Electric resistance and acoustic emission during cyclic tensile loading of CFRP laminates

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SUMMARY: This paper reports on simultaneous monitoring of electric resistance and acoustic emission (AE) during cyclic tensile loading of cross-ply carbon fibre reinforced plastics (CFRP). The observed electric behavior is dominated by the ohmic resistivity of the carbon fibre network. During loading and unloading the samples the electric measurements show a hysteresis in the corresponding resistance vs. strain plot. When the previous load maximum is exceeded in the subsequent load cycle a characteristic increase in the measured resistance-strain slope appears combined with a sudden rise in the AE (Kaiser effect). After unloading the resistance relaxes to a new equilibrium value. This behaviour is caused by the formation and the growing of cracks in the CFRP samples. The observed time dependence in the resistance hysteresis and relaxation can be attributed to the influence of the stressed polymeric matrix.

KEYWORDS: Carbon fibre reinforced plastics, Electric properties, Acoustic emission, Mechanical properties, Non-destructive testing

INTRODUCTION

Carbon fibre reinforced plastics (CFRP) consist of carbon fibres with an electric resistivity of about 10^{-5} Ωm, measured in the fibre direction and an insulating epoxy matrix (resistivity about 10^{13} Ωm) [1]. The fact that the fibres are intrinsically conductive allows for the possibility of using the electric response from the fibre network for non-destructive damage tests and failure prediction in composite structures. The fibre volume fraction of about 60 % in commercially available laminates results in the formation of a strongly connected electric network with anisotropic properties depending on the fibre orientation. The electric response also depends on the laminate stacking sequence and the position of the applied electrodes.

Previous work focused on the basic electric properties of CFRP laminates for electromagnetic shielding purposes and the prevention of electrostatic charging [2,3]. The detection of damage by electric resistance measurements in unidirectional laminates under tensile stress was reported by Schulte and Baron [1]. Their experimental technique with electrodes positioned at the fibre ends is mainly sensitive to fibre rupture and strain. Other groups have reported on the electric properties during fatigue [4,5] and on the AC-behaviour of CFRP during tension [6]. Only a few papers report on the comparison of acoustic emission (AE) and electric response of CFRP during mechanical testing [7]. Ceysson *et al.* performed post-buckling and three-point bending tests with electrodes placed at the ends of the specimen. The comparison of the AE with the monitored change in the electric resistance allowed them to identify different types of damage in the tested samples, such as: transverse intra-ply matrix cracks, delamination and friction between plies.

Our goal was to correlate the measured change in the electric resistance of the carbon fibre composite with the state of mechanical damage in the composite material. We therefore investigated the resistivity-strain behaviour of cross-ply CFRP under quasi-static cyclic tensile load using electrodes transverse to the laminate. The detection of the AE was used as additional method for investigating the origin of the change in electric resistance.

EXPERIMENTAL SETUP

The materials used for the tensile tests were cross-ply CFRP laminates with a stacking sequence of $[0_2, 90_2, 0_2, 90_2]_S$. The carbon fibres were HTA7 fibres and the epoxy matrix was the 6376 system from CIBA GEIGY.

