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Temperature/light sensing using carbon fiber polymer-matrix composite

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Abstract

A polymer (epoxy)-matrix composite with the top two laminae of continuous carbon fibers in a crossply configuration was found to be a temperature sensor. Each junction between crossply fiber tow groups of adjacent laminae is a sensor, while the fiber groups serve as electrical leads. A junction array provided by two crossply laminae allows sensing of the temperature/light distribution. The contact electrical resistivity of the junction decreases reversibly upon heating (whether using light or hot plate to heat), due to the activation energy involved in the jump of electrons across the junction. The contact resistivity decreases with increasing pressure during composite fabrication, due to the increase in pressure exerted by fibers of one lamina on those of the other lamina. The absolute value of the fractional change in contact resistivity per degree C increases with increasing pressure during composite fabrication, due to decrease in composite thickness, increase in fiber volume fraction and consequent increases in interlaminar stress and activation energy. A junction between unidirectional fiber tow groups of adjacent laminae is much less effective for temperature/light sensing, due to the absence of interlaminar stress. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: A. Carbon fiber; Polymer

1. Introduction

Sensing is a basic function of a smart structure. The sensing can pertain to strain, damage, light, temperature, etc. The information provided by sensing can be used to activate a certain response of the structure, whether the response is movement, healing, etc. In this way, the structure becomes smart. Sensing is conventionally achieved by the use of attached or embedded sensors that are located randomly in a structure. The sensors can be piezoelectric sensors for strain sensing, a semiconductor pn junction for light sensing and a thermocouple for temperature sensing. In general, the use of such sensors suffers from the high cost and poor durability of the sensors, in addition to the limited sensing volume (just here and there) and the degradation of the mechanical properties of the structure (in case of embedded sensors). A less conventional method involves the use of the structural material itself as the sensor, so that no attached or embedded sensors are needed and the problems mentioned above for attached or embedded sensors are removed. This method utilizing the structural

material as the sensor has been reported for the sensing of strain and damage in continuous carbon fiber epoxy-matrix composites [1–3], in a carbon–carbon composite [4] and in short carbon fiber cement-matrix composites [5–10]. This paper provides the first report of the use of this method for the sensing of light and temperature. The sensing of light enables the use of light for switching and the detection of a laser beam hitting a target (such as an aircraft). The sensing of temperature is always useful, as the temperature affects the performance of structures and devices. In this paper, the structural material that serves as a light/temperature sensor is a continuous carbon fiber epoxy-matrix composite, which is the dominant structural material for aircrafts and spacecrafts and is also used for automobiles, ships and civil structures. The composite is actually an array of light/temperature sensors, so that the light/temperature distribution is sensed. The composite serves both as the sensor array and the wiring (grid of electrical leads), as explained below, so that implementation is straightforward and durability is excellent. In contrast, a thermocouple array for temperature sensing or a pn junction array for light sensing requires extensive wiring, which adversely affects durability, degrades the mechanical properties of the structure (if the wiring is embedded in the structure) and adds to the implementation cost.

The origin of the ability of a continuous carbon fiber

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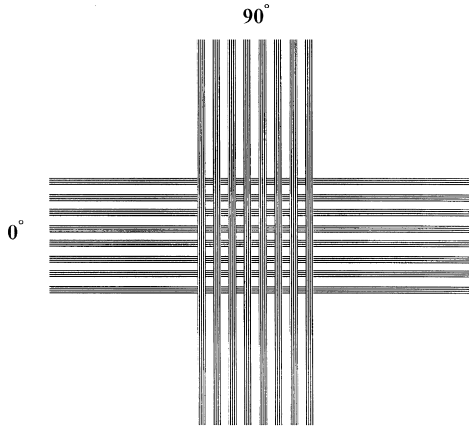*E-mail address:* ddlchung@acsu.buffalo.edu (D.D.L. Chung)

Fig. 1. Light/temperature sensor array in the form of a carbon fiber polymer-matrix composite comprising two crossply laminae.

polymer-matrix composite for sensing light/temperature lies in the effect of light/temperature on the DC contact electrical resistivity of the junction between crossply fiber groups (one or more tows in a group) in two adjacent crossply laminae of the composite. Light or temperature increase causes this resistivity to decrease reversibly, so that the resistance provides a measure of the light intensity or temperature. This photoconductive/thermal phenomenon is due to the activation energy for electron jumping from one lamina to the other. The higher the interlaminar stress (curing stress, thermal stress, etc.), the greater the activation energy [11].

A carbon fiber polymer-matrix composite temperature/ light detector can be in the form of two layers of fibers that are 90° from one another. Each junction of the 0 and
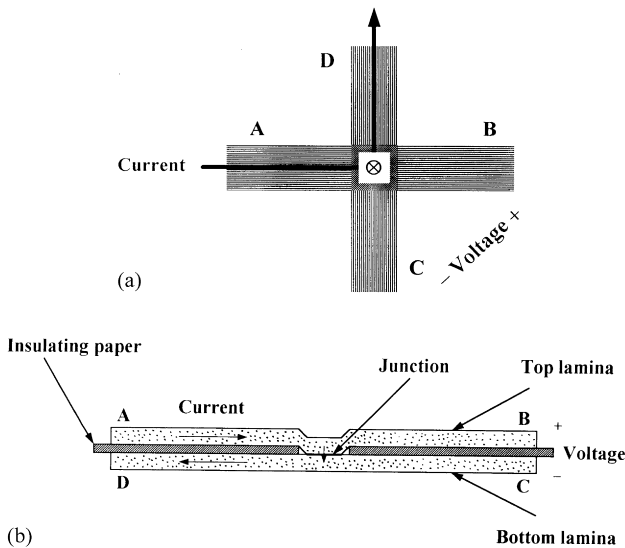

