POST-MORTEM INVESTIGATION OF THERMAL DAMAGE IN CARBON/EPOXY COMPOSITE MATERIALS CAUSED BY SIMULATED LIGHTNING STRIKES

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Keywords: Thermal damage, Joule heating, direct effects, lightning strike, composite material

Abstract

This work investigated experimentally the thermal damage characteristics of carbon/epoxy laminates caused by simulated lightning strikes using thermogravimetric analysis (TGA) aided with scanning electronic microscope (SEM) and Fourier transform infrared analysis (FTIR) with attenuated total reflection (ATR). The direct effects, responsible for the physical damage of lightning strikes, were represented by Joule heating and kinetic shock waves and the present experimental set-up was designed to maximize those effects by employing a solid conical rod electrode with a small electrode gap for the vertical strike. The damage mechanisms were found to be in the form of resin thermal degradation, resin sublimation and fibre tufting. Penetration into the laminates was found to be limited to the only top three plies in the extreme case. A range of locations were selected on each damaged panel and the FTIR-ATR examinations of those locations provided the infrared spectra to allow the variations of both functional groups and chemical compositions of the DGEBA-DDM epoxy matrix to be evaluated. The ether link C–O–C , ketone C=C stretch and *p*-phenylene C–C stretch were found to vary with the severity of the lightning damage. Several TGA samples extracted from those selected locations were tested with four different heating rates in both inert environment and in air. The test results showed the in-depth thermal behaviour along with activation energy data and offered the unique physical insight into the thermal degradation process of the carbon/epoxy laminates under the lightning strikes.

1. Introduction

Composite materials are increasingly used in aircraft and wind energy turbine blades and during service these large composite structures are often exposed to lightning strikes [1-4]. Past airline statistics indicate that passenger aircraft is struck by lightning at least once per year on average and statistics for composite blades indicate that damage caused by lightning strikes is a major contributor to down-time in the operations of wind farms due to high density and nearly stationary nature. The direct effects of lightning strikes are manifested not only in Joule thermal heating but also in kinetic shock waves. Moreover, they cause damage not only in unprotected composite structures but also in protected composite structures. This is because semi-conductive intact carbon/epoxy laminates don't conduct away lightning currents well, whereas intact E-glass/epoxy laminates are simply insulative. If the protected composite structures already carry some form of damage on or close to their surfaces, upon lightning strike, its direct effects could cause much greater damage or even catastrophic failure (to wind turbine blades). It is therefore essential to ensure that a thorough understanding of the nature of damage inflicted in composite structures is achieved, however challenging, in order for these premium-value composite structures are continuously used safely and cost-effectively in addition to be effectively protected against the lightning direct effects.

We have experimentally investigated the damage characteristics of both carbon/epoxy and E-glass/epoxy composite laminates caused by the direct effects of simulated lightning strikes. In this work, we report the in-depth post-mortem microscopic investigation of the thermal degradation damage of carbon/epoxy laminate specimens using SEM coupled with energy dispersive spectroscopy (EDS), FTIR-ATR and TGA.

2. Examination of Lightning Damaged Specimens

2.1. Lightning Strike Tests

The lightning strike experimental set-up, as illustrated in Fig. 1, was designed to maximise in a controlled manner the direct effects by employing a high current impulse generator, a solid conical-tipped copper rod electrode of 8 mm diameter, pointed vertically to the surface of each 3.5 mm thick carbon/epoxy specimen with a small electrode gap. In a group of lightning strike tests, the peak currents were regulated to vary between 3 kA and 91 kA such that a varying degree of damage sizes could be induced in the rigidly supported composite specimens with the in-plane dimensions of 150 mm by 100 mm. An overall duration of lightning strike was no more than 30 ms.

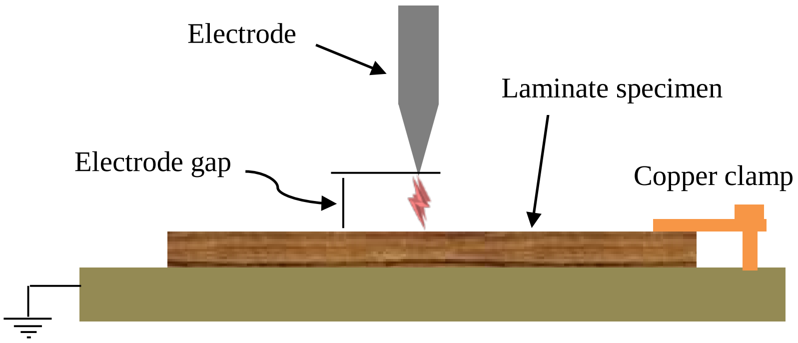

Figure 1. A simulated lightning strike test set-up.

