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Embedded Sensors in Rubber and Other Polymer Components

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ABSTRACT: Many polymer components are susceptible to catastrophic failure or are critical to the performance of the products they comprise. Because of this, the capability to monitor structural failures or performance reduction in these components is beneficial. It is difficult to fabricate sensors for polymer components because they often have complex shapes or are assembled in isolated locations. To solve this problem, micro-scale electronic sensors, embedded within polymer components, were developed at Purdue University. Conductive polymer materials were used as the primary sensing element in the sensors. Testing results reveal that embedded sensors in polymer components can successfully indicate significant signal changes more than 100 loading cycles prior to catastrophic failure. Multiple sensing methods and applications have been tested and more are being researched. These findings may open doors for future polymer sensors that can improve safety and provide useful measurements for polymer components.

KEY WORDS: *conductive, failure, polymer, resistance, rubber, sensor*

Introduction

All sensors require a sensing element that is highly responsive, repeatable and specific with regard to the phenomena being measured [1]. It is important that the material make-up of the primary sensing element be amenable to these characteristics. Materials used to construct sensing elements are typically limited to those with the desired electrical properties. However, sensors that are embedded or integrated into functioning components may not have optimal structural, chemical or other physical properties because of the selection of the material based on the requisite electrical properties. In this study, we examined the potential for using conductive polymer blends in place of traditional polymer blends to fabricate a primary sensing element that has electrically conductive characteristics, making feasible the use of embedded sensors in polymer components.

Conductive polymers have become widely used because of their antistatic properties [2]. The use of conductive polymers for transmitting electrical signals is less common. By utilising this possibility, electronic conducting materials can achieve physical properties that were atypical before. Polymers possess properties that are often desirable over typical conductors such as metal. Products such as vibration isolators, plastic containers and rubber belts do not function optimally if constructed of traditional conductive materials. At the same time, the structural integrity, loading and other measurable factors of polymer products [3–5] provide useful information. Having sensors embedded in polymers allows a product to have the desirable properties of a polymer while having sensing capabilities which have not previously been realised.

Achieving Conductivity in Polymers

Electrical sensors require a conducting element to transfer a signal. For example, a resistive sensor must have some measurable conductivity for resistance to be measured. A capacitive sensor must have two conducting plates separated by a dielectric. To fabricate an embedded sensor out of a polymer part, some type of conductor must be included. Adding metal parts or wires would be an intuitive solution; however, polymer blends can achieve adequate conductivity without metal components. Conductive filler materials, such as carbon black, can exponentially increase the conductivity of rubber and other polymers. Conductive salts can also be mixed into rubber compounds to provide the interface necessary for an electrically based sensor.

The simplest way to modify the electrical properties of a polymer material is to use a conductive filler or extender. Characteristics of filler materials must meet certain requirements and be cost-effective. A list of common rubber fillers and their respective resistivity is shown in Table 1. Many of these fillers are known for the insulating characteristic that they add to rubber. For example, using Cumar as filler in styrene-butadien rubber (SBR) has a volume resistivity of 1.1×10^{16} Ω cm. Conversely, carbon black can lower the resistivity of natural rubber by 6 orders of magnitude when added at a moderate level. If rubber is overloaded with carbon black resistivity becomes low enough that the rubber can become a good conductor.

It is believed that charge moves through carbon polymer composites by way of tunnelling of charge carriers. The reasons for this are discussed in detail by Sichel [7]. This model explains current flow as electrons travelling through continuous carbon pathways and jumping any gaps to get to the next pathway. Therefore, conductivity is largely dependent on the carbon black content (see Figure 1). A threshold of approximately 25% concentration by volume of conductive filler (such as carbon black) must typically be reached before significant conductive properties are recognized. Conductive polymers can achieve conductivities of the order of $10\ \Omega^{-1}\ \text{cm}^{-1}$.

