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Composites: Part A 37 (2006) 1490–1494

composites
Part A: applied science and manufacturing

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Short communication

Discussion on paper 'The electrical resistance response of continuous carbon fibre composite laminates to mechanical strain' by N. Angelidis, C.Y. Wei and P.E. Irving, Composites: Part A 35, 1135–1147 (2004)

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Received 8 September 2004; received in revised form 1 May 2005; accepted 16 May 2005

Abstract

The paper "The electrical resistance response of continuous carbon fibre composite laminates to mechanical strain" by Angelidis et al. (2004), as explained in this communication, contains questionable experimental results and questionable interpretation of experimental results.

Keywords: A. Laminate; A. Carbon fibre; Electrical resistance; Strain

1. Introduction

The paper under discussion contains questionable experimental results and questionable interpretation of experimental results, as explained below.

The abstract of the paper under discussion reads, "It was found that uniform current introduction at sample edges produced by sputtered Au–Cr contacts across the entire cross-section produced consistently low values of gauge factor… Non-uniform current introduction, produced variously by local point introduction of current, or use of viscous adhesives producing intermittent contact, resulted in a wide range of apparent gauge factors ranging from 20.6 to −89. These anomalous values may be explained by a model…".

2. Two-probe method used in configurations D and E

In the paper under discussion, the sputtered Au–Cr contacts were used in the two-probe configuration, whereas the adhesive contacts were used in the four-probe configuration. The prior work of Wang and Chung [1] has shown that, for the same composite of the type studied, negative piezoresistivity occurs when the four-probe method is used and that positive piezoresistivity occurs when the two-probe method is used. The quality of the electrical contacts is the same for the four-probe and two-probe methods. The two-probe method gives a measured resistance that includes the contact resistances, whereas the four-probe method gives a measured resistance that basically does not include the contact resistance. Thus, the resistance measured by using the two-probe method depends on the quality of the electrical contacts much more than that measured by using the four-probe method (Nevertheless, the resistance measured by using the four-probe method is still affected by the quality of the contacts.). As a consequence, degradation of one or more electrical contacts (as it may occur during loading/unloading due to the movement of the grips, the changes in the gripping pressure, and the

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doi:10.1016/j.compositesa.2005.05.041

Poisson shrinkage of the specimen) affects the resistance measured by using the two-probe method much more than the resistance measured by using the four-probe method. The longitudinal gage factor is consistently positive when the two-probe method is used [1]. In particular, it is +3.0 for the eight-lamina unidirectional composite studied by Wang and Chung [1] using the two-probe method. The longitudinal gage factor is +1.75 for the 16-lamina unidirectional composite of the paper under discussion. That these two values of the gage factor are quite close (compared to the values ranging from 20.6 to −89 in the paper under discussion) supports the notion that the resistance response reported in the paper under discussion for the case of sputtered Au–Cr contacts is due to the two-probe method used rather than the true behavior of the composite itself. Even if the contact resistance is small, the quality of the contact may change during loading, thereby resulting in apparent piezoresistivity (i.e. piezoresistivity that is not due to the composite material itself).

The local current distribution mentioned in the paper under discussion can be a cause for positive piezoresistivity. However, contact degradation remains a reasonable cause for the positive piezoresistivity.

3. Current spreading in the transverse and through-thickness directions

The paper under discussion is incorrect in its calculation of the extent of spreading of a longitudinal current flowing in a part of the cross-section of a unidirectional composite. The calculation, as described in the first paragraph of Section 4.2, is based on the ratio of the resistivity in the transverse direction to that in the longitudinal direction. The calculation led to the wrong conclusion that current spreading can only be up to a distance 0.1 mm in the transverse direction when the specimen is 280 mm long in the longitudinal direction. The correct calculation should be based on the resistance ratio rather than the resistivity ratio, with the recognition that the resistance depends on the resistivity, length and cross-sectional area. The cross-sectional area was neglected in the calculation in Section 4.2. Since the current is applied over a distance of 280 mm, the effective cross-sectional area is much larger for current in the transverse direction than for current in the longitudinal direction. As a result, the ratio of the transverse resistance to the longitudinal resistance is much lower than the ratio of the transverse resistivity to the longitudinal resistivity. Therefore, the extent of current spreading in the transverse direction is much more than 0.1 mm.