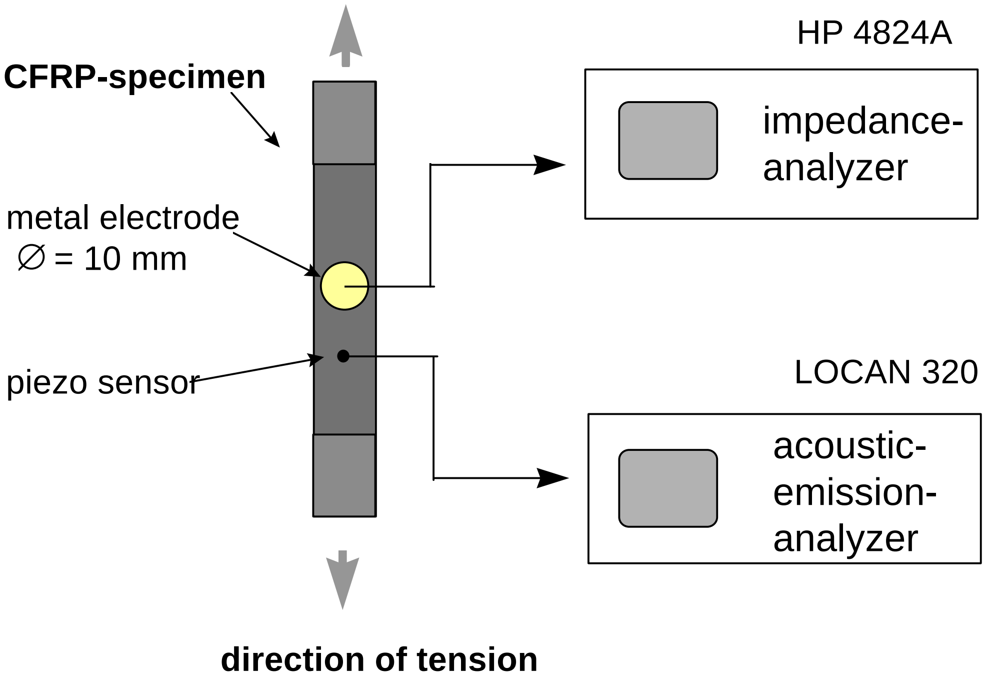

Fig. 1: Schematic measurement setup used for the simultaneous measurement of the electric resistance and the acoustic emission of the cross-ply laminates during cyclic loading.

The CFRP test specimens used for the tensile tests had a width of 25 mm and a length of 200 mm. End tabs of glass fibre reinforced plastic were chosen for load transfer and to insulate the samples from the clamps. The electric contacts were evaporated circular gold electrodes with a diameter of 10 mm, placed at the center on opposite sides of the sample (see Figure 1). For good electric coupling to the carbon fibres, the epoxy layer was removed from the surface.

The electric measurements were performed using HP4284A and HP4285A impedance analyzer with four-point probe technique. A voltage amplitude of 1 V was applied and the complex impedance Z versus the frequency was recorded from 20 Hz to 30 MHz. In Figure 2 is plotted the magnitude of the impedance Z versus the frequency for a unidirectional and a cross-ply CFRP specimen. The preliminary measurements showed that up to frequencies of 1 MHz the AC-electric response was dominated by the ohmic resistivity of the carbon fibre network. This result is in agreement with the work of J. F. Nascimento *et al.* [8]. Above this frequency we observe an increase of the impedance due to the rising influence of the skin effect in the material [2]. To avoid this, we chose a frequency of 75 kHz for our electric measurements to ensure a quasi-DC resistance value.