2.2. Damage Characteristics of Lightning Struck Specimens

After each lightning strike test, peak current was measured, transferred electric charge and action integral of the test were calculated. The action integral-peak current relationship of all carbon/epoxy tests is shown in Fig. 2. Action integral represents the strength of the thermal loading and can be seen to increase steeply with a small increment of lightning current towards the upper end of the lightning current range. One of the struck carbon/epoxy specimen is shown in Fig. 3. The area of the surface damage is estimated via visual inspections, aided with an optical microscope and some specimens were cut up for the examination of the penetration depth of the strikes.

Lightning damage in these laminate specimens was found to cover thermally degraded resin via discolouring, resin sublimation, fibre tufting due to shock waves and tufting-driven delamination. The resin degradation as shown in Fig. 4 ranges from discolouring, fragmented species and soot (invisible), to sublimation, whereas very limited delamination was believed to be induced by the action of fibre tufting. The penetration of the lightning arc into the laminates was found to be limited to the only top three plies in the extreme case, as the lightning strike direction was in the insulative thickness direction so that the attached lighting arc sublimated in only the shallow path of resin in the immediate vicinity to the surface. Local temperatures within the lightning channel may well have been above 1000^{0}C, as often speculated [1-2], where resin sublimation, the phase transition, was largely confined.

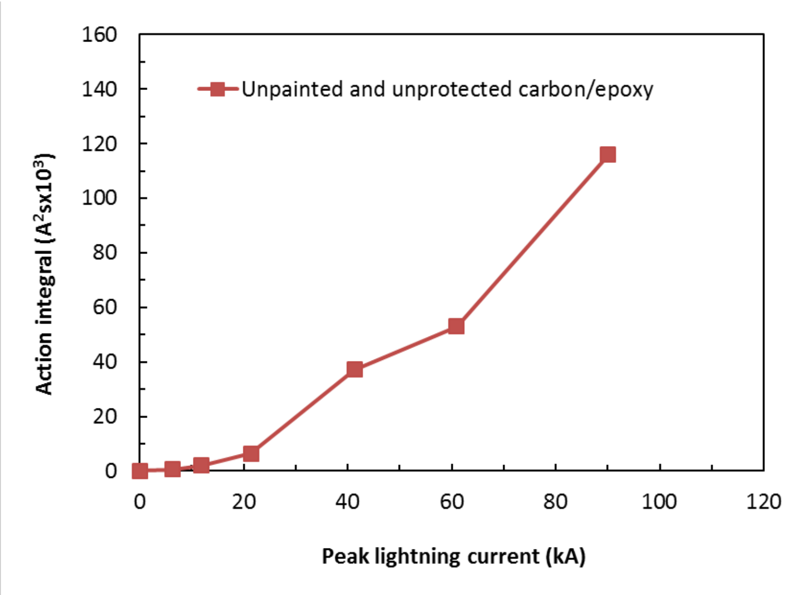

Figure 2. Action integral - lightning current relationship for carbon/epoxy specimens.

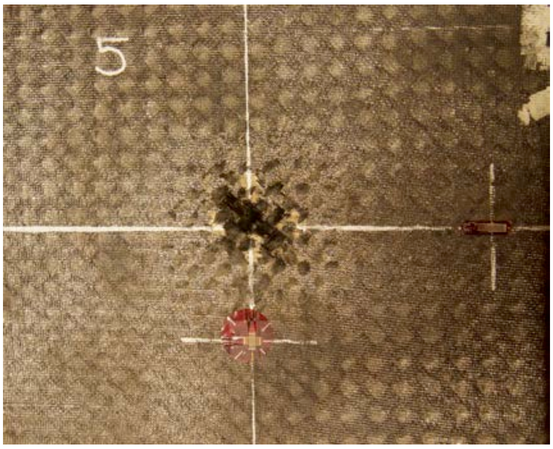

Figure 3. Carbon/epoxy specimen struck by lightning current of 61kA.

