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An evaluation of acoustic emission from fibre-reinforced composites

Part 1 *Acoustic emission interpretation of epoxy matrix and model composites containing glass beads, carbon and glass fibres*

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An analysis of acoustic emission(AE) from epoxy matrices of different amounts of hardener and model composites containing a glass bead, carbon and glass fibres has been carried out to identify the sources of emission. A few AE events generated by microcracking were observed for epoxy matrix near the final fracture strain. From microscopic and emission observations it was found that the emission was generated by interfacial debonding at the pole for the model composite containing a single particle of the glass bead, and that the source of AE bursts for a continuous single carbon fibre/epoxy composite was succeeding fibre fractures along fibre length. The high AE activity due to fibre fracture was observed for a composite consisting of a bundle of glass fibres. The total of AE events was in agreement with the number of fibre fracture counted with the aid of a microscope in a carbon/epoxy composite. The shear strength at the carbon/epoxy interface was evaluated by a critical length of the fractured fibres using the AE results.

1. Introduction

There is now increasing interest in the use of acoustic emission (AE) techniques for monitoring fracture processes in composite materials [1]. When a composite material consisting of fibres and a polymeric matrix is subjected to external loading, the acoustic emission may result from: (a) fibre fracture, (b) matrix cracking, and (c) debonding at the fibre–matrix interface. It is, therefore, important to identify the source of emission in order to obtain information about the fracture mechanism of the fibre-reinforced composites, and if possible to forecast their imminent fracture.

There have been a number of studies [1] which attempt to correlate the AE activity with fibre fracture for a composite containing brittle fibres in a polymer matrix based on the assumption that the energy released by fibre fracture is much greater than that associated with debonding or matrix cracking. However, except for an early study of Mehan and Mullin [2], who in testing a model composite made of a small number of fibres in an epoxy matrix, reported different characteristic AE signatures depending on the failure mechanism, little effort has been expended in correlating directly AE signals with what occurs micro-chemically within a loaded composite material.

In the present investigation attention has been confined mainly to a model composite containing one single or two fibres in epoxy matrices of different formulation, to identify the AE sources and to extend the AE results to evaluate the shear fracture strength between the fibre and matrix. Additionally for comparison purposes, the AE activity of the materials composed of a bundle of E-glass fibres, and of glass beads has been examined.

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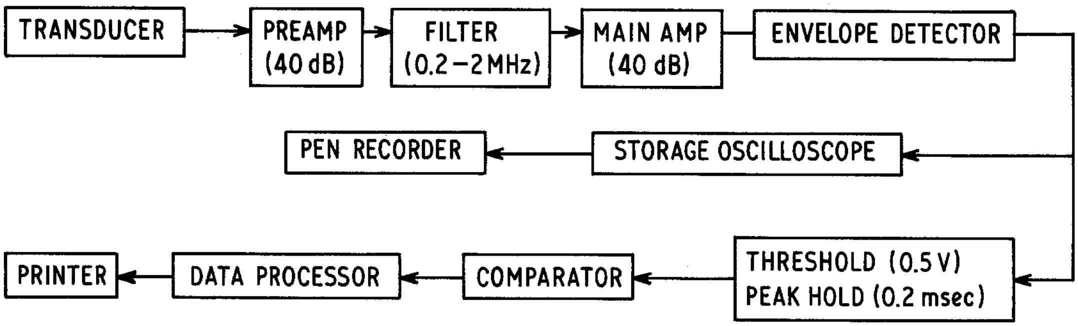

Figure 1 A block diagram of an acoustic emission measuring system.