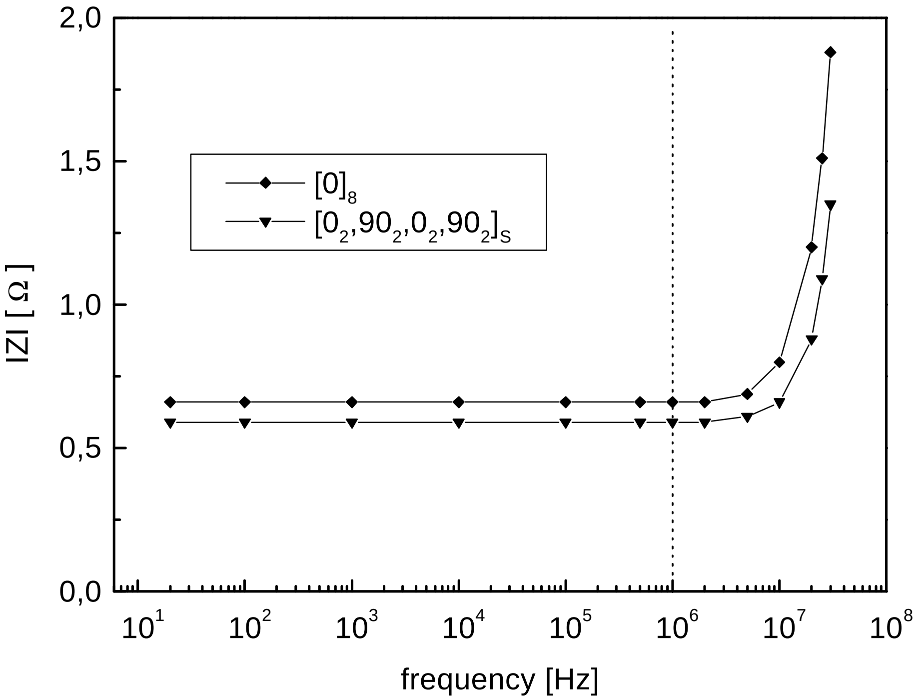

Fig. 2: Magnitude of the electrical impedance Z versus the frequency for a cross-ply and a unidirectional CFRP specimen

A LOCAN 320 AE-analyzer was used for the acoustic emission measurements (see Figure 1). The AE signals from the samples were detected with a piezoelectric sensor which has a frequency range from 150 kHz to 1 MHz and the maximum sensitivity at about 500 kHz. Acoustic emission signals above a given threshold were counted and integrated by the computer.

The tensile tests were performed using a MTS 810 test machine with a constant crosshead speed of 1 mm/min. Two blocks of five cycles were performed with an initial maximum strain of 0.3 % and an increase of 0.2 % in each subsequent cycle.

RESULTS

A typical stress-strain response of the cross-ply samples during cyclic loading is plotted in Figure 3. The nominal fracture strain of the HTA fibres is given as 1.4 % [1]. Up to the maximum applied strain of 1.1 % in the fifth load cycle there is a reversible stress-strain response and no steps can be observed. This behaviour indicates the minor contribution of rupture of the load bearing 0° fibres on overall damage in the tested CFRP samples.

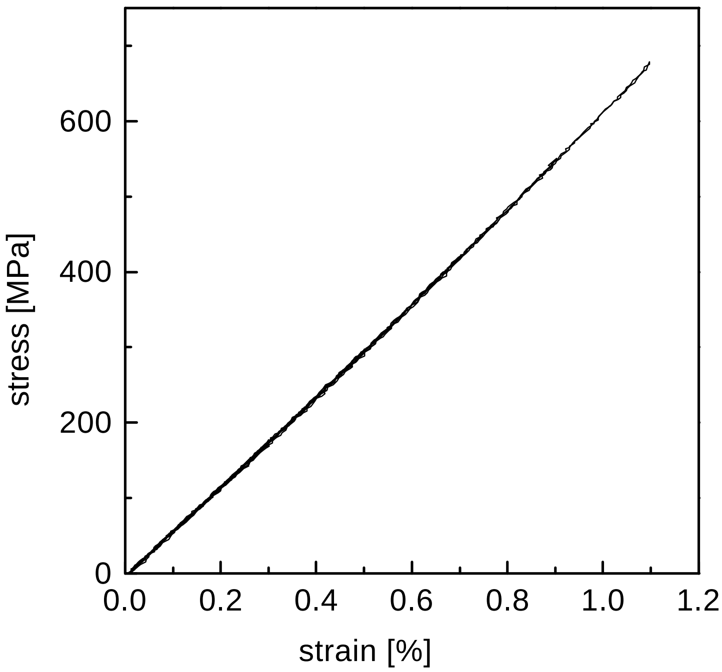

Fig. 3: Stress-strain behaviour of an investigated CFRP cross-ply laminate during the five tensile cycles.

Figure 4 shows the simultaneous measurement of the accumulated acoustic emission and the change in the electric resistance as a function of the laminate strain. The resistance increases during tensile loading and decreases during unloading. However, during loading and unloading the resistance follows different curves, leading to a hysteresis behaviour in the resistance vs. strain dependence. When the previous load maximum is exceeded the slope of the resistance-strain curve increases. At this point a strong increase in the AE occurs, this is shown in the upper part of Figure 4. This behaviour is known as the Kaiser effect for the AE in composites [9,10] and has also been used to describe the electric response of composite materials [11]. The increase in AE is due to further damage progression in the composite sample. This causes the rupture of bonds in the material, thus releasing a portion of the deformation energy into energy of elastic waves. There are numerous mechanisms in fibre reinforced composites which produce AE, e. g. plastic matrix deformation and cracking, fibre rupture, fibre-matrix and interlaminar debonding [12]. In the cross-ply laminates investigated, over the applied strain range, damage occurs mainly by matrix deformation and cracking as well as fibre-matrix debonding. AE occurs predominately during the propagation of the crack tips in the composite. The opening of previously formed cracks and crack closing does not create significant AE. The strong correlation of the acoustic emission and the increase in the resistance-strain slope indicate a similar origin of both effects.

