Modeling and testing of temperature behavior and resistive heating in a multi-functional composite

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ABSTRACT

Heat-activated self-healing is a desirable property of multi-functional composite materials, particularly if the components of the material itself can be used as a heating element. The heating capabilities and resultant temperature changes of such a composite are investigated in this paper, using finite element modeling and then experimental testing. The composite to be tested consists of thin-wire copper fibers, chosen for particular electromagnetic properties, and an epoxy matrix, which will later be replaced by a self-healing polymer matrix. Direct electrical current is passed through the wires and causes heat dissipation throughout the composite, a process known as resistive heating. For this particular composite, a temperature of 80°C is desired, because at this temperature the polymer can heal within a reasonable amount of time. Using finite element simulations and testing of an actual sample, it was found that resistive heating can achieve the desired temperature using electrical power inputs as low as 0.1 W per square cm of composite panel. The temperature results from the experiments agree with the results from the finite element simulations.

Keywords: composites, multi-functional, self-healing, resistive heating, resistance heating

1. INTRODUCTION

A multi-functional composite has been developed with controlled electromagnetic properties such as a tunable negative index of refraction and RF absorption. [1] Also, a polymer has been developed with self-healing properties at temperatures upwards of 80°C. [2] If manufactured in large enough quantities, this self-healing polymer, called 3M4F, can be used as a matrix material in the electromagnetic-functional composite. The composite incorporates arrays of thin copper wires arranged parallel to each other, which not only provide electromagnetic properties but can be used as heating elements to activate the self-healing process.

The use of fiber material as a heating element in a composite has been studied previously as an enhancement to the curing process. [3, 4] This method, known as resistive heating, involves passing a direct electrical current through the fibers of a composite to generate heat from electrical resistance. In these studies, carbon-fiber composites were tested. It was shown that cure times were reduced when resistive heating was employed. However, the use of resistive heating in a self-healing or repair situation has not been investigated in as much detail. Furthermore, the use of thin copper wire as a heating element is not documented.

To investigate the use of resistive heating in a self-healing context, a numerical model is developed in the finite element program NISA. The resistive heating process is simulated in the finite element model and the resulting temperatures are calculated. The initial and boundary conditions are modified to investigate how the temperature depends on electrical power input and other variables. The results from the finite element model are then confirmed by manufacturing a composite panel with thin-wire copper fibers and an epoxy matrix. Epoxy is used because the self-healing polymer can only be manufactured in small, experimental quantities. The composite panel is attached to an apparatus that allows a DC current from a power source to pass through the entire panel. Temperatures are recorded by thermocouple wires embedded in the composite. The desired temperature for these tests is 80°C, because at this temperature a small crack in the 3M4F polymer can be healed within 24 hours.

In this paper, the theoretical development of resistive heating for composites is discussed first, along with a description of the finite element model. Next, the details of the experimental test are outlined. Lastly, the results from these tests are presented and discussed.

2. THEORY AND MODELING

The resistive heating process involves passing a direct electrical current through the fibers of a composite. The power generated due to resistance can be calculated by Ohm's Law:

$$P = VI = I^2 R = \frac{V^2}{R} \tag{1}$$

where P is power in watts, V is the voltage across the fiber or fibers in question, I is the current through the fibers, and R is the resistance in that section of the circuit.

In this study, it is assumed that all electrical power generated is dissipated into heat. In the finite element analysis, a unit cell of the composite is considered. The unit cell consists of a 2-D cross-section of the copper wire and a portion of the surrounding polymer matrix. The entire copper wire is assumed to be a heat source, and the heat dissipates into the polymer where self-healing can occur. This problem can be solved by the heat conduction equation:

$$\nabla^2 T + \frac{q_{gen}}{k} = \frac{\rho c}{k}\frac{\partial T}{\partial t} \tag{2}$$

where T is the temperature as a function of location and time, q_{gen} is the heat generated per unit volume, k is the thermal conductivity of the material (either copper or the polymer), ρ is the mass density of the material, c is the specific heat of the material, and t is time.

