Available online at www.sciencedirect.com
SCIENCE DIRECT®
Composites: Part A 34 (2003) 933–940
composites Part A: applied science and manufacturing
www.elsevier.com/locate/compositesa

The interlaminar interface of a carbon fiber polymer-matrix composite as a resistance heating element

A. Fosbury, Shoukai Wang, Y.F. Pin, D.D.L. Chung*

Composite Materials Research Laboratory, The State University of New York at Buffalo, Clifford C Furnas Hall, Rm 608, P.O. Box 60440, Buffalo, NY 14260-4400, USA

Received 28 June 2002; revised 21 September 2002; accepted 6 June 2003

Abstract

The interface between two crossply laminae of a continuous carbon fiber epoxy-matrix composite is an effective resistance heating element. For an interface of area $5 \times 5\ mm^2$ and resistance 0.25 Ω, a DC electrical power input of 1.1 W (2.1 A, 0.53 V) results in a maximum temperature of 85 °C (initial temperature = 19 °C). The time to reach half of the maximum temperature is 10 s. The efficiency of energy conversion reaches 100% after about 47 s of heating, when the heat power output is about $2 \times 10^4\ W/m^2$ of the interlaminar interface. In case that the volume resistance of the laminae dominates the resistance, the response time is longer. An additional advantage of the use of the interlaminar interface as the resistance heating element is that the interface area can be divided to provide a two-dimensional array of heating elements for the purpose of spatially distributed heating.

Keywords: A. Carbon fibre; A. Polymer-matrix composites (PMCs); A. Smart materials; B. Electrical properties; Interface

1. Introduction

Heating is required in numerous industrial, commercial and domestic applications. The applications include the heating of large objects such as an airport runway for deicing. They also include the heating of small objects such as a semiconductor chip. Heating can be achieved by resistance (Joule) heating, inductive heating, hot fluid (e.g. air) flow and the use of infrared radiation, lasers, electron beams and ion beams. Resistance heating is particularly common due to its nearly 100% efficiency of conversion from electrical to thermal energy, low equipment cost and ease of implementation for the heating of both large and small objects.

A resistance heating element is a resistor. The resistance (R) must be sufficiently low for a current (I) to pass without the need of a high voltage (V). On the other hand, the resistance must not be so low that the heat output $VI = I^2R$ is too low. Furthermore, a resistance heating element must be made of a material that can withstand the elevated temperatures involved. Thus, graphite and high temperature alloys are commonly used.

Heating elements in the prior art are in the form of a volume of material, which is the resistor. The volume can have a large variety of shapes and sizes. The volume resistance of this volume is the resistance R responsible for Joule heating. The volume resistance R_v is related to the volume resistivity ρ_v, length d in the current direction, and cross-sectional A perpendicular to the current, i.e.

$$R_v = \rho_v \frac{d}{A} \tag{1}$$

Hence, both the material property (ρ) and the dimensions govern R_v.

In contrast to the prior art, the heating element of this paper is in the form of an interface. It is not a volume. The interface is the contact or joint between two components. The associated resistance is the contact resistance R_c, which is the resistance encountered upon passing a current through the interface in the direction perpendicular to the interface. The contact resistance R_c is related to the contact resistivity ρ_c and the contact area A by the equation

$$R_c = \frac{\rho_c}{A} \tag{2}$$

* Corresponding author. Tel.: +1-716-645-2593x2243; fax: +1-716-645-3875.
E-mail address: ddlchung@acsu.buffalo.edu (D.D.L. Chung).

1359-835X/03/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S1359-835X(03)00208-2

Hence, the interface property (ρ_c) and the contact area A govern R_c.

The concept of contact resistance is not new, but the contact resistance has not been previously exploited for heating, other than the heating associated with the induction processing of carbon fiber polymer-matrix composites [1–3]. This is mainly because of the difficulty of controlling the interface quality, i.e. ρ_c. It is also because the difference in geometry between a heating element in the form of an interface and one in the form of a volume may require a change in the heater configuration.

An interface can be in the form of a pressure contact, i.e. two components in contact without bonding [4,5]. The applied pressure and the surface roughness of the components greatly affect the contact resistivity. The need to control the applied pressure makes the use of pressure contacts for resistance heating not convenient. Furthermore, the asperities associated with the surface roughness can undergo plastic deformation even when the applied overall pressure is much below the yield strength [4]. The deformation will cause the true contact area to increase, thus decreasing the contact resistivity. As a result of the deformation at asperities, the contact resistivity cannot be kept constant over time. Therefore, interfaces in the form of a pressure contact are not suitable for use as a resistance heating element.

