ELECTRICAL RESISTANCE MEASUREMENT FOR RESIDUAL STRESS MONITORING DURING FABRICATION OF CARBON FIBER EPOXY-MATRIX COMPOSITE

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Introduction

Polymer-matrix composites with continuous carbon fiber reinforcement are widely used for lightweight structures. However, the fabrication of these composites tends to result in flaws related to the residual stress [1], which is a consequence of the elevated temperatures during composite fabrication and the thermal expansion mismatch between fiber and matrix. The most widely used polymer matrix is epoxy (a thermoset), which typically cures at an elevated temperature (e.g., 180°C). The flaws can be in the form of fiber-matrix interface degradation, residual stress in the fibers and delamination. Since the flaws are governed by the composite fabrication process, the production of a composite product with a consistent quality requires control of the composite fabrication process. For this purpose, the process needs to be monitored. The monitoring of the curing process of a fiber laminate is most commonly performed by dielectric analysis [2] and fiber optic sensing [3]. A less common method involves measurement of the DC electrical resistance [4]. Both dielectric analysis and fiber optic sensing require relatively expensive equipment, but DC electrical resistance measurement does not. Moreover, fiber optic sensing requires the embedment of intrusive optic fiber sensors in the laminate. Prior work [4] on the use of DC electrical resistance measurement was directed at resin state (ionic conductivity) monitoring, as the resin resistance in the plane of the laminate was measured by using electrical contacts that were in contact with the resin on one side of the laminate and not in contact with the carbon fibers in the laminate. Upon curing at a constant temperature the resistance increased because the ionic conductivity decreased. In contrast, by having the electrical contacts touching the carbon fibers in the laminate and measuring the resistance perpendicular to the fibers, both in the plane of the laminate and perpendicular to the laminate, we obtained resistances that were sensitive to the fiber-matrix interface quality, which was affected by the residual stress in the fibers. Furthermore, by having the electrical contacts touch the fibers and measuring the resistance in the fiber direction, we obtained a resistance that was sensitive to the fiber quality, which was affected by the residual stress in the fibers. Thus, we found that DC electrical resistance measurement in any of the three directions is effective for residual stress monitoring. The residual stress builds up significantly during cooling subsequent to curing. Resin melting and curing cause the resistance to decrease, due to the decrease of the distance between fibers. However, residual stress causes the resistance to increase, due to the increase in the resistivity of the fiber and/or the fiber-matrix contact resistivity.

Experimental methods

Composite samples were constructed from individual layers cut from a 30.5 cm wide unidirectional carbon fiber prepreg tape manufactured by ICI Fiberite (Tempe, AZ). The product used was Hy-E 1076E, which consisted of a 976 epoxy matrix and continuous unidirectional carbon fibers (Torayca T-300, 6 K, untwisted, UC-309 sized, of diameter 7 μm, density 1.76 g/cm^3, tensile modulus 221 GPa and tensile strength 3.1 GPa).

The composite laminates were laid up in a 3.8 x 10.2 cm^2 (1.5 x 4 in^2) platten compression mold with laminate configuration [0]. The individual fiber layers were cut from the prepreg tape. The layers were stacked in the mold with a mold release film on the top and bottom of the lay-up. No liquid mold release was used. The laminates were cured at various temperatures ranging from 123 to 210°C and at a pressure of 0.40 MPa. For example, curing at 123°C was conducted by heating to 123°C at 0.8°C/min, holding at 123°C for 130 h and then cooling at 0.2°C/min to room temperature.

DC electrical resistance measurement was made along the fiber direction, perpendicular to the fibers in the plane of a fiber layer, and perpendicular to the fiber layers. In each case, the four-probe method was used and copper wires of diameter 250 μm were used for electrical contacts embedded in the laminate. The use of the carbon fibers in the laminate as electrical contacts gave similar (but more noisy) results than the use of copper wires. For measuring the resistance perpendicular to the fiber layers, the voltage (inner) probes were separated by 264 fiber layers. For measuring the resistances in the plane of a fiber layer, the voltage probes were 60 mm apart, such that each probe was bent so that it was in contact with three fiber layers. A Keithley 2001 multimeter was used for resistance measurement. In addition, a QuadTech 7600 RLC meter was used for dielectric analysis, which gave the dissipation factor. The temperature was measured at the same time, using a Type T thermocouple.

Results and discussion

The resistance perpendicular to the fiber layers as well as that perpendicular to the fibers in the plane of a fiber layer decreased sharply during melting of the resin in the initial stage of heating and less sharply during subsequent curing, both due to decrease of the distance between fibers. The resistance in the fiber direction (much smaller than the other two resistances) also decreased sharply during melting of the resin, but did not change during subsequent curing, as the fibers were much more conductive than the matrix. The dissipation factor increased sharply during melting of the resin, due to the increase in ion mobility. During cooling after curing, all three resistances increased sharply, thus enabling residual stress monitoring. The higher was the curing temperature, the larger was the resistance increase during subsequent cooling.

During curing, imperfect temperature control caused the temperature to fluctuate within 1°C. Whenever the temperature fluctuated upward, all three resistances decreased slightly due to residual stress decrease; whenever the temperature fluctuated downward, all three resistances increased slightly due to residual stress increase. As curing progressed, such resistance changes became less noisy. Hence, the resistance measurement enables temperature monitoring during curing. On the other hand, the dissipation factor did not change in response to the temperature fluctuations, indicating the insensitivity of the dielectric analysis to the residual stress.

Conclusion

DC electrical resistance measurement during carbon fiber epoxy-matrix composite fabrication was found to be effective for monitoring the residual stress and the temperature. An increase in residual stress occurred when the temperature decreased, due to the thermal expansion mismatch between fiber and matrix. The residual stress increase was indicated by increase in the electrical resistance of the laminate in any of the three mutually perpendicular directions.

References

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