Fig. 2. (a) A single light/temperature sensor in the form of a junction between two crossply laminae (top view). The contact resistivity of the junction is measured by using current probes A and D and voltage probes B and C. The fibers serve as electrical leads. (b) A junction between two unidirectional laminae (side view). In both (a) and (b), the arrows indicate the current path.
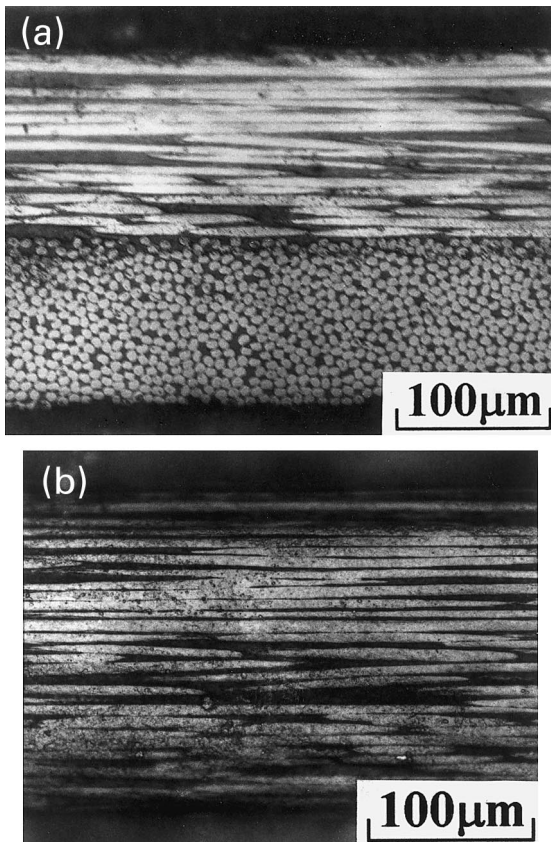
90° fiber groups (multiple tows per group) is an independent detector (Fig. 1). The crossing fiber groups serve as electrical leads for a detector, which is the junction of the crossing fiber groups (Fig. 2). The contact resistivity of each crossing can be best measured by using the four-probe method, in which two probes (A and D) are for passing the current and two probes (B and C) are for measuring the voltage. (The two-probe method is simpler but less accurate; it uses two probes so that the current and voltage probes are not separate and the contact potential resulting from the contact resistance of each probe is included in the measured voltage.) In the four-probe method, the current flows from current probe A along one fiber group, turns to the through-thickness direction and flows through the crossing from one fiber group to the other, and then turns direction again to flow along the other fiber group toward current probe D. The voltage between probes B and C gives the voltage across the junction. The voltage divided by the current is the resistance of the junction. The resistance multiplied by the junction area is the contact resistivity of the junction. The array of junctions in Fig. 1 allows determination of the location on the composite at which light or heat is applied. Computer data acquisition allows the contact resistivity of the junctions in the array to be measured one junction at a time, so that the whole array is measured in a reasonably short time. As the fiber groups serve as electrical leads, no wiring is needed. Not all the groups need to serve as leads, because the spatial resolution of the detection does not need to be excessive.

The top two fiber layers of a composite structure capable of temperature/light detection should be crossply (Fig. 1). The layers below can be in other lay-up configurations. The fibers in the top two layers should be longer than those in the other layers in order to facilitate electrical connection.

The fractional change in contact resistivity per degree C is around -0.13 to -1.10% (negative because the resistivity decreases upon heating) for a carbon fiber epoxy-matrix composite, as reported in this paper. The greater the volume fraction of the fibers, higher the interlaminar stress; the greater the activation energy, larger the magnitude of the fractional change in contact resistivity per degree C.

A thermocouple array can be used to provide spatially resolved temperature/light detection. However, a thermocouple array requires much wiring. In addition, the thermocouple tips must be at or near the outer surface of the composite structure. If the thermocouples are embedded in the composite, they are intrusive and degrade the mechanical properties of the composite. If the thermocouples are attached on the surface of the composite, they can come off easily. Therefore, in practice, a thermocouple array is not feasible for spatially resolved light or temperature sensing.

The light detection technology involving a carbon fiber polymer-matrix composite is unrelated to that involving a carbon film that is semiconducting [12].

Fig. 3. Optical micrographs of the cross-sections of the junctions, showing the two laminae: (a) crossply; and (b) unidirectional.

2. Experimental method

Composite samples were made from two layers of unidirectional carbon fiber prepreg tapes manufactured by ICI Fiberite (Tempe, AZ). The product used was Hy-E 1076E, which consisted of a 976 epoxy matrix and 10E (7 μm diameter, Torayca T-300, 6 K) carbon fibers. Two strips of carbon fiber prepreg were pressed together in a crossply [0/90] or unidirectional [0] configuration to form a square junction of typical size 5 × 5 mm (Fig. 2). For the unidirectional junction, the area of the junction was defined by the use of electrically insulating paper in the interlaminar space outside the junction area. Fig. 3(a) shows an optical micrograph of the cross-section of a crossply sample and Fig. 3(b) shows that of the cross-section of a unidirectional sample. The two laminae could be distinguished in the crossply junction, but not in the unidirectional junction. Every sample consisted of one or more such junctions. Pressure on the junction(s) was provided by a steel weight. A glass fiber epoxy-matrix composite spacer was placed between the weight and the junction(s) to make sure that the weight was applied to the junction(s) only.