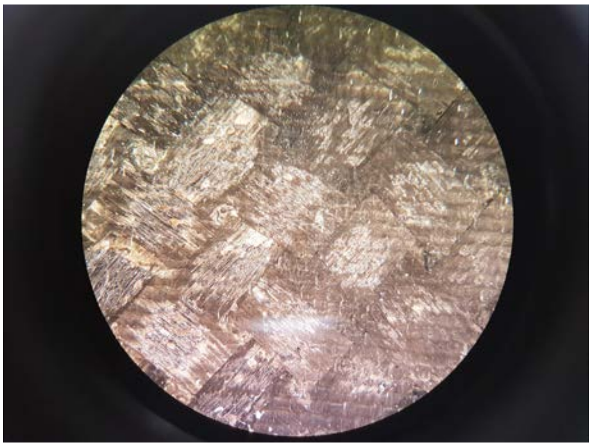

Figure 4. Resin thermal degradation via discolouring in a lightning struck carbon/epoxy panel.

Fig. 5 shows the border region between the remaining discoloured resin (on the left) and the resin sublimated patch (on the upper right) on one of the lighting struck specimens. The exposed individual carbon fibre filaments are visible, when resin on the top ply surface vapourated at the very high temperatures. There was no solid residue observable in the lightning attachment area. A tiny amount of soot could be felt, when one rubbed fingers through the attachment areas.

2.3. Fourier Transform Infrared Analysis of Damaged Specimens

Unlike traditional transmission FTIR replying on the transmission through the samples, the attenuated total reflection (ATR) feature of present FTIR spectrometer allows the infrared beams of evanescent wave radiations reflected off the surface of the samples in contact to be analysed. This non-destructive technique is particularly suited to identification of variations among functional groups and composition between the thermal damaged region and virgin region of the lightning struck specimens.

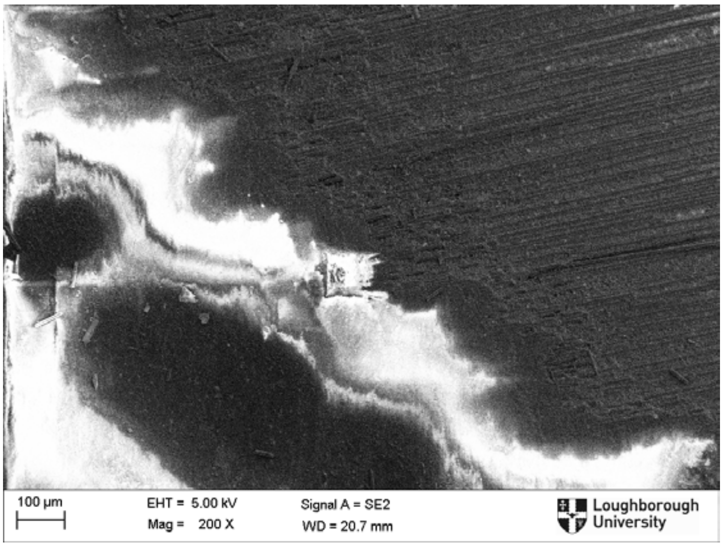

Figure 5. SEM-EDS image of a thermally degraded area by simulated lightning strike.

Typical FTIR-ATR infrared spectra in terms of absorbance versus wavenumber are shown in Fig. 6, in which wavenumber normally vary between 4000 and 400 cm^{-1}. A comparison with a common ATR spectrum library of chemical compounds allows the identification of not only the chemical compounds of DGEBA-DDM epoxy system but also specific functional groups. In general, the peak positions with a resolution of 4 or 5 cm^{-1} indicate the structures of the molecules in the sample and the peak intensities indicates the concentrations of molecules in the sample and the peak widths are sensitive to the chemical matrix of the sample. In the figure, it can be observed that the functional group region (from 4000 to 1800 cm^{-1}) shows the significant similarity, whereas the composition region 1800 to 500 cm^{-1} shows the substantial differences from 1400 to 700 cm^{-1}, which reflect the lightning damage.