2. Experiment

2.1. Acoustic emission monitoring

Cracking Monitor (San Denshi Co. Ltd) equipment has been used throughout this experiment. The block diagram of the system is shown in Fig. 1. In a conventional AE system a PZT resonant type transducer is widely used to transform the stress waves into electric signals. One of the difficulties in using this type of transducer is that they have essentially many sub-resonant frequencies within a monitoring frequency range and, as a result, the electric signals produced are not an exact analogue of the original stress waveforms. The frequency response of the transducer has a significant effect on the amplitude distributions obtained and frequency analysis of the AE events. To overcome this difficulty a broad band transducer with a resonant frequency higher than 10 MHz was made using a poly(vinylidiene fluoride)(PVDF) film. The relative sensitivity of this PVDF transducer is lower by about 15 dB than that of a PZT transducer, but a much flatter frequency response is obtained as shown in Fig. 2. The resultant electric signals which passed through a band filter from 100 kHz to 1 MHz were totally amplified by 80 dB and rectified to give an envelope output. The envelope output, which exceeded a chosen threshold level was used to produce one pulse per event. The event counts and amplitude distributions were obtained using a discriminator and data processing units.

2.2. Materials and specimen preparation

The matrix was a commercial diglycidyl ether of bisphenol A type epoxy resin, Epikote 828(Shell). Methylnagic acid anhydride (MNA) and tridimethyl aminomethyl phenol were used as hardener and curing agent, respectively. The four matrix systems with hardener ratios of 40, 60, 80 and 100 were studied. The content of curing agent was 1 phr for all systems.

The carbon fibre was also a commercial grade

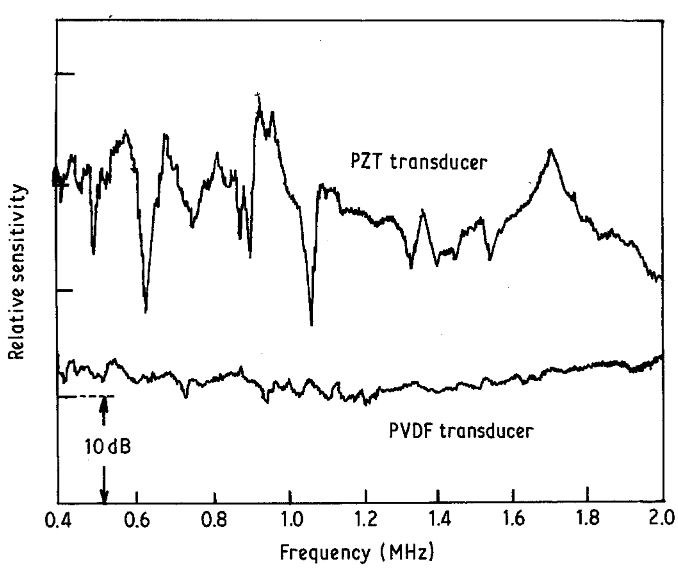

Figure 2 Frequency response of PVDF and PZT transducers used in this experiment.

TABLE I Dimensions and mechanical properties of reinforcements

Reinforcement	Diameter (μm)	Tensile modulus (GPa)	Fracture stress (GPa)	Fracture strain (%)
Carbon fibre	8.4	235.2	2.7	1.2
E-glass fibre	4.5	111.5	4.0	3.4
Glass bead	1000	–	–	–

of T-300A, provided by Toray Co. Ltd. The bundle of E-glass fibre was composed of 90 monofilaments. The dimensions and mechanical properties of the reinforcements are shown in Table I. The fibre and glass bead reinforcements were used without surface treatment other than cleaning with acetone.

Unidirectional model composites with single or two fibres and a bundle of glass fibres were prepared by casting the stirred mixture of resins and hardener into the mould consisting of a paper gasket, 0.3 mm thick, and clamped with glass plates. Model specimens which contain single or two particles of the glass bead were made in a way similar to that for the fibre composite specimens. Curing and post-curing were carried out at 363 K for 4 h and 423 K for 15 h, respectively.

2.3. Tensile tests

Rectangular specimens 30 mm long, 4.0 mm wide and 0.25 mm thick were loaded in the fibre direction on a tensile machine at a crosshead speed of 0.25 mm min^{-1}. They were mounted horizontally between two clamps so that fractures of fibres or matrix, or interfacial debonding during deformation could be observed with the aid of a polarized microscope. The AE transducer was attached to one of the clamps using silicone grease at the interface. All tests were made in air at 296 K and 65% relative humidity.

