Experimental Study of Mechanically Stressed Composite Materials

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Abstract. The phenomenon of stochastic electromagnetic emission (EME) from solids is based on the generation of an electromagnetic field accompanying the mechanical excitation of the solids in question. This phenomenon is generally termed fractoemission. Our experiments were carried out on a composite dielectric material, consisting of fibrous glass reinforcement which was bound with resin-based binding agents. Our model assumes that the crack walls get charged with electric charges $+q(t)$ and $-q(t)$ in consequence of the bonding electron statistical distribution during the crack forming process. The crack walls are moving with a velocity $v(t)$. Both mentioned quantities can therefore be regarded as random processes. The time development of a voltage $u(t)$ across a load resistor being connected in series with a sensing capacitor was measured. The time behaviour of the product of the electric charge and its velocity $q(t)\cdot v(t)$ can be determined from the voltages $u(t)$. The crack generation process may be split into two phases. The first phase includes the crack generation. In this phase, both this quantities are varying. During the second phase, the crack walls are moving while the charge they are carrying is virtually stabilized. This method is a convenient tool for study of microcracks arising in stressed solid dielectric materials.

Introduction

The phenomenon of stochastic electromagnetic emission (EME) from solids is based on the generation of an electromagnetic field accompanying the mechanical excitation of the solids in question. This phenomenon is generally termed fractoemission and it may be triggered, e. g., by external pressure, tensile force, bending, shearing, shocks, etc. Simultaneously with an EME signal, an acoustic signal (AE) is generated (Fig. 2).

Electromagnetic emission in the radio frequency region is a very important fractoemission component for the materials research in physics as well as engineering. In the past, great attention was paid to the application of EME from rocks and minerals being exposed to mechanical stress, both in connection with earthquake and volcanic activity prediction and in rock mechanics [1].

The application of EME to studying the behaviour of polymer-fibre based material exposed to mechanical stress has been very rarely covered in the literature recently, although this is an advanced structural material, featuring a high application potential, above all in civil and mechanical engineering [2, 3].

As a matter of fact, real materials contain a number of discontinuities, cracks, voids, etc., which behave like stress concentrators in the field of the acting pressure. At such locations, the application of external mechanical force fields, at the moment of crack creation, brings about a generation of EME and AE signals. The external mechanical action, through which the given technological defects are being detected, may be constant in time or it may exhibit any arbitrary time dependence.

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Due to the charge motion, a time-dependent electromagnetic field arises in its neighbourhood. In the case of unlike motion directions, measurable electric potentials are induced in the electrodes applied to the specimen. These potentials feature impulse waveform, the impulse occurrence time and shape being random.

Either capacitance or inductive sensors may be used to detect these quantities. Capacitance sensors are well suited for studying small-sized rectangular or cylindrical specimens in laboratory experiments, mainly due to their higher sensitivity and more appropriate transfer function. For our measurements, the capacitance sensor is conveniently designed in the form of a plate capacitor, for which the dielectric is the material under investigation.

If an electric charge, q, moves at a speed $\vec{v}$ between the plates of a sensing capacitor, an electric charge is induced on the capacitor plates. In consequence of the time rate of this charge change, there appears a current $i(t)$ flowing through the load resistor R. An electric voltage $u(t) = R\,i(t)$ arises across this resistor and an additional electric field $E = u(t)/d$ appears between the sensing capacitor plates, where d is the plate separation.

The time development of a voltage $u(t)$ across a load resistor R being connected in series with a sensing capacitor C, whose dielectric is the material under investigation, was measured. For this voltage, a differential equation holds [4]

$$\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{u}{RC} = \frac{1}{Cd}\, q(t)\, v(t)\,, \tag{1}$$

by means of which the time behaviour of $q(t)v(t)$ can be determined from the voltages $u(t)$ measured.

Characterization of the composite material under investigation

The specimens to be measured are prepared from extren 500 composite material based structural profiles. Each specimen is a block of dimensions (6-10) mm × 50 mm × 60 mm.

The material under study makes the base of long-fibre composite based structural profiles manufactured by the pultrusion method, which are based on a combination of fibreglass reinforcements and thermosetting isophthalic polyester resin systems.