Sample 1 (Fig. 4(a)) had two crossply junctions, labeled 1A and 1B. Sample 2 (Fig. 4(b)) had six crossply junctions; the contact resistivities of four of the six junctions, labeled 2A, 2B, 2C and 2D, were measured. Sample 3 (Fig. 4(c))

had one large crossply junction, which was subdivided into smaller areas by splitting the ends of each of the two lamina strips. The contact resistivities of four of the small areas, labeled 3A, 3B, 3C and 3D, were measured. Samples 4–8 described below were employed to study the effect of the curing pressure. Sample 4 had two crossply junctions, the pressures on which were respectively 0 and 0.19 MPa during curing. Samples 5–8 had only one junction each. Samples 5–7 were crossply; Sample 8 was unidirectional. The pressure on Samples 5–8 during curing were 0.062, 0.13, 0.33 and 0.42 MPa, respectively.

The samples were put between the two heating platens of a Carver hot press, where they were cured at 148 ± 2°C for 10.6 h (Samples 1–3) or 175 ± 2°C for 10 h (Samples 5–8). The average heating rate was either 4.4°C/min (Samples 1–3) or 2.5°C/min (Samples 4–8). After curing, the samples were furnace (platen) cooled to room temperature; this took about 11 h. Heating using the platens is referred to as hot plate heating.

To test the temperature sensing ability of the junctions that had completed curing, Samples 1–3 were heated back to the curing temperature (148 ± 2°C) at the rate of 4.4°C/min and then furnace cooled. Then, they were heated to 160 ± 2°C at the rate of 4.4°C/min and then furnace cooled. Further, they were heated to 105 ± 5°C (Samples 1 and 2) at the rate of 1.6°C/min or to 150 ± 2°C (Sample 3) at the rate of 0.18°C/min, and then furnace cooled. The other samples (Samples 4–8) were heated from 50 to 150 ± 2°C at the rate of 0.15°C/min and then cooled at the same rate.

To test the light detection ability of the junctions that had completed curing, either an incandescent desk lamp or a tungsten–halogen lamp (100 W) with a blue filter was used to shine light of spot diameter 50 mm on each sample. Unless stated otherwise, the former was used. For Samples 1, 4, 5, 6, 7 and 8, the light was aimed at the centers of the junctions in turn. For Samples 2 and 3, the light spot was at the centers of junctions 2A and 3A, respectively.

During temperature variation or light shining, the contact resistance R_c for each junction of interest was separately measured using the four-probe method, as shown in Fig. 2(a). The contact resistivity ρ_c was calculated from the equation $\rho_c = R_c A$, where A is the contact (junction) area. In Fig. 4(a), the current path I_{1B} and the voltage difference $V_{1B}^+ - V_{1B}^-$ are involved in measuring the contact electrical resistivity of junction 1B, whereas the current path I_{1A} and the voltage difference $V_{1A}^+ - V_{1A}^-$ are involved in measuring the contact resistivity of junction 1A. For each resistivity measurement, only one current path is possible. However, in Fig. 4(b), due to the larger number of fiber groups in each lamina, multiple current paths are involved when the contact resistivity of a junction is measured. For example, the measurement of the contact resistivity of junction 2A involves current paths $I_{2A}^{(1)}$, $I_{2A}^{(2)}$ and $I_{2A}^{(3)}$. Path $I_{2A}^{(1)}$ gives information on junction 2A, path $I_{2A}^{(2)}$ gives information on junctions 2E, 2C and 2B, and path $I_{2A}^{(3)}$ gives information on junctions 2D, 2F and 2B. Because three contact resistances
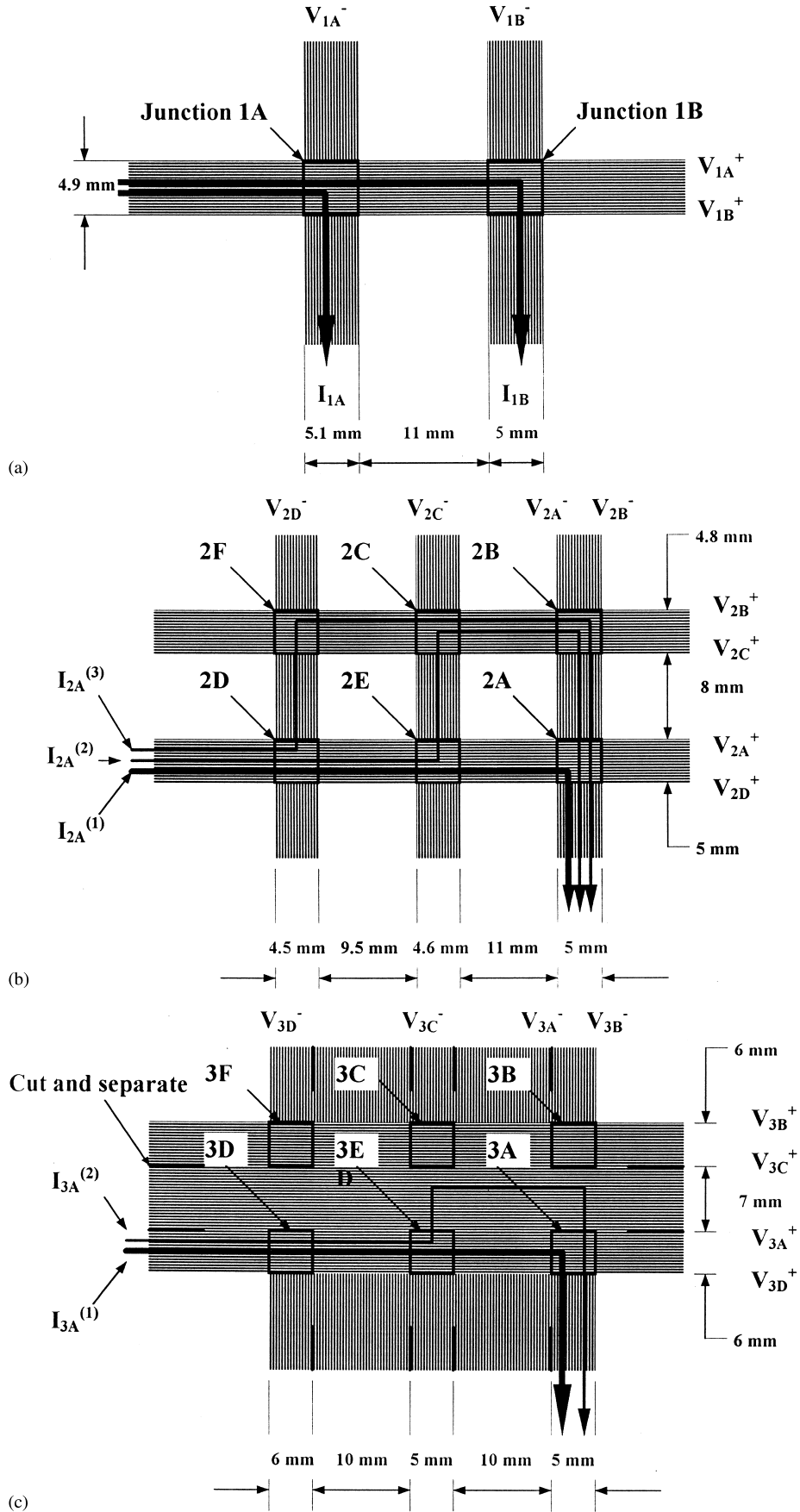
Fig. 4. Junction arrays and configurations for measuring the contact resistance: (a) Sample 1; (b) Sample 2; and (c) Sample 3.
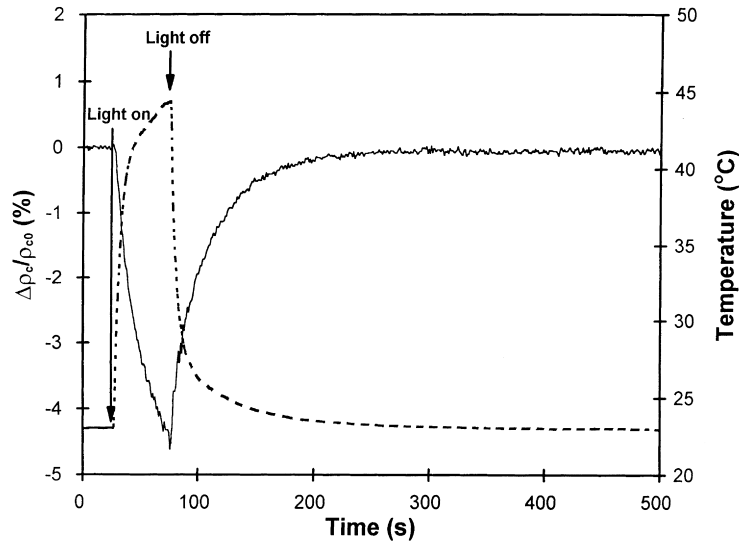
Fig. 5. The fractional change in contact resistivity (solid line) of junction 1A and the temperature (dashed line), obtained simultaneously during light shining.