In Figure 5 is plotted the time-dependent relaxation of the electric resistance after unloading. The new equilibrium value of the resistance is higher than the original resistance of the sample. This relaxation causes a partial recovery of the electric network in the material, while the increase in the equilibrium resistance of the sample can be attributed to irreversible damage. During the crack extension process a mismatch between the crack surfaces is created, contributing to the irreversible increase in the resistance [12]. The origin of the resistance relaxation can be attributed to the time dependent closing of cracks in the matrix. We must therefore take into account the viscoelastic behaviour of the stressed polymeric matrix in the vicinity of the cracks [13], which causes creep of the polymer after unloading. This mainly affects the electric and mechanical properties of the 90° plies, while the load bearing 0° plies show negligible creep and seem to be unaffected [14].

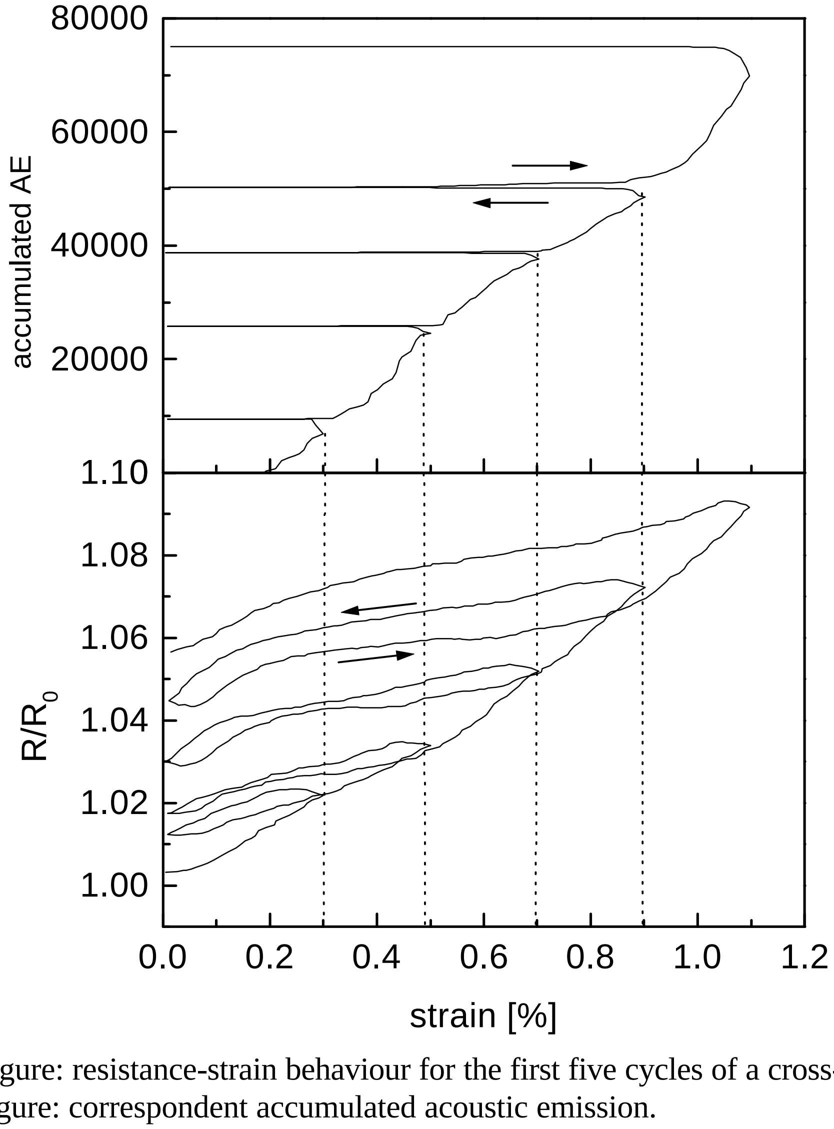

Fig. 4: Lower figure: resistance-strain behaviour for the first five cycles of a cross-ply laminate. Upper figure: correspondent accumulated acoustic emission.