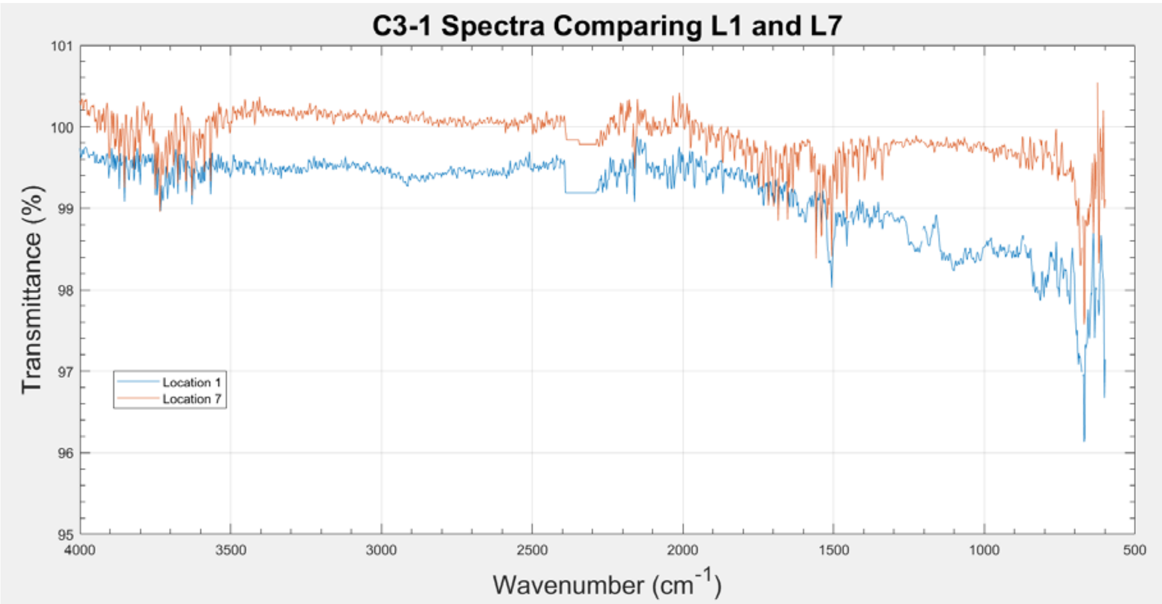

Figure 6. FTIR-ATR spectra from two different locations of a lightning struck carbon/epoxy panel.

The functional groups found to vary according to the severity of the lightning strike damage include ether link C–O–C aroud 1150-1070 cm^{-1}, ketone C=C stretch aroud 1750-1720 cm^{-1} and *p*-phenylene C–C stretch aroud 850-800 cm^{-1}.

3. Thermogravimetric Analysis

After SEM-EDS and FTIR-ATR examinations, the lightning struck panels were cut up and TGA samples of about 48 mg each were extracted from seven selected locations (circles on the diagnol line with the 6 mm centre-to-centre distance), as illustrated in Fig. 7. The reason that the relatively larger sample weight was used was controlled by the choice of the in-plane dimensions of 3 mm by 3 mm so as for test results to be representative. The 1-2 locations (i.e. L1 and L2) are from the so-called central region, which was damaged by the lightning strike in all the panels, whereas the L6 and L7 locations were from the pristine region, which was undamaged even on the most damaged panel. The L3-L5 locations were from the 'border' region, which was dependent on the severity of the damage.

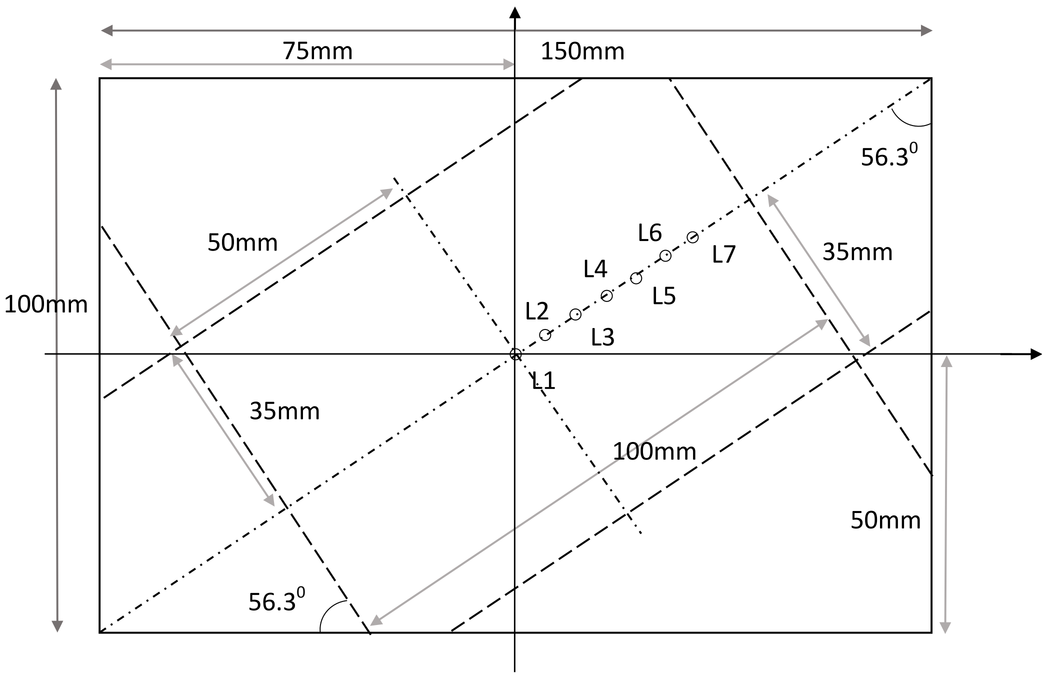

Figure 7. Locations of TGA samples extracted out of a lightning struck carbon/epoxy panel.