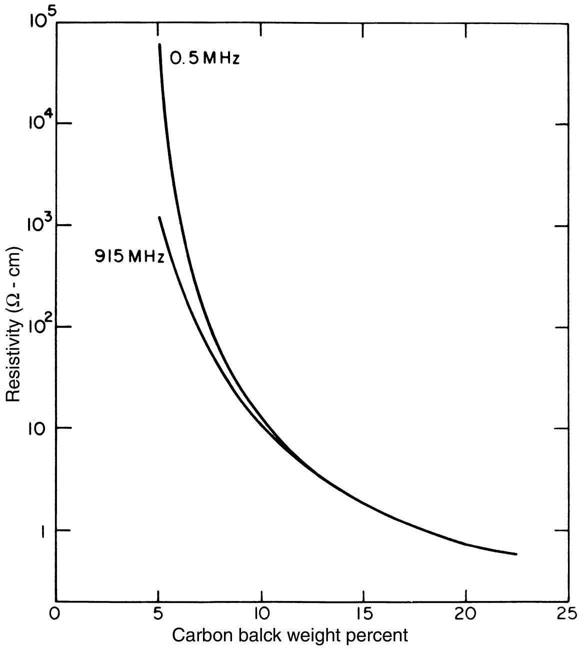

Figure 1: Resistivity of a PVC polymer as a function of carbon black loading [7]

Testing and Results

Preliminary tests were conducted to validate the sensitivity of resistive polymer sensors and to determine if the inductance, capacitance and resistance (LCR) properties of conductive polymers could be used for sensors. The polymer utilized in the experiment was a rubber compound 'SE877 TUFEL® manufactured by Momentive (Wilton, CT, USA). This black semi-conductive rubber compound is often used for discharging static electricity. The sample was developed into a 50 mm wide by 1 mm thick strip and cured according to GE Silicones' specifications. A Hewlett-Packard 3435A multi-meter (Palo Alto, CA, USA) was used to make the resistance measurements.

Table 1: Volume resistivity of rubber fillers [6]

Filler material (volume)	Volume resistivity, Ω cm Natural rubber (111.1 vol.)	 Styrene-butadiene rubber (115.25 vol.)
No filler	4.4×10^{16}	3.7×10^{15}
Zinc oxide (50 vol.)	8.2×10^{13}	3.9×10^{12}
DIXIE CLAY (R.T. Vanderbilt, Norwalk, CT, USA) (50)	3.6×10^{15}	1.8×10^{15}
Calcined clay (50)	4.3×10^{15}	3.0×10^{15}
Whiting (50)	8.4×10^{15}	4.5×10^{15}
NYTAL 300 (R.T. Vanderbilt, Norwalk, CT, USA) (50)	4.4×10^{15}	4.4×10^{15}
THERMAX (Cancarb, Medicine Hat, Alberta, Canada) (25)	1.5×10^{16}	4.5×10^{15}
THERMAX (Cancarb) (50)	2.5×10^{10}	2.8×10^{15}
Carbon Black, N-765 (25)	9.1×10^{10}	1.8×10^{15}
Cumar MH $2\frac{1}{2}$ (25)	–	1.1×10^{16}
Mineral rubber (25)	4.7×10^{15}	1.3×10^{15}
Mineral rubber (50)	2.2×10^{15}	8.6×10^{14}

A 50-mm-long strip of the rubber (1 mm × 40 mm) was used to perform the calibration curve. The strip was clamped on both ends and put in tension. The force on the strip was measured with a spring scale accurate to 0.5 N (0.11 lb). Figure 2 is a plot of the results. The rubber strip broke after 1.38 MPa

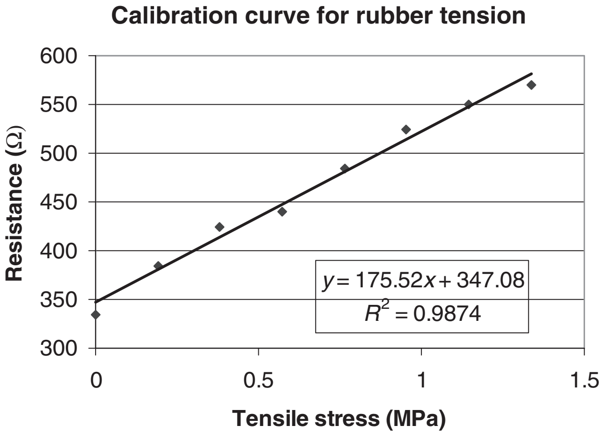

Figure 2: Preliminary sensitivity testing results

(200 psi) of tensile stress was applied. A regression line was fit to the data to determine the slope of the curve, which equals the sensitivity. The results show that the sensitivity of the conductive rubber was 175.5 Ω MPa^{-1} (1.21 Ω psi^{-1}).