In the context of Configuration A, which is the most practical configuration among the various configurations in the paper under discussion, the spreading of the longitudinal current in the through-thickness direction (rather than the transverse direction) should be considered. Consider a related configuration in which the current contacts are on one side of the composite bar (Fig. 1). In other words, current is introduced from one side. The question pertains to the depth of penetration of this current in the through-thickness direction. This depth depends on the distance d between the adjacent current and voltage contacts (Fig. 1). Let us roughly calculate the distance d required for current penetration to the middle of the specimen along the through-thickness direction (i.e. penetration to a depth of $t/2$, where t is the thickness of the specimen) to be attained in the part of the specimen between the voltage probes (B and C in Fig. 1).

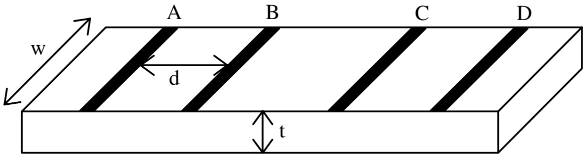

Fig. 1. Configuration for calculating the extent of current spreading in the through-thickness direction. A, B, C and D are the electrical contacts, which are all on one side of the specimen. A and D are current contacts; B and C are voltage contacts.

The resistance in the longitudinal direction R_L for the part of the specimen between A and B is given by

$$R_L = \rho_L \frac{d}{w(t/2)}, \tag{1}$$

where ρ_L is the longitudinal resistivity and w is the width of the specimen (Fig. 1). The resistance in the through-thickness direction R_T for the part of the specimen between A and B is given by

$$R_T = \rho_T \frac{t/2}{wd}, \tag{2}$$

where ρ_T is the through-thickness resistivity. If R_T is much higher than R_L, current penetration will be small. If R_T and R_L are comparable, current penetration will be large. For R_T and R_L to be equal, Eqs. (1) and (2) mean that

$$d = \sqrt{\frac{\rho_T}{\rho_L}}\frac{t}{2} \tag{3}$$

If $\rho_T/\rho_L = 10^4$,

$$d = 50t. \tag{4}$$

In the paper under discussion, $t = 2$ mm, so $d = 100$ mm. In Configuration A, d exceeds 100 mm. Thus, complete current penetration through the entire thickness of the specimen is expected for Configuration A, even if each current contact were covering just the ends of a very small portion of the fibers, such as the fibers in the mid-plane of the composite bar.

Such a calculation also shows complete current penetration from current contacts that are on the surface all the way around the perimeter of the composite bar in the prior work of Wang and Chung [1]. The complete current penetration is also supported by the fact that the measured (four-probe method) and calculated (Rule of Mixtures) values of the longitudinal resistivity are close.

In a separate experiment (unpublished), we have measured the longitudinal resistance using the four-probe method and perimetric electrical contacts for various distances between the adjacent current and voltage probes. This study shows that the measured resistance decreases as the distance increases only up to about 30 mm. The curve of resistance vs. distance levels off beyond 30 mm. This means that the longitudinal distance required for complete current penetration can be as small as 30 mm.

The finite element modeling in the paper under discussion is for a configuration involving voltage contacts that are not in line with the current contacts. In contrast, the model presented above is for a configuration (Fig. 1) in which the voltage contacts are in line with the current contacts. The in-line configuration is that needed for resistance measurement.

The above analysis shows that, due to current spreading, a current contact at an end of the specimen in Configuration A does not need to cover most of the area of the end surface. The large effect of the current contact quality on the variation of the potential with strain, as reported in the paper under discussion, is attributed at least partly to experimental problems such as those related to current control and potential measurement. Such experimental problems are also suggested by the unreasonably low value of the resistivity (0.015 mΩ m, which is only 60% of the calculated value based on the Rule of Mixtures), as obtained from the measured potential using voltage contacts on the surface of the Configuration A specimen with carbon cement.