An interface can also be in the form of a joint, such as an adhesive joint. No pressure is needed after the joint has been made. Although the adhesive is typically insulating, the touching of the asperities on the surfaces of the adjoining components (which are conductive) allows an electrical contact to be made [6]. In the absence of pressure, the asperities will not deform and the contact resistivity will remain constant over time. However, in the presence of some pressure, asperity deformation may occur. The surface roughness affects the contact resistivity. The control of the contact resistivity requires surface roughness control prior to interface formation.

The problem of surface roughness control mentioned above for an interface in the form of a joint is alleviated in this work by use of a joint that is between two laminae of a continuous carbon fiber polymer-matrix composite [7]. Before the joint is made, each component is a commercially available prepreg sheet, i.e. a sheet of parallel and continuous carbon fibers with the matrix (e.g. a resin) around each fiber (although the coverage is not exactly 100%). Due to the presence of the matrix in the prepreg, no additional adhesive is needed at the joint. Upon hot pressing the two laminae of prepreg, as is conventionally performed in making carbon fiber polymer-matrix structural composites, bonding occurs and a joint is made. Due to the incomplete coverage of the fibers by the matrix in the prepreg and due to the flow of the matrix (e.g. the resin) during hot pressing, contact occurs between fibers of the adjoining laminae, thus resulting in non-zero conductivity in the direction perpendicular to the interface. The extent of fiber–fiber contact is increased by applying pressure in the direction perpendicular to the interface [7,8], thus decreasing the contact resistivity. However, there is no plastic deformation of the carbon fibers, due to the high stiffness and brittleness of carbon fibers. Thus, the contact resistivity of the interface can be controlled by controlling the pressure during and after hot pressing, though the pressure during hot pressing is by far the main factor [7].

The interface between laminae of continuous carbon fibers in a polymer-matrix composite is referred to as the interlaminar interface. Its contact resistivity is 0.1 Ω cm^2 for the case of the matrix being epoxy that is cured during hot pressing at a pressure of 0.33 MPa (a typical pressure for epoxy curing) [8]. This interface is shown in this work to be an effective heating element.

The use of the interlaminar interface as a heating element is attractive not only because of the effectiveness of the heating (as shown in this work), but is also because the interface is a part of a conventional structural composite material. As a consequence, the use of the interface as a heating element means the use of a conventional structural material as a heating element. Since carbon fiber polymer-matrix composites are lightweight structural materials that are widely used for aircraft and sporting goods, this application allows a structure to serve as a heating element while maintaining the structural function. In other words, the structure becomes multifunctional. As deicing is important for aircraft, this application is particularly valuable for aircraft.

Another attraction of the use of the interlaminar interface as a heating element is that the interface area between two crossply laminae can be subdivided so as to provide a two-dimensional array of heating elements (Fig. 1). The fiber groups associated with the subdivision serve as an x–y grid

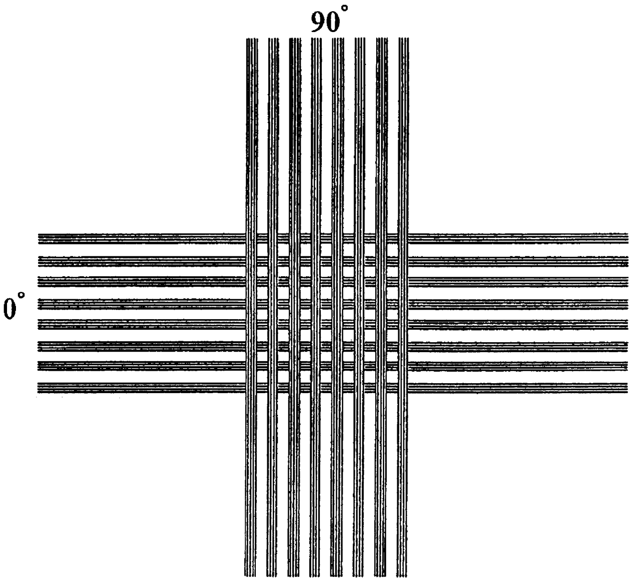

Fig. 1. Sensor array in the form of a carbon fiber polymer-matrix composite comprising two crossply laminae.

of electrical wiring. Hence, both the heating element array and the wiring grid are built in to the composite. The array allows localized heating to be directed at chosen locations and allows attainment of a chosen temperature distribution.

Yet another attraction of the use of the interlaminar interface as a heating element is that the interface is low in mass (compared to the fiber composite volume, which can also serve as a heating element due to its volume resistance [9,10]) and as a consequence is associated with a low value of the heat capacity. A low value of the heat capacity means less heat absorption by the heating element and hence more heat power output for the same level of electrical power input, i.e. a higher efficiency of conversion from electrical energy to thermal energy. Another consequence of the low mass of an interface is the fast response of the heating element, as shown in this paper.