The finite element program NISA is used to numerically solve the heat equation for various resistive heating scenarios. The geometry of the NISA model is based on the unit cell as described before. A quadrilateral element mesh is applied to the unit cell. Boundary and initial conditions are prescribed on the model based on material properties, electrical power input, conditions at the edges of the unit cell, and initial ambient temperature. The results show that the final temperatures are affected primarily by the boundary conditions at the edges of the cell and the power input.

3. EXPERIMENTS AND TESTING

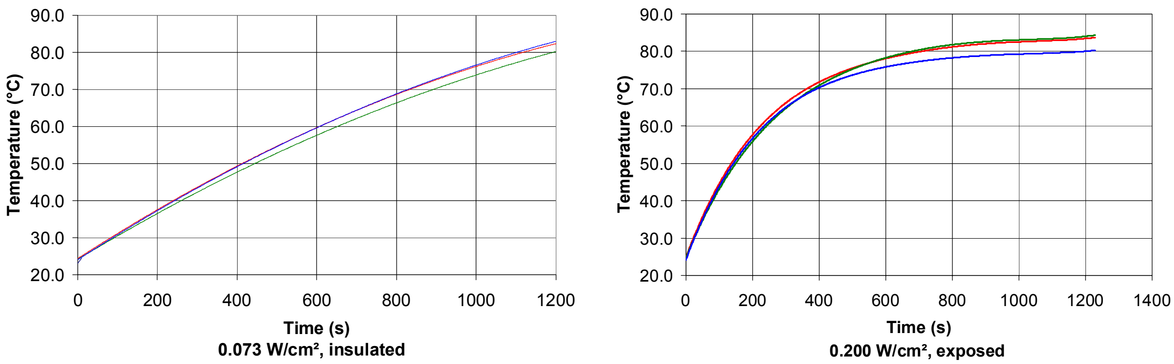
To confirm the results of the finite element model, a single-layer panel of the multi-functional composite was manufactured. Because the 3M4F self-healing polymer is not available in mass quantities, a substitute of epoxy was used as matrix material. The fibers consist of a single unidirectional layer of 100-μm copper wires. Three thermocouple wires are inserted at various locations in the panel.

A custom apparatus called a "conductor frame" is used to connect the copper wires into a single circuit. The end result is a combined series-parallel wiring that can be connected to an electrical power source, forming a DC circuit for resistive heating. The DC power source used for these tests was a voltage generator with maximum outputs of 36 V and 8 A. The electrical power input is measured by connecting two multimeters to the circuit. The temperature is measured by connecting the thermocouple wires to a multi-channel thermocouple monitor.

Data is gathered by performing a series of tests at various levels of constant power input. The panel is tested under two different types of conditions: exposed to air, and insulated by sheets of cotton-like fiberglass.

4. RESULTS

From a qualitative standpoint, the temperature behavior of the composite panel is in agreement with the finite element model. For insulated conditions, the temperature curve is approximately linear. Under exposed conditions, the temperature increases rapidly in the first few minutes and then holds constant (Figure 1).



(a) **(b)**

Figure 1. Temperature vs. time for (a) insulated and (b) exposed composite panel.

From a quantitative standpoint, the temperature vs. time profiles in the experiment differ somewhat from the results of the finite element model. For insulated conditions, the model predicts a temperature of 300°C after 1200 seconds. The experimental result for insulated conditions gives a final temperature of 80°C for the same power input and heating duration (Figure 1a). This can be attributed to heat losses in the insulation material. For exposed conditions, the finite element model predicts a maximum temperature of 70°C. The experimental result for exposed conditions, however, predicts a final temperature between 80°C and 85°C (Figure 1b).

5. CONCLUSIONS

The resistive heating process, which is normally used to enhance the curing and repair of various carbon-fiber composites, has been shown to be effective for a multi-functional composite with thin-wire copper fibers. Both finite element analysis and experimental tests show that the copper wires can be used as heating elements. The self-healing polymer 3M4F can be employed as a matrix material in the composite and is healable by resistive heating. Furthermore, the electrical power input required to reach self-healing temperatures can be achieved by a standard voltage generator.

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