3. Results

3.1. Mechanical and AE properties of epoxy matrices

In general, it is possible to vary the mechanical properties of the epoxy matrices using different types and quantities of hardner and different curing processes. Fig. 3 shows the variation of Young's modulus and tensile yield or fracture stress with hardener (MNA) content. As can be seen, the modulus and fracture or yield stress increase as the amount of MNA is increased. The epoxy matrices containing 40 and 60 phr of MNA showed the yield accompanied by formation of a number of small shear bands within the material, but the matrices with 80 and 100 phr fractured in a brittle manner without yielding. Fig. 4 shows typical results for the epoxy resin with 40 phr of MNA. The AE count rate, total counts and stress are plotted against applied strain. Generally, the AE activity of a polymeric matrix is relatively lower than that observed in metals [3]. No detectable signals can be seen at a low strain level and the AE count rate gradually rises as the yield point is approached. The microscopic observations reveal that the AE bursts during post yield are generated by initiation of microcracks at the intersection of the shear bands. The AE activity was reduced by an increase of hardener constant as shown clearly in Fig. 5. A few but large in amplitude AE signals were detected immediately prior to final fracture for the brittle matrices, which showed a nearly linear stress–strain relationship up to the final fracture.

3.2. AE characteristics of glass bead composites

Because of no special surface treatment of the glass bead, the emission will be generated by debonding at the interface between the matrix and glass bead. Fig. 6 shows typical AE results for a relatively ductile matrix with 40 phr MNA content in which a single particle of the glass bead is embedded. As is clear from comparing Fig. 6 with Fig. 4, the initiation of interfacial bond fracture can be distinguished from microcracking of the matrix by a few sporadic emissions at 6 to 8% strain. The microscopic observations revealed that the interfacial debonding occurred at the two poles at this strain level. The final fracture was initiated by microcrack formation in the matrix near the equatorial interfaces. For a brittle specimen with high MNA content the emissions due to debonding occurred at a narrow strain range between 5.0 and 5.3%, and they can be more easily distinguished from those generated by final microcracking in the matrix.

The specimen with a single glass bead is suitable

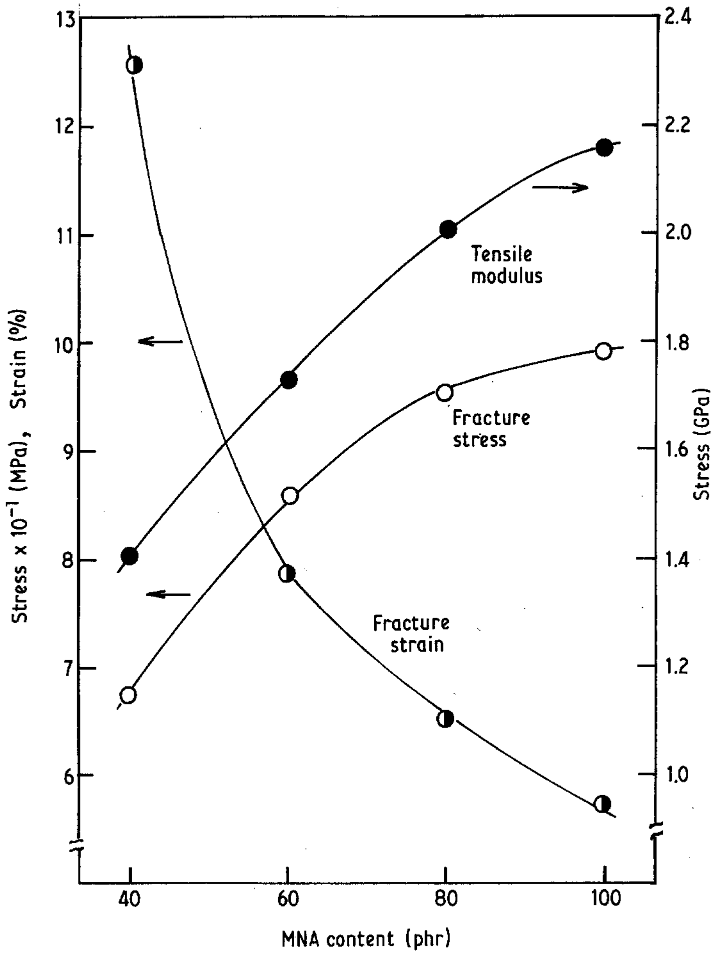

Figure 3 Variation of tensile modulus, tensile strength and strain of epoxy matrix with hardener (MNA) content.