The most common prior art in relation to resistance heating of carbon fiber polymer-matrix structural composites involves the embedding of a heating element between the laminae. The heating element may be continuous metal-coated carbon fibers, which are attractive in the low volume resistivity provided by the metal coating. Although the heating element can serve as a reinforcement, its presence modifies the mechanical properties of the composite, the specifications of which must be highly controlled for aircraft applications.

The use of the volume resistance of continuous fibers as the heating element also suffers from the difficulty of performing localized heating or spatially distributed heating, as the entire length of the fibers acts as the heating element.

This paper provides an investigation of the use of the interlaminar interface of a composite as a heating element. The investigation shows that the heating element is effective, particularly in relation to the fast response, low required voltage and high heat power output per unit area. In addition, this paper provides a demonstration of spatially distributed heating, as attained by using multiple interlaminar junctions in a crossply composite with two laminae.

2. Experimental methods

Two laminae of unidirectional carbon fiber epoxy-matrix prepregs (provided by Cape Composites Inc., San Diego, CA) (Table 1) in the form of strips crossing one another, with one strip on top of the other (Fig. 2), were fabricated into a composite at the overlapping region (5.0×5.0 mm^2) of the two laminae by applying pressure and heat to the overlapping region (without a mold). The pressure (0.33 MPa) was provided by weights. A glass fiber epoxy-matrix composite spacer was placed between the weight and the junction (the overlapping area region of the two strips). The heat was provided by a Carver hot press. A Watlow model 981C-10CA-ARRR temperature controller was used to control the temperature and

Table 1
Carbon fiber and epoxy matrix properties (according to Cape Composite Inc., San Diego, CA)

Fortafil 555 continuous carbon fiber	
Diameter (μm)	6.2
Density (g/cm^3)	1.8
Tensile modulus (GPa)	231
Tensile strength (GPa)	3.80
Cape C2002 epoxy	
Processing temperature (°C)	121
Flexural modulus (GPa)	99.9
Flexural strength (GPa)	1.17
T_g (°C)	129
Density (g/cm^3)	1.15

the ramping rate. Each of the specimens was put between the two heating platens of the hot press and heated linearly up to 121 ± 2 °C at the rate of 2 °C/min. Then it was cured at that temperature for 3 h and subsequently furnace cooled to room temperature.

Evaluation of the interlaminar interface as a heating element was conducted by passing a fixed DC current (ranging from 1.2 to 3.0 A, corresponding to power ranging from 0.19 to 1.1 W) from A to D, while measuring the voltage between B and C (Fig. 2). The specimen was placed between two refractory bricks during the evaluation. The electrical contacts at A, B, C and D were in the form of silver paint in conjunction with copper foil. The silver paint was applied between the end of the lamina (at A, B, C or D) and a copper foil, which covered the lamina end. The distance between the edge of the foil near to the junction and the nearest edge of the junction was 35 mm. A copper wire was soldered to the copper foil of each of the four contacts. The voltage between B and C, multiplied by the current from A to D, gave the electrical power input. The resistance between A and D was the resistance involved in the resistance heating. It was the sum of the contact resistance of the interlaminar interface and the volume resistance of each of the two lamina portions that protruded out of the junction to A and D. The contribution of the volume resistances to this sum was around 0.2 Ω [11]. The contact

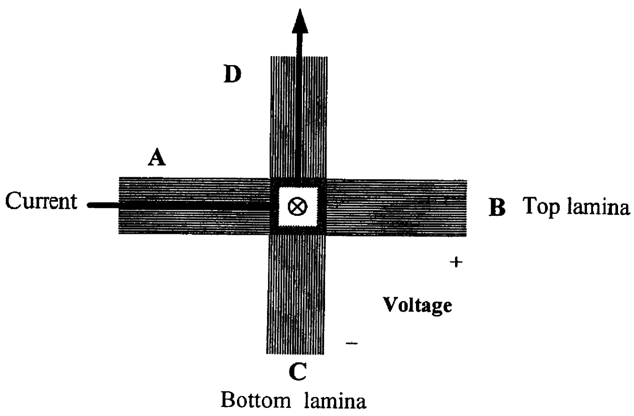

Fig. 2. Composite configuration for measuring the contact electrical resistivity.

resistance was given by the dividing the voltage between B and C by the current between A and D; i.e. A, B, C and D constituted the four contacts in the four-probe method of resistance measurement. Note that the current was essentially zero between the junction either B or C, so that the voltage between B and C was essentially the voltage across the junction. Room temperature was 19 °C. The temperature of the specimen was measured as a function of time during constant current application and in the subsequent period in which the current was off by using a T-type thermocouple located at the top surface of the junction between the two laminae. The constant current period (120 s) was long enough for the temperature to essentially level off to a maximum.