are involved in either path $I_{2A}^{(2)}$ or path $I_{2A}^{(3)}$, and only one contact resistance is involved in path $I_{2A}^{(1)}$, path $I_{2A}^{(1)}$ is the path of least resistance. Therefore, $I_{2A}^{(1)}$ is much greater than either $I_{2A}^{(2)}$ or $I_{2A}^{(3)}$. Although $I_{2A}^{(2)}$ and $I_{2A}^{(3)}$ contribute information on junctions that are not under resistivity measurement to the measured resistivity of junction 2A, the contributions are small. Nevertheless, their contributions mean that one junction's contact resistance can affect the measured contact resistance of another junction in a junction array.

A Keithley 2001 multimeter was used for DC electrical resistance measurement. For a sample with multiple junctions, R_c for each junction was measured separately—one at a time. The time delay between the resistance measurement of two junctions was less than half a second. Hence, all the junctions in a sample were measured at essentially the same time. The epoxy at the ends of each prepreg strip was burned out to expose the carbon fibers for the purpose of making electrical contacts. These exposed fibers were wrapped by pieces of copper foil, with silver paint between the copper foil and the fibers.

The temperature of the samples was continuously measured by one or more T-type thermocouples. A thermocouple was put just beside each of junctions 1A, 2A and 3A for samples 1, 2 and 3, respectively, and just beside each of the junctions for the other samples. The light shining experiments were performed twice under the same condition for each sample. During the first experiment, a thermocouple was put just beside the junction being shone. During second experiment, the thermocouple was put on the top of the junction center. The temperature difference between the two situations was from 2 to 4°C. The contact resistance was measured during the first experiment and the temperature was measured during the second experiment. To measure the temperature distribution, four thermocouples were put right on the centers of junctions 2A, 2B, 2C and

2D in case of Sample 2 (3A, 3B, 3C and 3D in case of Sample 3). To compare the effect of light shining and hot plate heating, after the light shining experiment, each of Samples 4–8 was hot plate heated up to the highest temperature reached during prior light shining at 0.5°C/min, and then furnace cooled. At the same time, the contact resistance was measured.