The quality of a current contact at the end of a specimen may degrade during longitudinal loading due to the Poisson shrinkage or mechanical disturbance of the specimen. Although the current spreading is appreciable, it is possible for changes in the quality of a current contact during loading to contribute to causing the observation of apparent piezoresistivity (i.e. piezoresistivity that is not due to the composite material itself).

4. Possible origins of apparent piezoresistivity

Piezoresistivity refers to variation in the resistance due to resistivity change rather than merely variation due to dimensional changes. The gage factor is positive and around +2 (depending on the Poisson ratio) if the resistance change is merely due to dimensional changes.

The sign of the piezoresistivity of the composite is not necessarily the same as that of the individual fibers, due to the difference in structure between the composite and a single fiber. For example, the piezoresistivity of a single T-300 carbon fiber is essentially absent, as the gage factor is only +2 [2]. However, the T-300 carbon fiber epoxy–matrix composite exhibits negative piezoresistivity [3].

The simple model in the paper under discussion is incapable of showing negative piezoresistivity, due to its assumption of the electrical disconnect between fibers and electrical contact to be responsible for the change in measured resistivity. That this model cannot show negative piezoresistivity does not mean that negative piezoresistivity cannot occur.

In the paper under discussion, the four-probe method with the intention of attaining uniform current density throughout the cross-section of the composite was conducted by using current contacts that were at the ends of the composite bar (i.e. the ends of the 0° fibers). The current contact was a copper strip attached to each of the two ends of the composite by using a bonding agent, i.e. silver paint or carbon cement.

Effectiveness of the copper strip contact requires good mechanical and electrical connection between the copper and the composite. The need for good mechanical connection is because mechanical disturbance can be detrimental to the quality of an electrical contact. This quality ideally should not change during measurement of the electrical resistance under repeated loading and unloading. Degradation of a current contact can result in fewer fibers (randomly distributed as fiber groups in the cross-section of the composite, as illustrated in Fig. 2(a)) receiving current and thus, in spite of the current spreading, effectively fewer fibers available for electrical conduction in the part of the composite between the voltage contacts and consequently a higher measured (apparent) resistance of the composite. Such variation in the apparent resistance does not reflect the true behavior of the composite itself, as it is an artifact of the current contact imperfection. The simple model for explaining positive piezoresistivity, as described in Eqs. (7)–(9) of the paper under review, is consistent with the abovementioned notion that the current contact degrades upon loading, thereby causing less fibers to experience current flow. Thus, the positive piezoresistivity (gage factor = +20.6) for Configuration A and silver paint is attributed to current contact degradation in the form of Fig. 2(a), which occurs reversibly upon loading and causes loosening of the electrical connection with fiber groups that

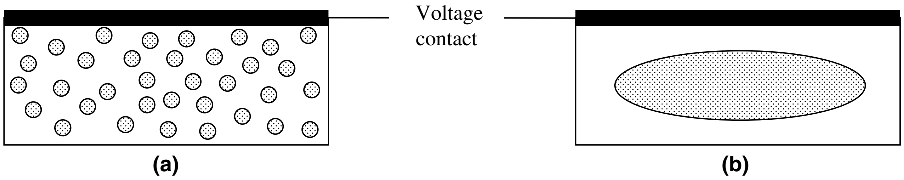

Fig. 2. Two forms of current density non-uniformity at the cross-sectional area. The shaded regions are the regions of high c urrent density. The unshaded regions are regions of low current density, (a) Regions of high current density are randomly distributed, resulting in apparent positive piezoresistivity. (b) Region of high current density is away from the rim of the cross-sectional area, resulting in apparent negative piezoresistivity.

are randomly distributed throughout the cross-section. The reversible loosening of the electrical contacts has been previously shown by the apparent positive piezoresistivity observed by using the two-probe method [1].

Silver paint is not an adhesive, so it cannot give a mechanically reliable connection. Carbon cement is perhaps an adhesive, but it is not as conductive as silver paint. Thus, the quality of the mechanical/electrical connection between copper and composite is questionable, whether silver paint or carbon cement is used as the bonding agent.