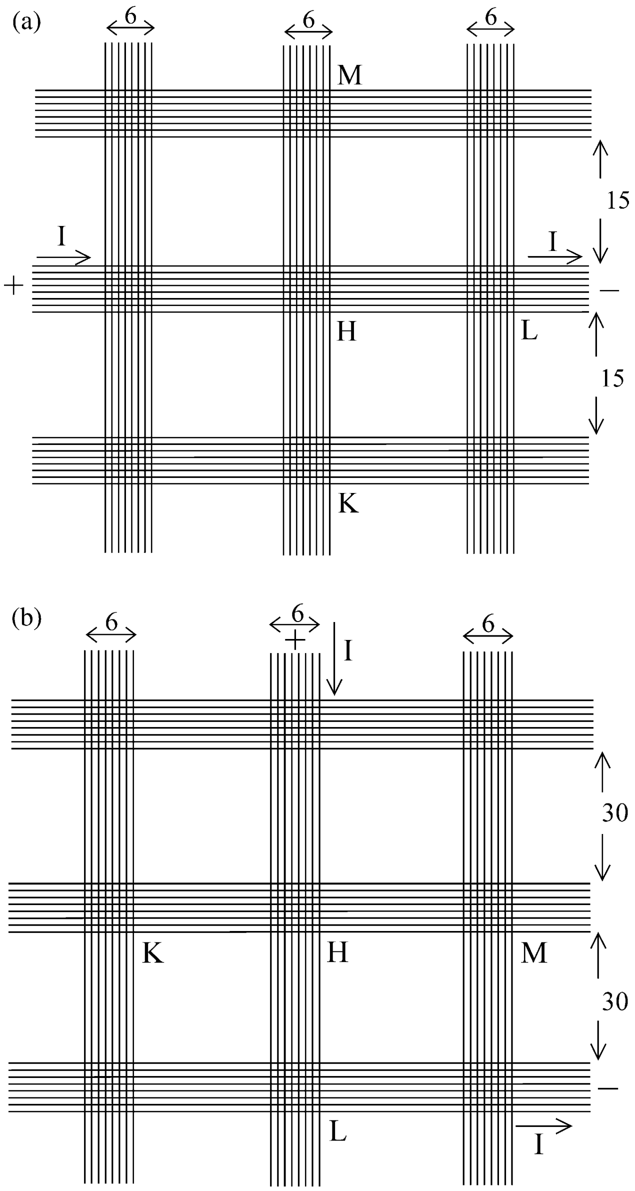

Fig. 3. Configurations for (a) Specimen 3 and (b) Specimen 4. All dimensions are in mm. The arrows indicate the current directions. The applied voltage V has its positive and negative ends at the ' + ' and ' − ' points, respectively. The current I is such that VI = power.

The specimens (labeled 1 and 2) in the form of Fig. 2 were prepared. The contact resistance of the interlaminar interface was 0.25 and 0.067 Ω for Specimens 1 and 2, respectively. The difference in contact resistance between these specimens is due to the experimental difficulty of controlling the interlaminar interface microstructure, which, in general, is affected by the temperature, humidity, stress and curing pressure [7,8].

Since the volume resistance of the lamina portions was around 0.2 Ω, the resistance used in resistance heating involved considerable contribution from the volume resistance for Specimen 1 and involved even more contribution from the volume resistance for Specimen 2. Hence, comparison of the results for Specimens 1 and 2 provides information on the difference between the two modes of resistance heating.

For the purpose of demonstrating spatially distributed heating, specimens (labeled 3 and 4) in the form of Fig. 3 were prepared. Each specimen consisted of nine junctions, in contrast to the single junction (Fig. 2) for Specimens 1 and 2. While a constant voltage was applied between the ' + ' and ' − ' points in Fig. 3, the temperatures of the four junctions were measured by using four T-type thermocouples, which were located on the top surface of the junctions. For the case of Fig. 3(a), which was associated with a resistance of 3.88 Ω, the voltage was 2.36 V (current $I = 0.616$ A in Fig. 3(a)) for 300 s and then abruptly increased to 4.22 V ($I = 1.144$ A) and held at this voltage for 700 s. After this, the voltage was turned off. For the case of Fig. 3(b), which was associated with a resistance of 5.26 Ω, the voltage was 2.08 V ($I = 0.387$ A) for 200 s and then abruptly increased to 4.51 V ($I = 0.858$ A) and held at this voltage for 800 s. After this, the voltage was turned off.

3. Results and discussion

The behavior of heating elements in the form of single junctions (Specimens 1 and 2) and multiple junctions (Specimens 3 and 4) is separately addressed.