The manufacture of composites is based on continuous drawing of unidirectional rovings and continuous filament mats through a resin bath, followed by section shaping and, finally, resin curing in a mould. The manufacturing process should ensure perfect fibre-to-matrix bonding, i.e., perfect fibre soaking and integration into the structure, providing high load resistance. The quality of the bonding can be judged, e.g., by means of SEM photographs (figure 1a) of the specimen fracture surface. Relatively clean glass fibre surfaces can be seen at certain points, which has been proved, for example, at point 1 in figure 1a, by chemical analysis. This is the case of imperfect matrix-to-fibre bonding at this point. A cross-section of the specimen in the unidirectional roving direction is shown in figure 1b. The composites feature several advantages, such as low density, high corrosion resistance, electromagnetic transparency, extremely low electrical conductivity, low thermal conductivity and temperature dilatation and high tensile strength.

Fibreglass reinforced thermoset plastic composites are non-homogeneous: their strengths and behaviour are dependent upon the design of the composite and reinforcement. The binder protects the reinforcement from mechanical damage, maintains the structural profile shape and transfers the tension into the reinforcement. The fibre composite strength and rigidity vehicle consists in the reinforcing fibres, the contribution of the binder being not particularly high. The principle of the fibre based reinforcement results from the reinforcing fibres' strength and rigidity being one to two orders of magnitude higher than that of the binder. When subject to an external stress, the deformation of the reinforcing fibres is lower than that of the binder. In this way, shearing forces arise at the fibre-to-binder interface, allowing transfer of the tension from the infirm matrix to the fibres. The latter are able to bear all the tension acting upon the composite elements, so that the infirm but deformable binder is virtually tension-free.

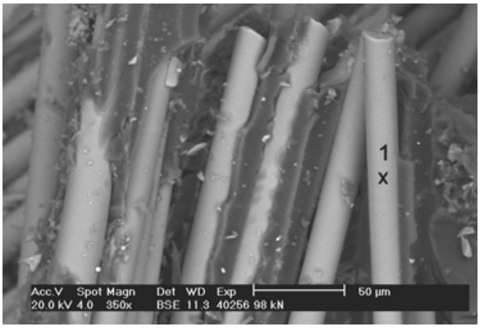

Fig. 1a. SEM photograph of the specimen fracture surface.

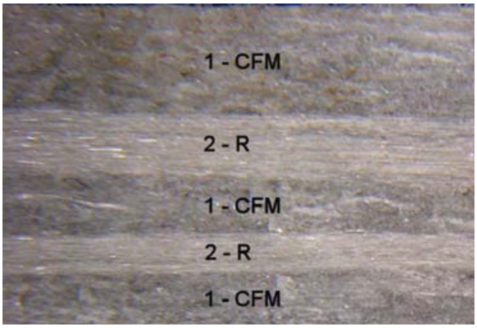

Fig. 1b. Specimen section in the direction of unidirectional rovings, R – rovings, CFM – continuous filament mat.

The material under investigation features the following mechanical properties: fibre-direction modulus of compressibility $E = 17$ GPa, Poisson's ratio 0.33. Fibre-perpendicular and continuous filament mat complanar modulus is $E = 11.4$ GPa. E-glass fibre content is 58 % by weight, single-fibre diameter is 16 µm, composite density is 1700 kg.m^{-3}. The fibre-parallel mechanical wave propagation velocity is 3880 m.s^{-1}, at right angles to the fibres and in the mat direction, 2930 m.s^{-1}, and at right angles to both the fibres and the mats, 2700 m.s^{-1}.

The applied mechanical stress was perpendicular to the reinforcing glass fibre direction.

Experimental

A fully automated apparatus for simultaneous measurement of EME and AE signals has been designed and implemented [3]. A 10 kN ÷ 100 kN hydraulic press was employed to provide the specimen mechanical load. AE and EME signals were picked up and subsequently amplified in separate channels.

The EME channel consists of a capacitance sensor with the sample, a high-pass-filter-type load impedance, a low-noise pre-amplifier (20 Hz – 1 MHz) and an amplifier, featuring a total gain of 10^{3}. The EME signal was fed into one channel of HP 54645A sampling oscilloscope. The AE signal which was picked up by an SAE sensor of B-K 4344 type or SHS-WB sensor (30 kHz to 1 MHz), subsequently amplified by a pre-amplifier (20 Hz – 1 MHz) and an amplifier (3 kHz – 1 MHz), this chain gain totalling 10^{3}, was fed into the other oscilloscope channel.

