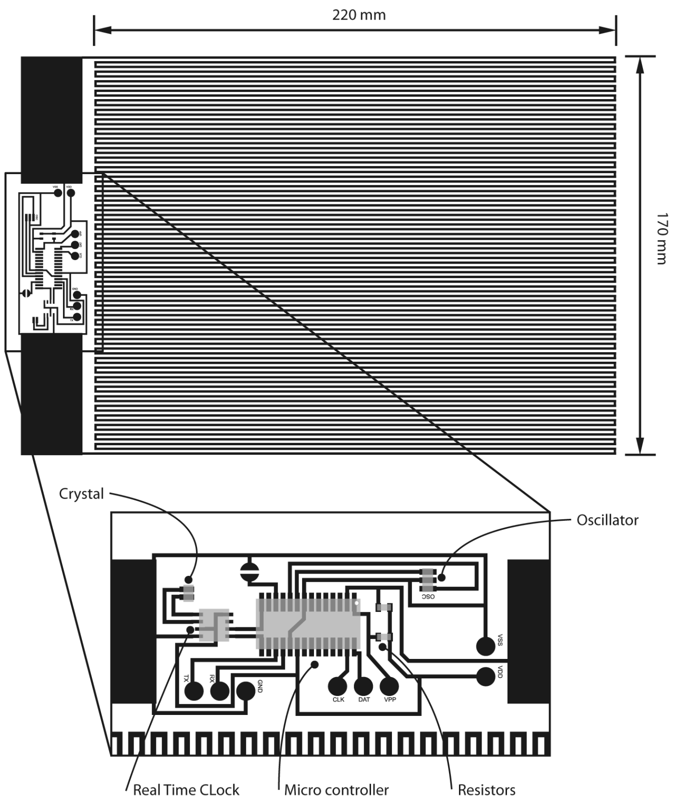

Figure 8. Printed microcontroller circuitry.

5.1. Practical testing of PIC™ controlled prototype

Testing of initial A4 structure prototypes containing a microcontroller circuit replicated experiments conducted in section 4.2, whereby systems were subjected to differing magnitudes of linear straining. Typical data contained within a CSV file generated from testing was used to generate the 10-bit digital output against time plot detailed in figure 9.

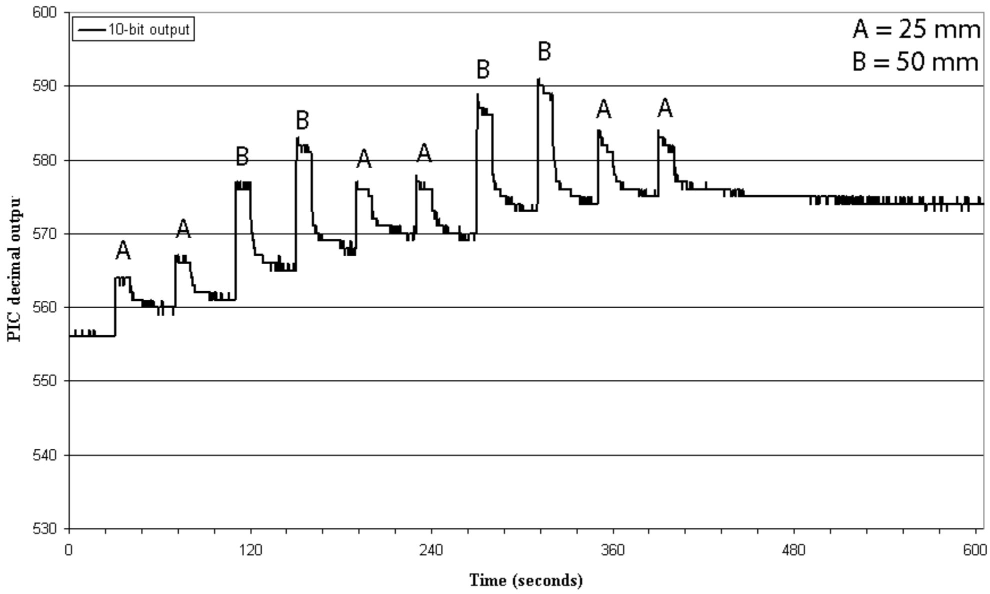

Figure 9. Output from microcontroller circuitry.