3.1. Single junction behavior

Fig. 4 shows the change in temperature with time, which was proportional to the electrical energy, since the power (product of voltage and current) was constant, for Specimen 1 at a power of 1.10 W. The temperature increased with time, as expected, but it leveled off gradually. Upon subsequent turning off of the current, the temperature dropped, as expected. Similar effects were obtained at all power levels. Table 2 shows a quantitative comparison of the results obtained at various power levels. The higher the power, the higher was the maximum temperature, as expected. The heat output is given by the electrical energy input minus the heat absorbed by the specimen. The heat

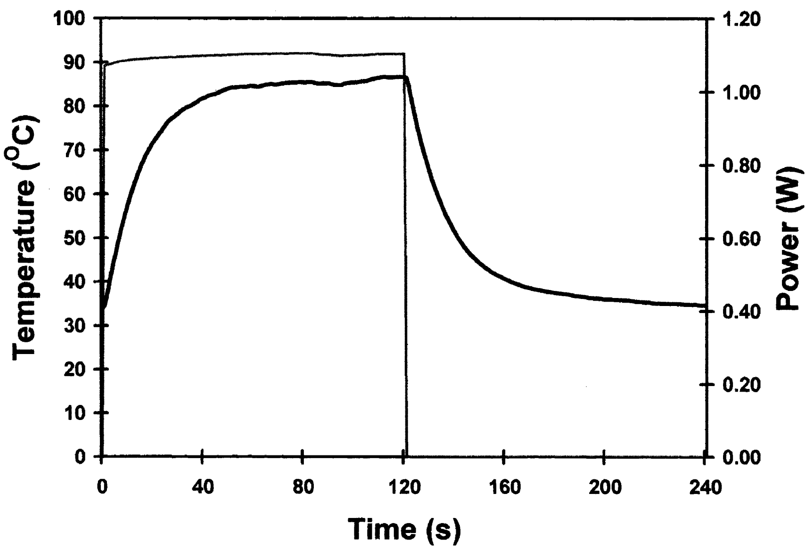

Fig. 4. Temperature variation during heating (current on) and subsequent cooling (current off) for Specimen 1 at a power of 1.10 W. Dark curve: temperature. Light curve: current.

absorbed is given by the product of the specific heat, mass and temperature change. Assuming that the specific heat is constant at 902 J/kg K, as calculated by using the Rule of Mixtures and taking the specific heats of carbon fiber and epoxy to be 830 and 1050 J/kg K, respectively [12], the heat output was calculated.

The ratio of the heat power output to the electrical power input is the efficiency (η) of the conversion from electrical energy to thermal energy. It is given by the equation

$$\eta = \frac{IV\Delta t - C_p m \Delta T}{IV\Delta t}, \quad (3)$$

where ΔT is the change in temperature over a time period of Δt, C_p is the specific heat, m is the mass, I is the current and V is the voltage. Fig. 5 shows a plot of η vs. time for Specimen 1 at a power of 1.10 W. The efficiency was about 40% at the start of heating (underestimated due to the conservative calculation which used in Eq. (3) the mass of the entire specimen rather than that of the junction portion). It increased with the time of heating, reaching 100% by about 55 s (overestimated due to the underestimation of the efficiency at the start of heating) of heating.

The time to reach half of the maximum temperature rise was longer for Specimen 2 than Specimen 1. This is attributed to the larger mass of the heater portion of Specimen 2, which involved the volume resistance as the main source of resistance for resistance heating. A larger mass led to more heat absorption, and thus more time taken for the heat absorption and more time taken for the temperature of the environment to rise.

The lower electrical power input and the lower maximum temperature rise for Specimen 2 than Specimen 1 were due to the lower resistance (i.e. lower contact resistance) for Specimen 2. The electrical power input of 1.10 W (Specimen 1; about the highest value in Table 2) corresponds to a total heat power output (including contributions by contact

Table 2
Effectiveness of the interlaminar interface for resistance heating

Specimen	Current (A)	Voltage (V)	Electrical power input (W)	Maximum temperature rise (°C)	Time to reach half of maximum temperature rise (s)	Time to cool to half of maximum temperature rise (s)	Time to reach 100% efficiency (s)
1	1.204	0.303	0.365	51.6	11.5	11.0	46
1	1.229	0.314	0.385	51.8	11.0	12.7	47
1	1.693	0.425	0.720	66.9	10.0	12.8	52
1	1.689	0.428	0.723	67.4	10.5	13.0	62
1	2.096	0.530	1.110	85.4	10.1	12.8	47
1	2.109	0.520	1.098	86.8	10.5	12.9	55
1	2.118	0.514	1.089	88.2	10.3	12.7	54
2	1.646	0.113	0.186	34.6	14.7	16.5	60
2	1.927	0.130	0.250	54.9	11.0	9.5	55
2	2.263	0.155	0.351	60.8	12.0	16.5	58
2	2.430	0.164	0.398	74.2	12.5	14.2	62
2	2.456	0.166	0.407	80.0	15.9	15.1	53
2	2.953	0.199	0.588	89.1	15.2	14.5	52