Testing was also preformed on a specific proprietary application of embedded polymer sensors. The sensor used in the project utilized LCR measurements (operating at 10 kHz) to monitor changes in the structure that would be critical to the performance. The purpose of the sensor was to alert the user prior to any failure of the component. The failure mode of concern was cracking or breaking of the rubber.

Initial tests were performed on six samples of the embedded sensor to determine the correlation between pressure and impedance. Each sample contained slight structural differences that led to minor discrepancies in the nominal measurement value. However, the slope of the pressure curve is approximately equal for each of the six samples. The data from this test is presented in Figure 3. Details of the testing are withheld because of the confidentiality of the project.

To test the functionality of the sensor, a fatigue test was performed for the embedded polymer sensor. Figure 4 displays the results obtained when a cyclic load was applied to the sample. As expected, the measurement value is near the magnitude shown in the pressure loading curve. However, 100 cycles before catastrophic failure, the measurement dropped to zero. The sensor continued to produce magnitudes that were much lower than expected until failure (failure occurred at cycle 177503). At approximately 25 cycles before failure, the impedance became constant at a small magnitude (near zero) until catastrophic failure and after.

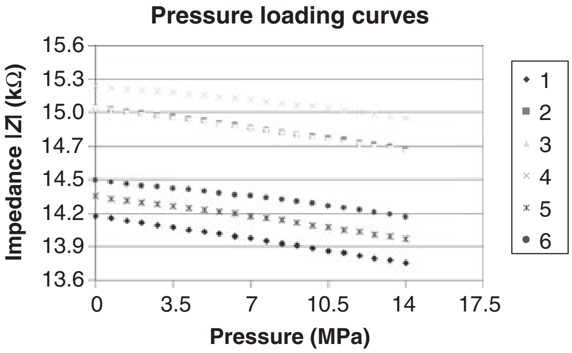

Figure 3: Pressure loading curve for six samples

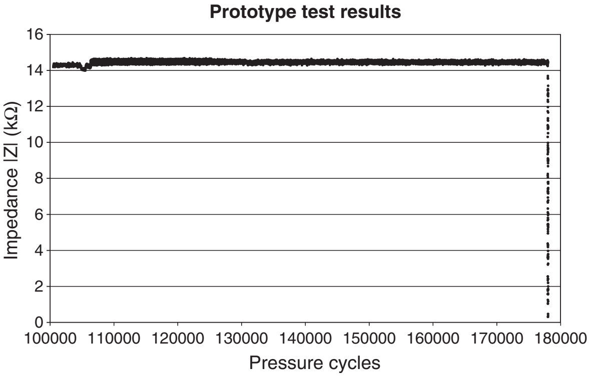

Figure 4: Testing results for a prototype embedded polymer sensor

Table 2: Summary of test sample results

Sample no.	Initial impedance measurement, |Z| (kΩ)	Measurement of significance, |Z| (kΩ)	Cycles before failure
1	13.3	0.71	526
2	14.5	1.00	101
3	14.3	3.58	195
4	0.99	0.99	Failed at cycle no. 1
5	13.5	1.16	313
6	13.7	0.18	561

The results for each of the six samples were similar, with the exception of sample no. 4. Sample no. 4 contained an assembly error. Because of this error, the impedance measurement was lower than expected before any load was applied. The test was then aborted so that the sample could be inspected. Table 2 contains a summary of the results for each of the six samples. Note that each of the samples detected low impedance measurements more than 100 cycles prior to failure.

Conclusions

It was hypothesised that conductive rubber could be used to fabricate a sensing element to measure useful parameters. Test results show that embedded polymer sensors can adequately and consistently predict changes in structure that may lead to catastrophic failure. The sensor was proven to be effective at sensing impending failures in the range of 100–600 cycles before failure. Changes in the electrical properties are on the magnitude of 100% for particular applications. This high sensitivity limits the number of erroneous signals given by the sensor. It is expected that embedded sensors in rubber and other polymers may be used for additional applications in the future. This sensor could be used to indicate a problem to an operator or may be input as a control parameter. Measurements can be taken continuously or periodically depending on the application of the sensor. Two US patents have been filed and proprietary research is being conducted for particular embedded sensor products.

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