Assuming that the current density is uniform throughout the cross-section of the specimen, the potential data given for Configuration A implies that the electrical resistivity is 0.023 mΩ m for the specimen with silver paint at the current contacts and 0.015 mΩ m for the specimen with carbon cement at the current contacts. We obtained these values by simple calculation using the potential, current and dimensions. These resistivity values are considerably lower than the measured value of 0.028 mΩ m for Configuration E or the theoretical value of 0.027 mΩ m. Such low resistivity values are unreasonable and mean that the current density is less at the surface than the interior of the specimen (Configuration A) for both silver paint and carbon cement cases, as illustrated in Fig. 2(b). Such non-uniformity in the current density can be due to the silver paint or carbon cement being a little loose from the composite end at the rim of the composite end. As the potential was measured by using voltage contacts on the surface on one side of the specimen, the lower current density at the rim resulted in a lower measured potential at the voltage contacts. That the apparent resistivity is lower for the carbon cement case than the silver paint case means that the rim loosening is worse for the carbon cement case. Due to the high viscosity of carbon cement compared to silver paint, it is reasonable that carbon cement spreads less easily than silver paint, thereby causing the bond to experience more loosening at the rim.

During loading, the rim loosening worsens (i.e. the region of high current density in Fig. 2(b) becomes smaller), thereby causing the current density at the rim to be even lower and consequently the measured potential at the voltage contacts at the surface to decrease. The very negative gage factor of −89 for Configuration A and carbon cement can be explained by the loosening at the rim during loading, in addition to the true negative piezoresistivity of the composite itself. The true negative piezoresistivity of the composite has gage factor values (e.g. −23 or less in magnitude [1]) that are much less negative than −89. Thus, the negative piezoresistivity reported in the paper under discussion for Configuration A and carbon cement is dominated by the loosening of the current contact loosening at the rim.

The paper under discussion reports that, when carbon cement is used as the adhesive for bonding copper to the composite end, the values of the gage factor are opposite in sign for the two sides of the composite. This means that, the current density distribution is non-uniform, so that the voltage contacts, which are on one side, cannot provide a representative value for the overall composite.

The paper under discussion reports without data that removal of the silver paint at the current contact, followed by abrasion of the composite end and reapplication of silver paint to parts of the composite end, results in change from positive piezoresistivity to negative piezoresistivity. The change from positive piezoresistivity to negative piezoresistivity may be due to the looser bond (after silver paint partial reapplication) between copper and composite end and the consequent decrease in the measured potential at the voltage contacts, which are on the surface on one side, during subsequent loading.

Silver epoxy is a better conductive adhesive than carbon cement. Among the three bonding agents used (silver epoxy, silver paint and carbon cement), silver epoxy has the best combination of electrical and mechanical properties. For the case of silver epoxy (Configuration A), the gage factor is +3.6, which is much smaller in magnitude than the values for silver paint (+20.6) or carbon cement (−89). This observation supports the notion that the strong apparent piezoresistivity observed for silver paint and carbon cement is related to the poor quality of the electrical contact. However, even with silver epoxy, the bond at the composite end can be disturbed upon longitudinal loading, thereby resulting in weakly positive apparent piezoresistivity.

For Configuration B, channel 1 (point voltage contacts in line with point current contacts) gave positive piezoresistivity, whereas channel 2 (point voltage contacts not in line with point current contacts) gave negative piezoresistivity. The apparent positive piezoresistivity for channel 1 is due to the four contacts being on one side of the composite bar. This contact geometry means that the surface resistance was measured. The surface region is mainly the top lamina, since the interlaminar interface is associated with considerable resistance [4]. The prior work of Gordon et al. [5] has shown that the piezoresistivity is positive (gage factor ranging from +1.8 to +3.5) for a single-lamina composite and is negative (gage factor ranging from −6.0 to −5.1) for a two-lamina composite. The surface resistance reflected mainly the behavior of the surface lamina (like a single-lamina composite, which exhibits positive piezoresistivity). The negative piezoresistivity for channel 2 is due to the transverse component in the current path and the Poisson effect. As longitudinal tension is applied, the transverse strain is negative (Poisson shrinkage), thereby causing the transverse resistance to decrease.