Figure 6 shows the electric response and the acoustic emission during a second block of cyclic loading for the specimen of Figure 4. The electric and acoustic behaviour of the sample is significantly different to that in the first block of cycles. The total AE activity is about eight times less compared to that of the first block. There is an onset of AE at lower strain values, and there is no pronounced increase in the number of AE events when a previous load maximum is exceeded, indicating no further damage development at this point. For the electric resistance we observe initially an increase in the resistance-strain slope up to a strain of 0.2 % for all cycles, which is a result of the elastic deformation of the specimen and the opening and closing of existing cracks in the material. However, a further load increase leads to a reduced gradient of the curve, which can be explained by continued opening of cracks without the appearance of additional damage. There is no characteristic rise in the slope of the resistance vs. strain curve after a previous load level is exceeded, while the hysteresis in the electric resistance over a load cycle is still present.

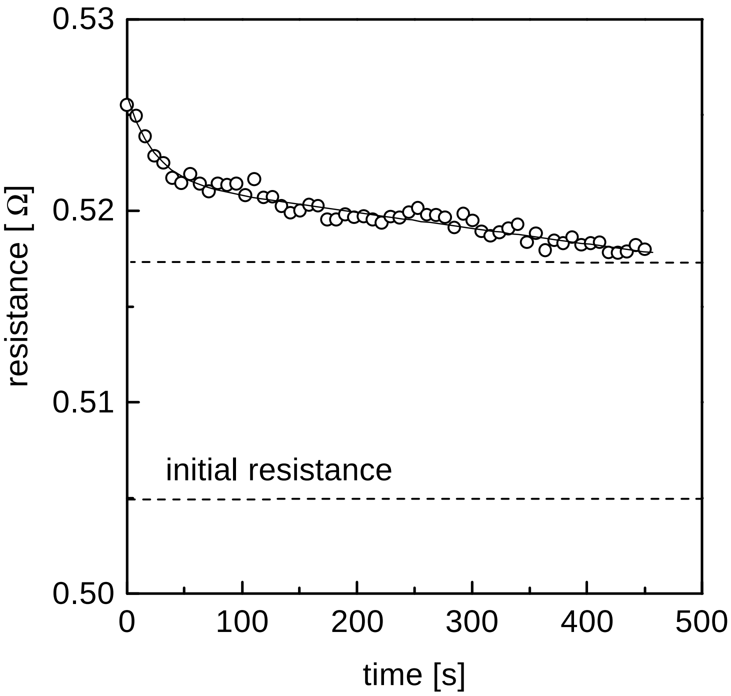

Fig. 5: Time dependence of the electric resistance after unloading of the sample.

In principle, the resistance of the composite is strongly influenced by fibre rupture, opening and closing of fibre-fibre contacts, fibre strain and temperature effects. The simultaneous measurement of the AE and the change of the sample resistance during cyclic loading enables us to eliminate fibre strain as a possible cause of the observed electric behaviour at high strain values. An increase in the CFRP specimen temperature should result in a reduction of the resistivity and *vice versa* [1], this was not visible in the cyclic tensile tests or in the relaxation experiments. The observed resistance variation is mainly caused by the opening and closing of fibre-fibre contacts and to a lesser degree by the rupture of load bearing 0° fibres. These mechanisms effect both, the electric response and the acoustic emission of the samples. Other authors [4] explain the increase in the sample resistance by the increase in the degree of fibre alignment of the 0° fibres in unidirectional laminates, this explanation corresponds to an opening of fibre-fibre contacts.