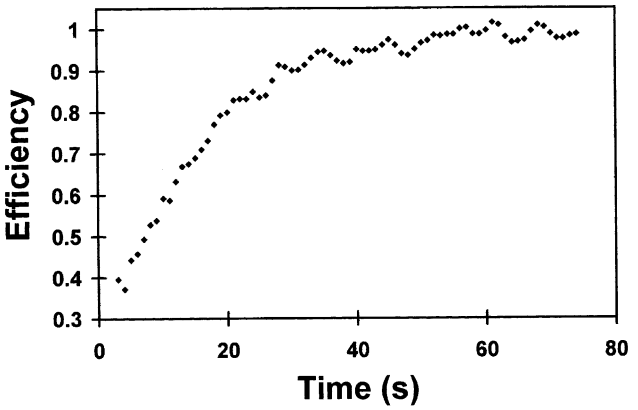

Fig. 5. Efficiency vs. time during heating for Specimen 1 at a power of 1.10 W.

and volume resistances) of 1.10 W (assuming that $\eta = 1$), and hence a heat power output (due to the contact resistance) per unit area of the interlaminar interface of 2×10^4 W/m^2.

For the sake of comparison, let us consider the most widely used heating element, which is a metal wire (say, resistivity $= 10^{-4}$ Ω cm and diameter $= 0.5$ mm). A length of 49 mm is needed to provide a resistance of 0.25 Ω (the value for Specimen 1). For the same power of 1.10 W (as used for Specimen 1), the heat power output per unit surface area of the wire is 1.4×10^4 W/m^2. Thus, the heat power output per unit area is comparable for the interlaminar interface and the metal wire having the same resistance.

3.2. Multiple junction behavior

The variation of temperature with time during stepped heating and subsequent cooling for Specimens 3 and 4 is shown in Figs. 6 and 7, respectively. For Specimen 3, junction H (Fig. 3(a)) was the hottest, followed by junction L; junctions M and K were only slightly heated. For Specimen 4, junction L was the hottest, followed by junction H; junctions K and M were only slightly heated. The temperature response during heating and cooling was fast for both Specimens 3 and 4, as shown by the abrupt changes in temperature in Figs. 6 and 7.

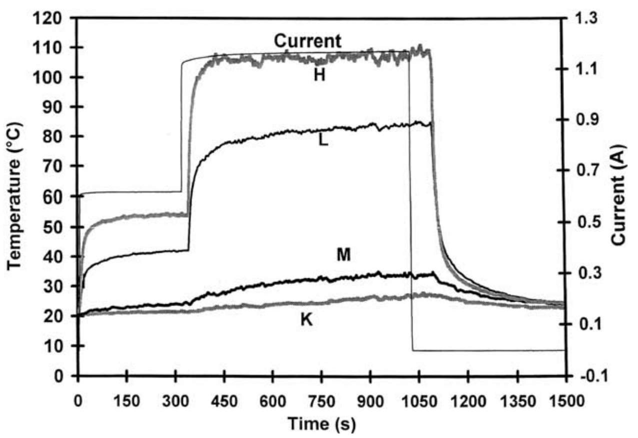

Fig. 6. Temperature variation during stepped heating and subsequent cooling for Specimen 3.

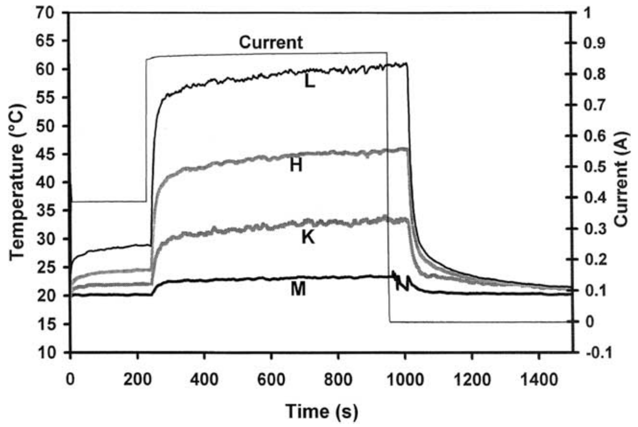

Fig. 7. Temperature variation during stepped heating and subsequent cooling for Specimen 4.

3.3. Electrical circuit model

For the purpose of illustration of the method of electrical circuit analysis, a four-junction specimen with the two current paths indicated in Figs. 8 and 9 is analyzed by using the circuit models shown in Figs. 10 and 11, respectively.