3. Results and discussion

Fig. 5 shows how the fractional change of contact resistivity ($\Delta\rho_c/\rho_{co}$) and temperature of junction 1A changed when the tungsten–halogen lamp was turned on and then off. When the lamp was turned on, the contact resistivity decreased, while the temperature increased. When the lamp was turned off, the contact resistivity increased while the temperature decreased. The effect was reversible. Fig. 6 shows a similar result, but the incandescent lamp used was much weaker. Although the range of temperature change was only about 0.3°C, the change in contact resistivity was detectable.

Fig. 7 shows the variation of $\Delta\rho_c/\rho_{co}$ of junction 1A with temperature during hot plate heating and cooling (without shining light). The $\Delta\rho_c/\rho_{co}$ decreased when the temperature increased and $\Delta\rho_c/\rho_{co}$ increased when the temperature decreased; the effect was essentially totally reversible.

The results above indicate that shining light has a strong influence on the contact resistivity, and this influence does not result mainly from the light itself but from the heat effect of the light. That light failed to affect the electrons directly is due to the inability of the light to penetrate the top lamina (120 μm thick, Fig. 3(a)) and reach the junction.

Table 1 shows the influence of the curing pressure and composite configuration. For the same composite configuration (crossply), the higher the curing pressure, the
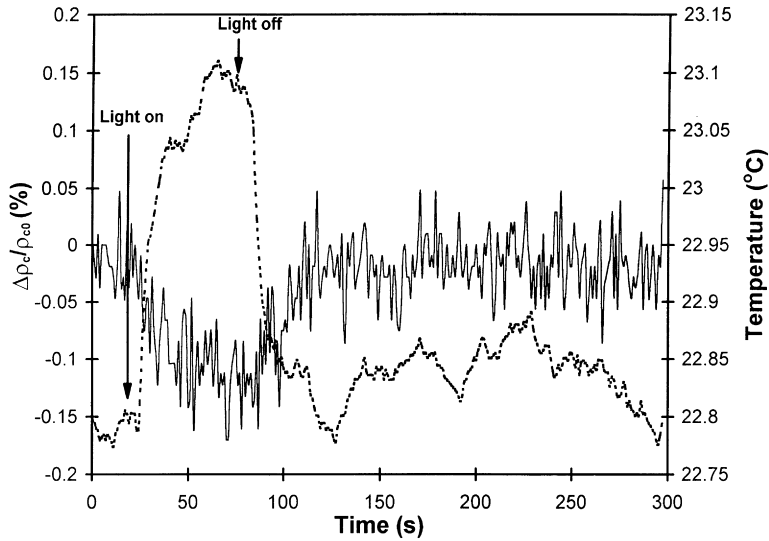
Fig. 6. The fractional change in contact resistivity (solid line) of junction 1A and the temperature (dashed line), obtained simultaneously during light (weaker than that in Fig. 5) shining.

smaller was the composite thickness (because of more epoxy being squeezed out); the higher the pressure exerted by the fibers of one lamina on those of the other lamina at the junction, and the lower was the contact resistivity. A higher curing pressure corresponds to a higher fiber volume fraction in the composite. (The fiber volume fractions for the curing pressures of 0.13, 0.33 and 1.4 MPa were measured and found to be 0.50, 0.52 and 0.58, respectively.) During curing and subsequent cooling, the matrix shrinks while the carbon fibers essentially do not, so a longitudinal compressive stress will develop in the fibers. For carbon fibers, the modulus in the longitudinal direction is much higher than that in the transverse direction. Moreover, the fibers are continuous in the longitudinal direction. Thus, the overall

shrinkage in the longitudinal direction tends to be less than that in the transverse direction. Therefore, there will be an interlaminar stress in the two crossply layers in a given direction. This stress accentuates the barrier for the electrons to jump from one lamina to the other. The greater the interlaminar stress, the higher the barrier, which is the activation energy. After curing and subsequent cooling, heating will decrease the thermal stress, due to the CTE mismatch between fibers and matrix. However, the thermal stress is probably smaller than the curing stress, so the activation energy does not decrease upon heating [11]. Therefore, the higher the curing pressure, the larger the fiber volume fraction, the greater the interlaminar stress, the higher the activation energy, and the greater is the absolute
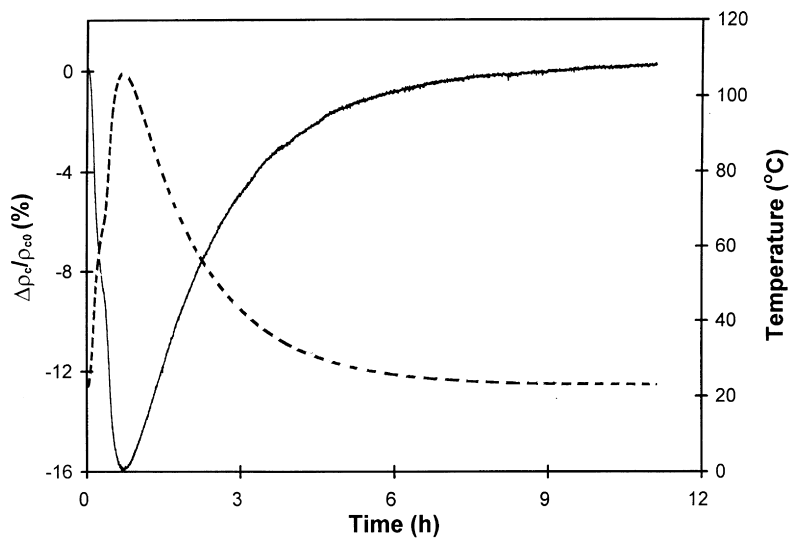

Fig. 7. The fractional change in contact resistivity (solid line) of junction 1A and the temperature (dashed line) during hot plate heating and cooling without light shining.