Microscopically, the formation and opening of matrix cracks in the 90° and 0° plies and the appearance of fibre fracture in the 0° plies just ahead of the transverse crack tips, cause the increase of the resistance during loading. During unloading crack closure occurs and the partial recovery in the conductivity is due to new fibre-fibre contacts. The time dependence of crack closure produces the observed resistance-strain hysteresis during the cyclic loading and the resistance relaxation after unloading the samples. The viscoelastic properties of the locally stressed matrix around the crack tips appear to determine the observed relaxation behaviour. After unloading and relaxation of the specimen an irreversible increase in the sample resistance remains, which can be attributed to a static displacement of the fibres at the closed cracks.

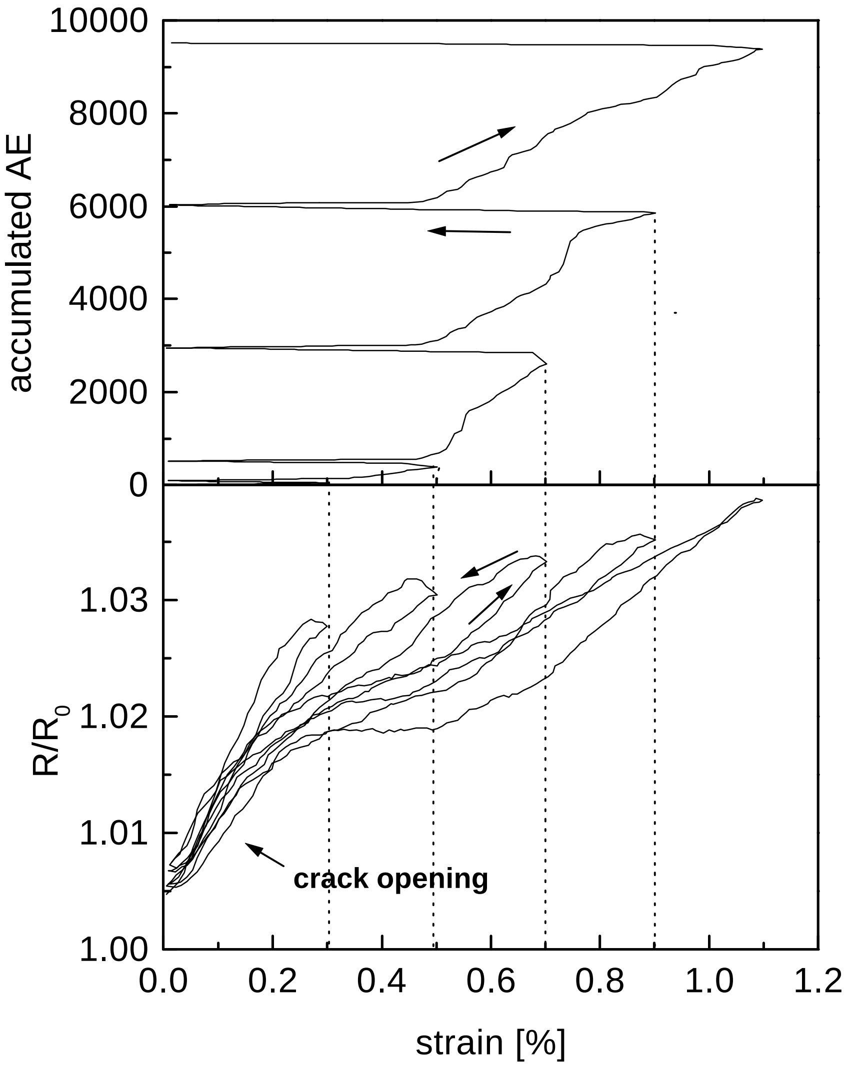

Fig. 6: Lower figure: resistance-strain behaviour for the second block of cycles of the same sample as in Figure 4. Upper figure: correspondent accumulated acoustic emission.

CONCLUSIONS

The comparison of acoustic emission and electric measurements on CFRP materials is an useful tool to explain the origin of the observed electric characteristics during cyclic mechanical testing. The electric response of the investigated cross-ply CFRP laminates allows the determination of the damage state in the samples. The method is able to distinguish previously strained and damaged laminates from those stressed for the first time and also to detect a previously reached load maximum by the characteristic change in the measured resistance-strain curve. It therefore has the potential to be used for *in situ* damage monitoring on CFRP structures.

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