For Configuration C, the observed positive piezoresistivity is due to increase in the degree of fiber alignment as tension is applied in the longitudinal direction. This increase causes decrease in the number of contacts between adjacent fibers in the same lamina, thus increasing the transverse resistivity. A similar positive piezoresistivity had been previously reported by Wang and Chung [6] for the through-thickness resistance, which increases with longitudinal strain/stress due to decrease in the number of contacts between fibers of adjacent laminae.

For a crossply composite in Configuration A, the paper under discussion reported weakly positive piezoresistivity, whether the bonding agent was silver paint or carbon cement at the current contact. This behavior reflects the greater difficulty of contacting all the fibers at the composite end when the composite is crossply rather than unidirectional. As a result, the current distribution was non-uniform (Fig. 2(a)), whether carbon cement or silver paint was used. This non-uniformity, along with the fact that the voltage contacts were on one side, resulted in apparent positive piezoresistivity.

For Configuration B, Channel 2 gave positive piezoresistivity for the crossply composite (Fig. 14(b) of the paper under discussion), but negative piezoresistivity for the unidirectional composite (Fig. 10(b) of the paper under discussion). This is because the Poisson effect in the transverse direction is diminished by the 90° fibers in the crossply composite.

For Configuration C, the crossply composite (Fig. 15 of the paper under discussion) gave negative piezoresistivity, because of the Poisson effect in the transverse direction. In contrast, the unidirectional composite (Fig. 11 of the paper under discussion) gave positive piezoresistivity because the effect of increase of the degree of fiber alignment dominates, due to the absence of 90° fibers.

The paper under review fails to explain the observed negative piezoresistivity for Configuration A. The explanation in terms of a high resistance transverse conduction path is applicable to Configuration B, but not to Configuration A. Even for Configuration B, the explanation is weak, since it is based on the assumption that the gage factor is more positive in the transverse direction than the longitudinal direction. The values of these gage factors used in the calculation are those for Configurations D and E, which give unreliable gage factors due to the two-probe method used.

5. Possible origin of true piezoresistivity

Our explanation of true negative piezoresistivity is in terms of the increase in the degree of fiber alignment. A lower degree of fiber alignment enhances the negative piezoresistivity, as shown by separate experimental work on composites with different inherent degrees of fiber alignment [3,5]. The degree of fiber alignment is increased upon tension, thereby decreasing the longitudinal resistivity and increasing the through-thickness resistivity [3,7,8].

For observing the true negative piezoresistivity of a unidirectional composite, it is important to avoid strain-dependent non-uniformity in the current density. Reliable contacts at the ends of a composite bar are more difficult to attain than those on side surface(s) of the bar, due to the relatively small area and greater roughness of the end surfaces. By using contacts on side surfaces, around the whole perimeter, Chung et al. [1,3–7] attained reliable electrical contacts and uniformity in the current density, thereby observing true negative piezoresistivity for multilamina composites.

6. Summary

The results in the paper under discussion show that both apparent positive piezoresistivity and apparent negative piezoresistivity can be obtained in the longitudinal direction of a unidirectional composite (Configuration A) if the current density is non-uniform in the cross-section of the composite and the non-uniformity depends on the longitudinal strain. Strain-dependent non-uniformity in the form of Fig. 2(a) results in apparent strong positive piezoresistivity, as observed for silver paint as the bonding agent in the current contact. Strain-dependent non-uniformity in the form of Fig. 2(b) results in apparent strong negative piezoresistivity, as observed for carbon cement or for partially applied silver paint as the bonding agent. The apparent strong negative piezoresistivity has a minor contribution from the true negative piezoresistivity of the composite. Measurement of the potential (resistance) using voltage contacts on one side of the composite does not give a representative potential (resistance) for the composite when the current density is non-uniform. The use of the two-probe method for studying piezoresistivity does not give reliable results, due to the slight loosening of the electrical contacts during loading causing apparent positive piezoresistivity.

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