Table 1
The influence of curing pressure and composite configuration

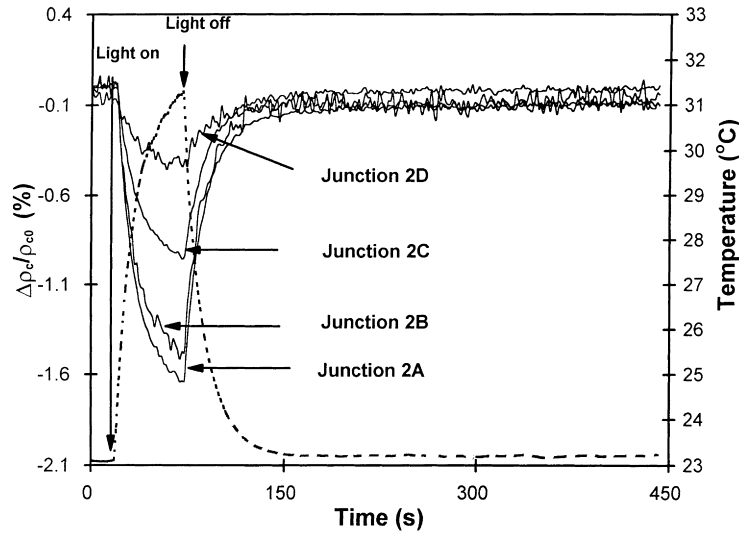| Composite configuration	Curing pressure (MPa)	Composite thickness (mm)	Contact resistivity ρ_{co} (Ω cm^2)	$(\Delta\rho_c/\rho_{co})/\Delta T$ ($°C^{-1}$)	
				Due to light shining	Due to hot plate heating
[0/90] (crossply)	0	0.36	0.73	− 0.132%	− 0.0959%
	0.062	0.32	0.14	− 0.133%	− 0.0898%
	0.13	0.31	0.18	− 0.160%	− 0.126%
	0.19	0.29	0.054	− 0.269%	− 0.179%
	0.33	0.26	0.0040	− 1.10%	− 0.888%
[0] (unidirectional)	0.42	0.23	0.29	− 0.0145%	− 0.0457%

Fig. 8. The fractional change in contact resistivity (solid line) of junctions 2A, 2B, 2C and 2D and the temperature (dashed line) of junction 2A, obtained simultaneously during light shining. The center of the light spot was at the center of junction 2A. The distance of the centers of 2A, 2B, 2C and 2D from the center of the light spot was 0, 12.9, 20.4 and 29.9 mm, respectively.

value of the fractional change in contact resistivity per degree C.

The fact that this absolute value for the case of shining light is a little higher than that for the case of hot plate heating probably indicates that light has some additional effect on the contact resistivity other than its heat effect. This phenomenon also may be because light shining gave a higher heating rate, less uniformity in temperature, and hence higher thermal stress.

The curing pressure for the sample in the unidirectional composite configuration was higher than that of any of the crossply samples. Consequently, the thickness was the lowest. As a result, the fiber volume fraction was the highest. However, its contact resistivity was the second highest

rather than being the lowest, while the absolute values of $(\Delta\rho_c/\rho_{co})/\Delta T$ was very low compared to the crossply samples. Hence, the difference in composite configuration made a big difference to the contact resistivity and its response to temperature changes. In the crossply samples, the pressure during curing forced the fibers of the two laminae to press on to one another and hence contact tightly. In the unidirectional sample, the fibers of one of the laminae just sank into the other lamina at the junction, as suggested by Fig. 3(b), so pressure helped relatively little in the contact between fibers of adjacent laminae. Moreover, in the crossply situation, every fiber at the lamina–lamina interface contacted many fibers of the other lamina, while, in the unidirectional situation, every fiber had little chance
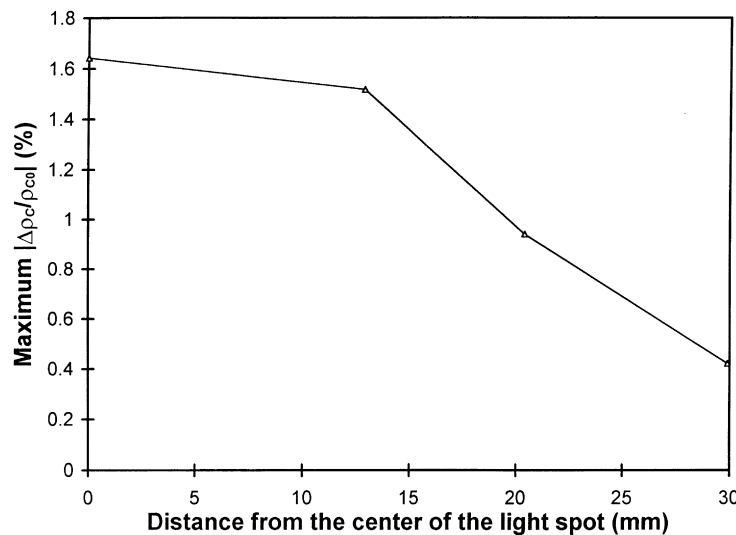