Fig. 10 shows two currents (I_1 and I_2) in parallel. The total current $I = I_1 + I_2$. In Fig. 10, R_v refers to the volume resistance of a 30 mm length of a lamina strip, R_c refers to the contact resistance of a junction (with the junction label

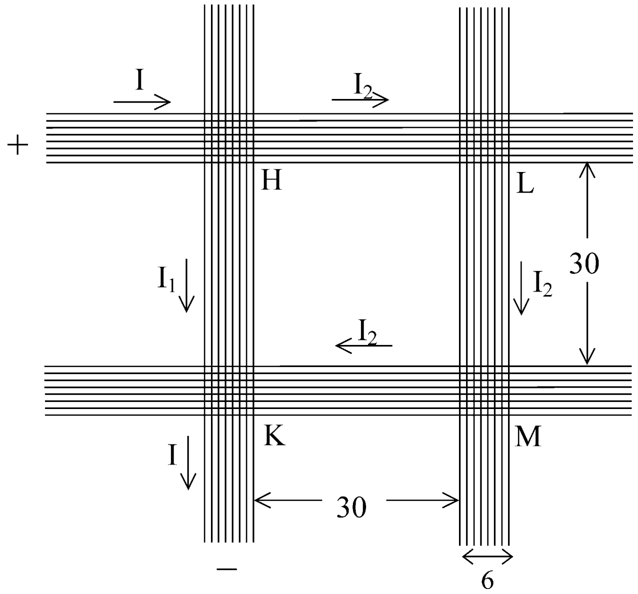

Fig. 8. A four-junction specimen. All dimensions are in mm. The arrows indicate the current directions. The applied voltage V has its positive and negative ends at the ‘ + ’ and ‘ − ‘ points, respectively. The current I is such that $VI =$ power.

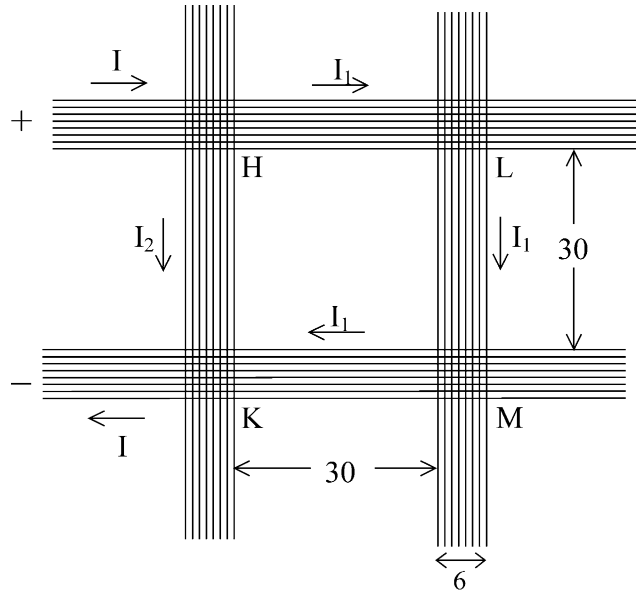

Fig. 9. The same four-junction specimen as in Fig. 8, but with a different current path.

as a superscript) and R_{vc} refers to the volume resistance of a lamina strip of the size of a junction (6.5×6.5 mm^2 rather than 6.0×6.0 mm^2, due to the deformation during composite fabrication by hot pressing).

Assuming a contact resistivity of 0.0956 Ω cm^2 (measured in this work from a single-junction specimen prepared under the same curing conditions), R_c is 0.226 Ω (for a junction of area 6.5×6.5 mm^2). Based on resistance measurement of a lamina, the volume resistance of a lamina is 0.021 Ω/mm length of the 6 mm wide lamina. Hence $R_v = (0.021\ \Omega/\text{mm})\ (30\ \text{mm}) = 0.63\ \Omega$ and $R_{vc} = (0.021\ \Omega/\text{mm})\ (6.5\ \text{mm}) = 0.137\ \Omega$.

From the circuit model in Fig. 10,

$$\frac{I_1}{I_2} = \frac{R_{vc}^{H} + R_v + R_c^{L} + R_v + R_c^{M} + R_v + R_c^{K}}{R_c^{H} + R_v + R_{vc}^{K}}$$

$$= 1 + \frac{2R_v + 2R_c}{R_c + R_v + R_{vc}} = 2.72$$

For $I = 1.07$ A (the second step of heating for Specimen 3), $I_1 = 0.782$ A and $I_2 = 0.288$ A. For junction H,

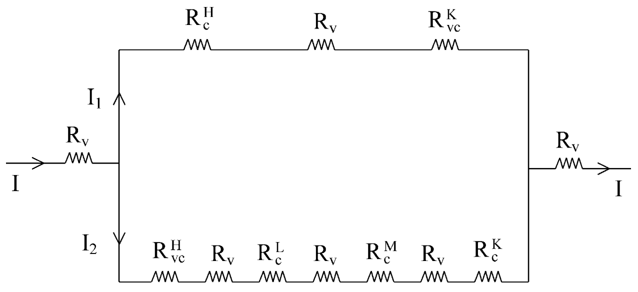

Fig. 10. Electrical circuit model for Fig. 8.