Experimental results and evaluation

Our measurement processes having been automated, a great number of experiment results, in the form of EME and AE signals versus time plots, were obtained. All EME signal realizations can be divided – based on the response voltage time dependence shape - into 5 basic groups. The crack generation is a two-stage process. In the first stage, the crack unclenches and charges $+q$ and $-q$ arise on the crack opposite faces; whereas, in the second stage, the charge magnitudes may be considered stabilized and only mechanical motion (such as damped or quasi-periodic vibrations) of the crack faces plays the role.

The 1st group EME signals (Fig. 2) feature a steep pulse front and an exponential trailing edge. The measured EME signals correspond to a fast crack development, which, once unclenched does not show any tendency to return to the original position.

The 2nd group (Fig. 3) includes the realizations with a slow pulse front growth as well as a slow decay, their time constants being of the order of 10^1 μs. These curves correspond to a slow crack growth followed by a slow return to the original condition.

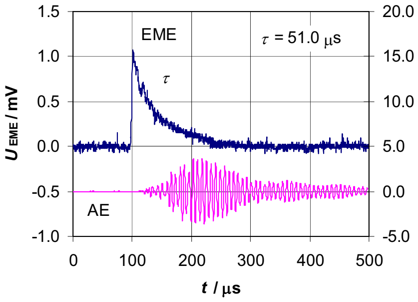

Fig. 2. EME and AE waveforms, 1st group, extren 56.014.

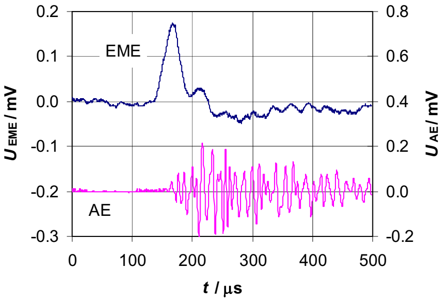

Fig. 3. EME and AE waveforms, 2th group, extren 21.012.

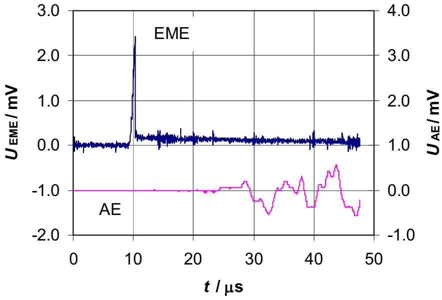

Fig. 4. EME and AE waveforms, 3rd group, extren 64.047.

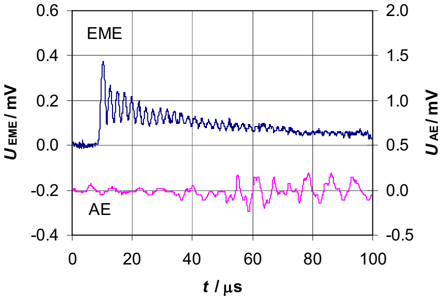

Fig. 5. EME and AE waveforms, 4th group, extren 77.009.

In the 3rd group (Fig. 4), the response voltage represents a fast crack growth and a fast partial return of the crack faces to the original position, the respective time constants equalling 1 μs approximately.

The 4th group (Fig. 5, Fig. 6) type realizations prove to be of high importance for the crack formation diagnostics. Here, damped quasi-harmonic oscillations are observed. It is after the crack faces have unclenched that they are executing this type of damped harmonic oscillations. The crack dimensions can be derived from the oscillation frequency f_m and the mechanical wave propagation velocity.

The fifth group of realizations consists of various combinations of the four indicated basic types and includes the remaining realizations (Fig. 7).

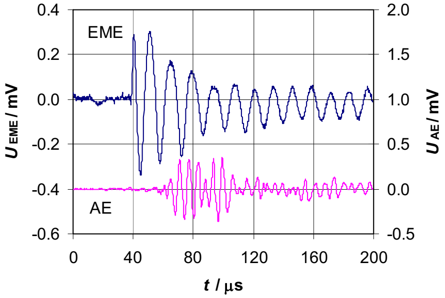

Fig. 6. EME and AE waveforms, 4st group, extren 90.013.