Fig. 9. The peak value of the fractional change in contact resistivity as a function of the distance from the center of the light spot.
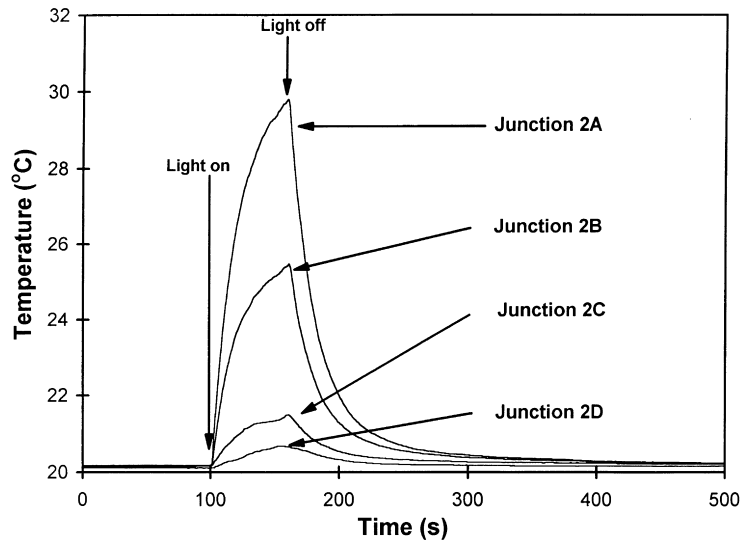
Fig. 10. The temperature changes of junctions 2A, 2B, 2C and 2D during light shining, obtained by putting a thermocouple at the center of each of junctions 2A, 2B, 2C and 2D.

to contact the fibers of the other lamina. Therefore, the number of contact points between the two laminae was less for the unidirectional sample than the crossply samples. Consequently, the unidirectional sample had a higher contact resistivity. The very low absolute value of $(\Delta\rho_c/\rho_{co})/\Delta T$ for the unidirectional sample probably resulted from the fact that there was no CTE or curing shrinkage mismatch between the two laminae, so that the interlaminar stress was absent and the activation energy was very low [11]. The fact that the absolute value of $(\Delta\rho_c/\rho_{co})/\Delta T$ due to light shining was smaller than that due to hot plate heating for the unidirectional sample is yet to be elucidated. Both values for light shining and hot plate heating were much lower than those of the crossply samples. Thus the unidirectional junction was not

as effective for light/temperature sensing as the crossply junction.

Fig. 8 shows the fractional changes in contact resistivity for junctions 2A, 2B, 2C and 2D of Sample 2 when the light (incandescent) was turned on and off. The center of the light spot was at the center of junction 2A. The distance between the center of the light spot and the center of junction 2A, 2B, 2C and 2D is 0, 12.9, 20.4 and 29.9 mm, respectively. Fig. 9 shows the relationship between the peak magnitude of the fractional contact resistivity change and the distance from the center of the light spot. The temperature distribution given by thermocouples under the same incandescent light source is shown in Fig. 10. The relationship between the peak temperature change and the distance from the center of the light spot is shown in Fig. 11. Figs. 8–11 indicate that
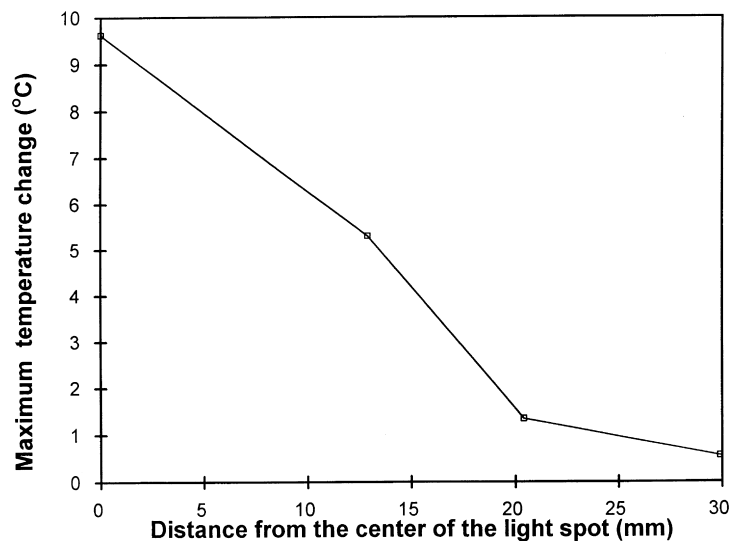

Fig. 11. The maximum temperature change as a function of the distance from the center of the light spot.
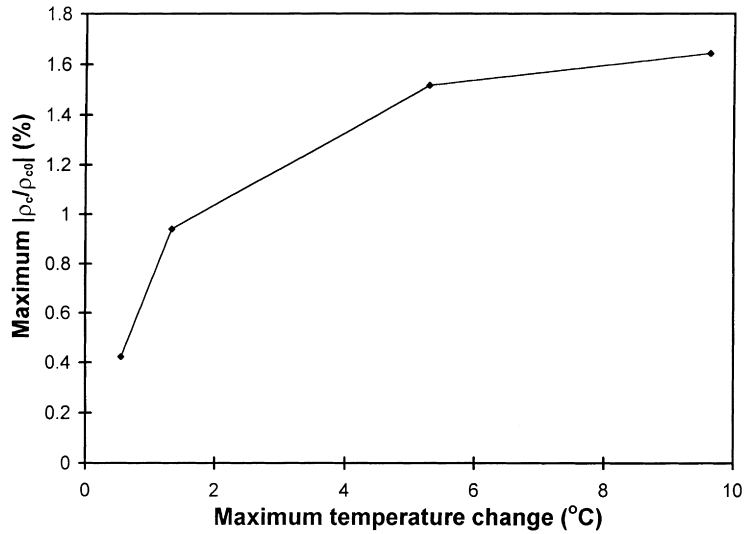
Fig. 12. The relationship between the peak absolute value of the fractional change in contact resistivity and the peak value of the temperature change for junctions 2A, 2B, 2C and 2D.

nearer to the center of the light spot, the greater the magnitude of the fractional contact resistivity change and the greater the temperature change. The contact resistivity decrease is because the temperature increase results in an increase in the number of electrons that are energetic enough to jump from one lamina to the other. The fractional contact resistivity change can be used to locate the light spot, since the difference in $\Delta\rho_c/\rho_{co}$ between the different positions is large. Comparison among Figs. 8–11 shows that the value $\Delta\rho_c/\rho_{co}$ of junctions 2B and 2A (Fig. 8) are quite close, while the temperatures of these junctions are quite different (Fig. 10). On the other hand, the changes in $\Delta\rho/\rho_{co}$ of junctions 2C and 2D are quite different (Fig. 8), but the temperatures of these junctions are quite close (Fig. 10). Fig.