Analysis of figure 9 indicates that results from the PIC™ controlled system possess many characteristics of similar structures which gave the test results described in section 4.2. The magnitude of response generated from 50 mm deflections is considerably greater than that generated by 25 mm deflections. As with previous testing, hysteresis is recorded over the duration of testing and is similar in magnitude to that noted previously. It can be concluded that a PIC™ controlled system is capable of recording results comparable to those obtained from systems connected to resistance measuring equipment.

5.2. Practical testing of PIC™ controlled prototype incorporating RTCC

Figure 10 details the response gained from a microcontrolled system incorporating time/date information produced by the RTCC. Results were generated over a 90 minute period and structures were subjected to deformation after 30, 45, 60 and 75 minutes. As in previous testing, deformation incidents lasted for 10 seconds.

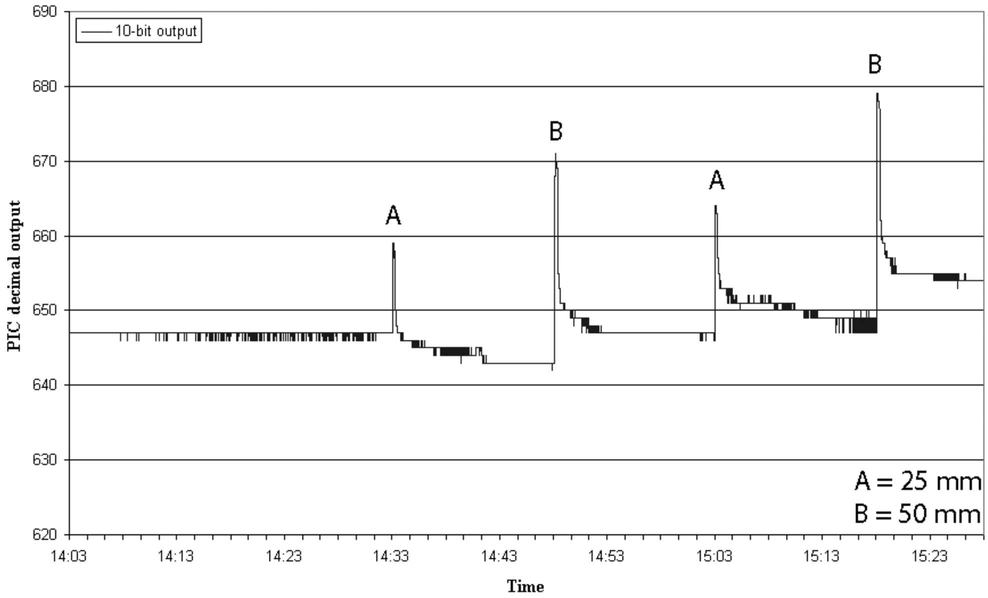

Figure 10. Output from microcontroller circuitry incorporating time/date data.

Time detailed on the *x* axis of the plot illustrates real time produced by the RTCC. In common with previous testing, 25 mm deflections produce a smaller change in structure resistance than 50 mm equivalents, and significant hysteresis is recorded after each deformation incident.

Table 3 illustrates typical data recorded during the experiment detailed in figure 10. The data, extracted from the CSV file created during testing contains information regarding the 10-bit conversion, day, date and time. By considering the column detailing 10-bit conversions, it is possible to note that the system was subjected to deformation. This is indicated by a sharp increase in value from 648 to 668. Since figure 10 proves that 25 mm deflections cause an increase in the 10-bit value of approximately 10, and a 50 mm deflection of 20, it can be concluded that, for the example data show, the system was subjected to a 50 mm deflection. Considering that the test began at 14:03 on the 15/05/07, it is possible to conclude that the deformation incident in question occurred 45 minutes into the test.