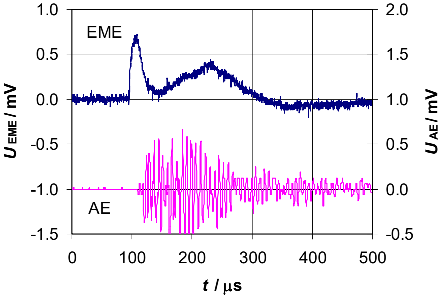

Fig. 7. EME and AE waveforms, 5th group, extren 55.006.

Of significant importance for material diagnostics is also the statistics of time lags of the AE signal behind the EME signal which provides information about the distribution of inhomogeneities in a material. The frequency diagram of the distance of cracks from the sensor AE placed in the middle of the sample wall is shown in Fig. 8 for the mechanical wave propagation velocity $c_l = 2357$ m.s^{-1}. It can be seen that cracks appear with the maximum occurrence at a distance of 20 mm to 34 mm from the AE sensor.

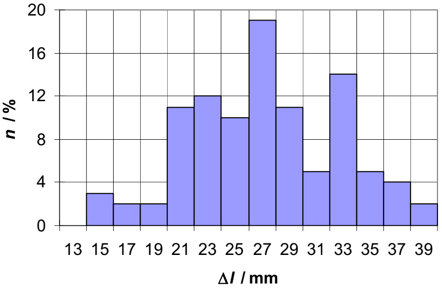

Fig. 8. The frequency diagram of the distance of cracks from the sensor AE.

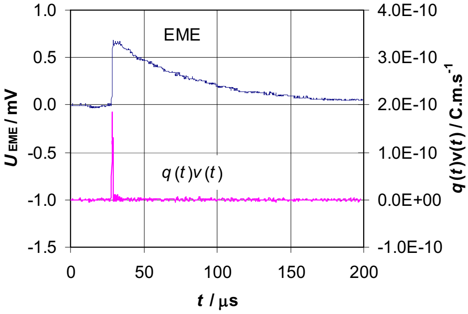

Fig. 9. EME and $q(t)v(t)$ waveforms, extren 80.004.

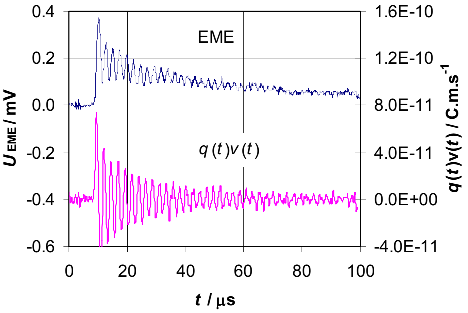

Fig. 10. EME and $q(t)v(t)$ waveforms, extren 77.009.

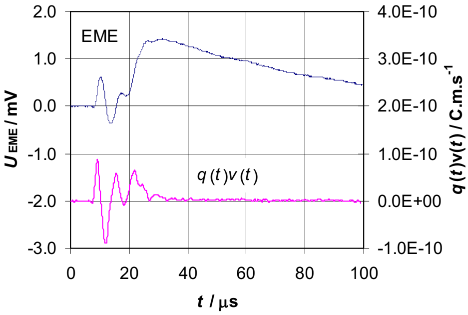

Fig. 11. EME and $q(t)v(t)$ waveforms, extren 82.047.

The experimentally observed curves of the monitored voltage $u(t)$ can then be used to evaluate the product of the magnitude of the charge on crack walls and of the crack wall velocity $q(t)v(t)$ (Fig. 9 – Fig. 11). These quantities describe the kinetics of the crack formation process and they are characteristic for various types of materials examined.

Conclusion

Based on our experimental study of the crack formation processes in a composite material, we may draw following conclusions:

a) The magnitude of the signal induced in the sensor and its time behaviour depend on the crack face movement velocity, the face charge and these quantities' time rate.
b) Once the crack unclenches, its faces may execute various types of damped oscillations with diverse mechanical damping coefficients.
c) Sub-critically damped quasi-harmonic oscillations are best suited for studying the crack parameters.
d) Once EME signals are measured, one may use differential equation (1) to evaluate the $q(t)v(t)$ product, where $q(t)$ is the crack face charge and $v(t)$ is the crack face movement velocity.

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