12 shows the relationship between the peak magnitude of the fractional contact resistivity change and the peak temperature change of junctions 2A, 2B, 2C and 2D. Fig. 13 shows the same type of relationship for the single junction of Sample 7. The curve is quite linear. However, the curve in Fig. 12 is not linear. This is because multiple current paths exist in the case of multiple junctions. The measured change in contact resistance of one junction is affected by the change in contact resistance of the other junctions. For the case of multiple junctions, the greater the temperature change, the more gradual the increase of the peak fractional contact resistivity change; the sensitivity was good when the temperature change was less than 6°C.

Similar results for Sample 3 are shown in Fig. 14. Sample
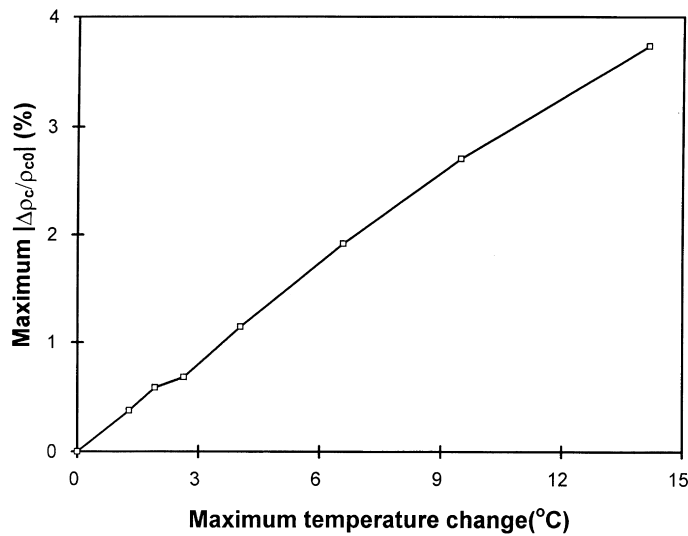

Fig. 13. The relationship between the peak absolute value of the fractional change in contact resistivity and the peak value of the temperature change for the single junction of Sample 7.
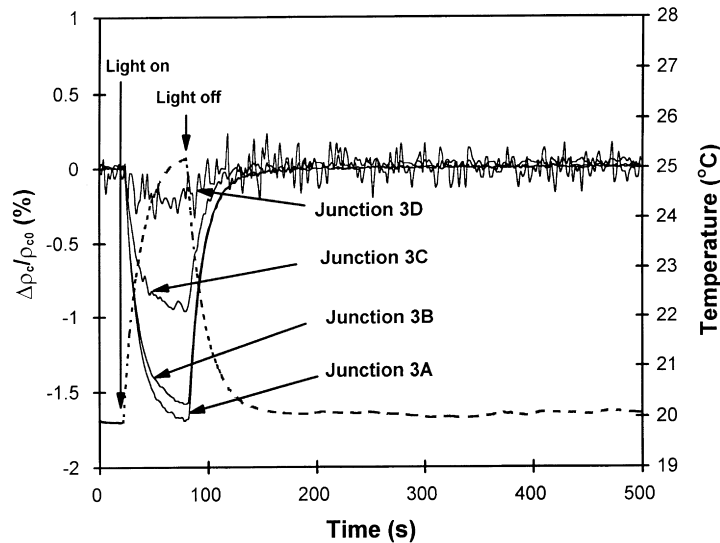
Fig. 14. The fractional changes in contact resistivity (solid line) of junctions 3A, 3B, 3C and 3D and the temperature (dashed line) of junction 3A, obtained simultaneously during light shining. The center of the light spot was at the center of junction 3A. The distances of the centers of 3A, 3B, 3C and 3D from the center of the light spot were 0, 13.0, 19.8 and 30.5 mm, respectively.

3 gave a similar distribution of fractional contact resistivity change as Sample 2 (Fig. 8). The configuration of Sample 3 is closer to the situation of practical application than that of Sample 2. The similarity of the results of Samples 2 and 3 means that the fiber groups of adjacent junctions do not need to be separated by a gap in practical application.

4. Conclusion

An epoxy-matrix continuous carbon fiber composite comprising two crossply laminae was found to be a temperature sensor, which could be used as a light sensor. Each junction between crossply fiber tow groups of the adjacent laminae was a sensor, while the fiber groups served as electrical leads. A junction array allowed temperature/light distribution sensing. The contact electrical resistivity of the junction decreased reversibly upon heating, due to the electron hopping between the laminae. The fractional change in contact resistivity provided an indication of temperature/light. The contact resistivity decreased with increasing pressure during composite fabrication, due to increase in pressure exerted by fibers of one lamina on those of the other lamina. The magnitude of the fractional change in contact resistivity per degree C increased with increasing curing pressure (fiber volume fraction), due to the increase in interlaminar stress with increasing fiber volume fraction and the consequent increase in activation energy. A crossply junction is much better than a unidirectional junction as a temperature/light sensor, due to the absence of interlaminar stress in the latter.

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