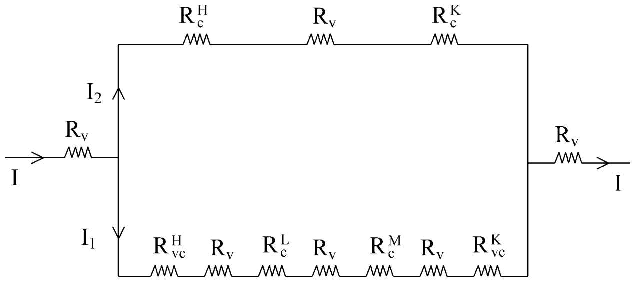

Fig. 11. Electrical circuit model for Fig. 9.

the power is given by

$$P_H = I_1^2 R_c + I_2^2 R_{vc} = 0.149\ \text{W}$$

For junction K, the power is given by

$$P_K = I_2^2 R_c + I_1^2 R_{vc} = 0.102\ \text{W}$$

For junctions L and M,

$$P_L = P_M = I_2^2 R_c = 0.019\ \text{W}$$

The temperatures of the four junctions only roughly scale with the powers at the four junctions, due to the effects of heat absorption by the specimen and of heat dissipation from a hotter point to a colder point in the same specimen. Nevertheless, the circuit model provides a basis for analysis of the spatially distributed heating performance of the junction array.

A similar analysis of Fig. 11 shows that $I_2 > I_1$ and

$$P_H = P_K > P_L = P_M$$

The correctness of the temperature distributions calculated for the two current paths in the four-junction specimen has been qualitatively confirmed in this work by experimental measurement. Extension of the model to a nine-junction specimen is quite complicated, so it is not presented here.

4. Conclusion

The interlaminar interface of a carbon fiber epoxy-matrix composite was found to be an effective resistance heating element. For an interface of area 5×5 mm^2 and resistance 0.25 Ω, a DC electrical power input of 1.1 W (2.1 A, 0.53 V) resulted in a maximum temperature of 85 °C (initial temperature = 19 °C). The time to reach half of the maximum temperature rise was 10 s. The efficiency of conversion from electrical to thermal energy increased with time of heating, reaching 100% after about 47 s, when the heat power output was up to 2×10^4 W/m^2 of the interlaminar interface area. In case that the volume resistance of the laminae dominated the resistance, the time to reach half of the maximum temperature rise was longer—up to 16 s, due to the high mass of the volume compared to the mass of the interlaminar interface. An additional advantage of the use of the interlaminar interface as the heating element is that the interface area can be divided to provide a two-dimensional array of heating elements for the purpose of spatially distributed heating.

References

[1] Yarlagadda S, Kim HJ, Gillespie Jr. JW, Shevchenko NB, Fink BK. A study on the induction heating of conductive fiber reinforced composites. J Compos Mater 2002;36(4).

[2] Kim H, Yarlagaqdda S, Gillespie Jr. JW, Shevchenko NB, Fink BK. A study on the induction heating of carbon fiber reinforced thermoplastic composites. Adv Compos Mater: Off J Japan Soc Compos Mater 2002;11(1):71–80.

[3] Augh L, Gillespie Jr. JR, Fink BK. Degradation of continuous carbon fiber reinforced polyetherimide composites during induction heating. J Thermoplast Compos Mater 2001;14(2):96–115.

[4] Luo X, Chung DDL. Materials contacts under cyclic compression, studied in real time by electrical resistance measurement. J Mater Sci 2000;35(19):4795–802.

[5] Luo X, Chung DDL. Irreversible structural change at the interface between components during fastening. Fastener Technol Int 2002; 25(1):86–7.

[6] Poeller M, Chung DDL. Effect of heating on the structure of an adhesive joint, as indicated by electrical resistance measurement. J Adhes 2003; 79(6):549–58.

[7] Wang S, Chung DDL. Interlaminar interface in carbon fiber polymer-matrix composites, studied by contact electrical resistivity measurement. Compos Interfaces 1999;6(6):497–506.

[8] Wang S, Kowalik DP, Chung DDL. Effects of the temperature, humidity and stress on the interlaminar interface of carbon fiber polymer-matrix composites, studied by contact electrical resistivity measurement. J Adhes 2002;78:189–200.

[9] Hung C-C, Dillehay ME, Stahl M. Heater made from graphite composite materials for potential deicing application. J Aircraft 1987; 24(10):725–30.

[10] Prokushin VN, Shubin AA, Klejmenov VV, Marmer EhN. Carbon heater elements for high temperature furnaces. Khimicheskie Volkna 1992;(6):50–1.

[11] Wang S, Chung DDL. Piezoresistivity in continuous carbon fiber polymer-matrix composites. Polym Compos 2000;21(1):13–19.

[12] Callister Jr.WD. Materials science and engineering, 6th ed. New York: Wiley; 2003. p. 759.