Non-isothermal TGA tests were conducted at four different heating rates from 5^0C/min to 20^0C/min and in both inert environment and air. Typical TGA results in terms of weight loss and derivature weight loss versus temperature are shown in Fig. 8. A comparison of the thermal decomposition performances of the samples from the selected locations was conducted. It was found that the thermal degradation process of the TGA samples was dictated by dehydration characterised by bond scission and ended with sublimation. There is a similarity of qualitative nature between the TGA thermal decomposition process and the thermal degradation and sublimation process at the centre of the lightning attachment area. The average values of activation energy for the DGEBA-DDM LTM45 epoxy system were found to be 61.5 kJ/mol using the Kissinger method and 64.8 kJ/mol using the OFW method. These values are close to 58.3 kJ/mol from [5] for the Kissinger method. Similarly, our value 64.8 kJ/mol for the OFW method is very close to 62.9 kJ/mol from [5].

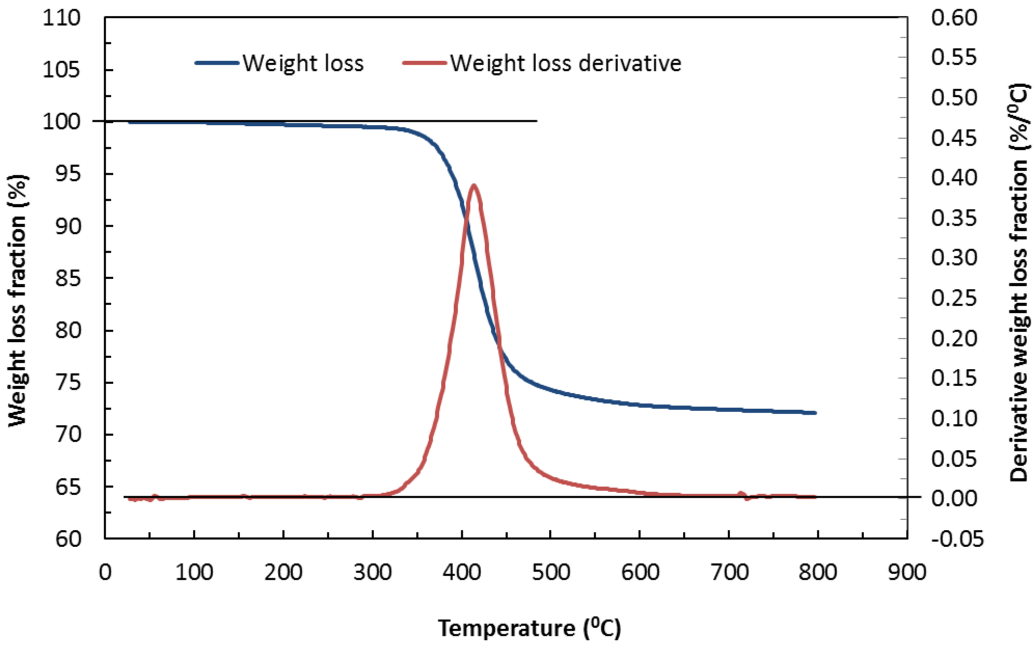

Figure 8. TGA test results of a carbon/epoxy sample with a heating rate of 20^0C/min.

4. Closing Remarks

The process and characteristics of the thermal heating damage inflicted in carbon/epoxy composite materials by simulated lightning strikes have been investigated in a forsensic manner using SEM-EDS, FTIR-ATR and TGA. Taking the advantage of the non-destructive nature of SEM and FTIR-ATR, in-depth prior information obtained enhanced the interpretations of the subsequent TGA test results.

Acknowledgments

The first author would like to acknowledge the financial support from the 2011 Loughborough University Networking/EPSRC–Bridging the Gaps grant. The lightning strike testing assistance from Messrs Z. Wang and X. Zhang and support from General Manager Mrs H.Y. Ma from C-Power Ltd are also acknowledged.

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