Table 3. Data output from microcontroller.

10-bit values	Day	Date	Time
643	Mon	15/05/2007	14:48
643	Mon	15/05/2007	14:48
643	Mon	15/05/2007	14:48
648	Mon	15/05/2007	14:48
668*	Mon	15/05/2007	14:49
668	Mon	15/05/2007	14:49
671	Mon	15/05/2007	14:49
671	Mon	15/05/2007	14:49
671	Mon	15/05/2007	14:49
671	Mon	15/05/2007	14:49
671	Mon	15/05/2007	14:49
671	Mon	15/05/2007	14:49
670	Mon	15/05/2007	14:49
670	Mon	15/05/2007	14:49
670	Mon	15/05/2007	14:49

*start of deformation incident

5.3. PIC™ controlled prototype conclusion

It has been proven that strain / deformation information can be recorded via a microcontrolled system printed concurrently with the sensing element. The ADC capability of a PIC16F876SO microcontroller has been used to convert the analogue change in resistance of the sensing element into a 10-bit digital value. Analysis of data recorded by the microcontroller driven system is comparable to that recorded using resistance measurement equipment, such that deformation incidents of 25 mm produce a smaller response than deformation incidents of 50 mm. It is also apparent that the microcontrolled system records similar hysteresis errors to the previous method of data capture.

The incorporation of an RTCC enables time and date information to be recorded and associated with each 10-bit conversion value. With this system it is possible to accurately log time and date information of deformation incidents.

While not demonstrated in this initial prototype, the inclusion of a threshold driven event logger is readily achievable through modification of PIC™ firmware. This could be implemented by storing a threshold value in PIC™ memory. ADC values below the threshold would not prompt any further processing, whilst values above the threshold would be associated with time and date data from the RTCC and stored in an EPROM module.

Whilst beyond the scope of this paper, modifications to firmware could be used to eliminate hysteresis effects. Since hysteresis is proportional to the magnitude of deformation, a suitable algorithm could be developed to proportionally adjust the threshold value based on the ADC of the previous event.

6. Conclusion

A study concerned with the development of a lithographically deposited time – strain monitoring system has been conducted. Following initial testing of A5 sized thick and thin track structures, an A4 size convoluted track sensor structure utilising 1 mm – 1 mm track and gap spacing was designed and lithographically printed on Teslin. Structures were adhered to A4 reinforced paper – cardboard document envelopes for the purpose of deformation analysis.

Testing concluded that structure resistance change to 25 mm deformation is approximately three times less than resistance changes recorded due to 50 mm deflections. In common with results published previously for convoluted track structures deposited on differing substrate material, hysteresis is apparent during deforming incidents. Hystereses following 50 mm deformation incidents are greater than those recorded following 25 mm deformations.

Multi direction deformation has proved that structures exhibit similar magnitudes of resistance change due to linear and diagonal deformation and reduced resistance change due to transverse deformation. It is proposed that a system incorporating an array of sensing elements designed to measure deformation in specific directions would allow better distinction between linear and diagonal deformation incidents.

Structures including printed circuit interconnect allowing inclusion of a microcontroller and RTCC have permitted deformation incidents to be recorded and transmitted in a digital format capable of being interpreted by analysis software. Such a system has proved that a digital conversion of the analogue structure resistance change is comparable to resistance measurements recording using measuring equipment.

The final system tested has recorded deformation incidents along with associated time / date information, clearly demonstrating that a lithographically printed time – strain monitoring system is achievable.

It is believed the system discussed in this paper could be deposited concurrently with lithographically printed humidity [7] and temperature [8] sensors. The addition of such sensors would allow monitoring of changes in ambient humidity and temperature. Such information could be processed by the microcontroller to prevent erroneous deformation data being collected due to variations in sensor resistance.

In addition, current work at Brunel University regarding the development of lithographically printed thermochromic displays [22] and voltaic cells [23] could, in the future, be incorporated to realize a lithographically printed strain – temperature – humidity monitoring system with integrated display and power source.

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