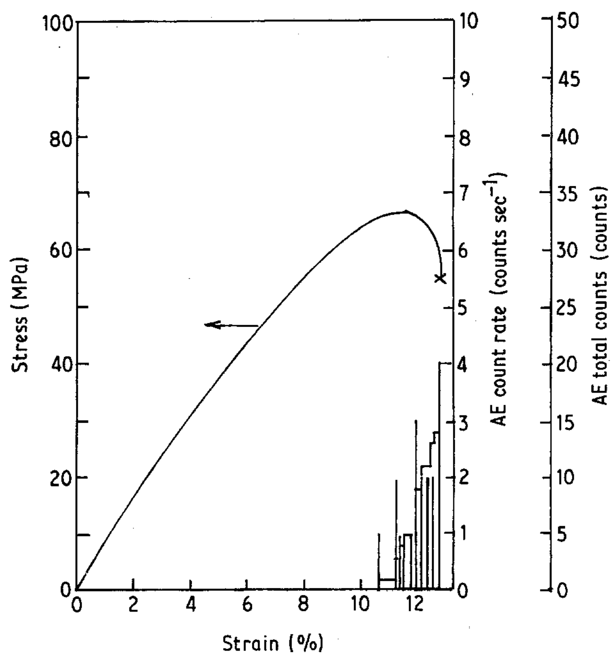

Figure 4 A typical example of acoustic emission characteristics and stress as a function of strain for epoxy matrix with 40 phr hardener (MNA) content.

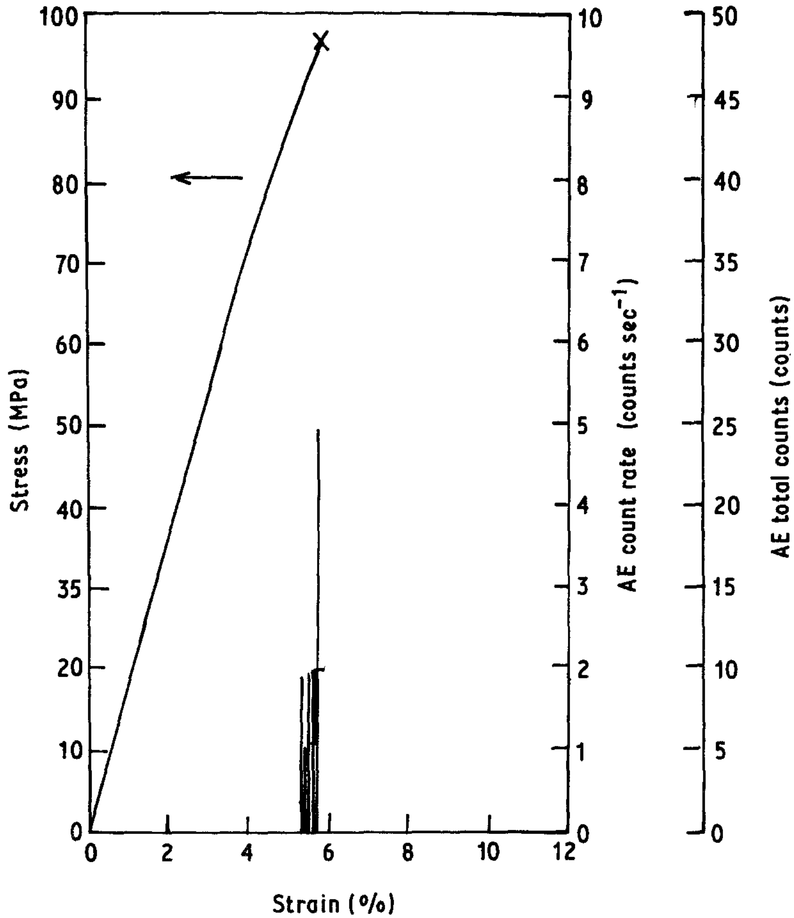

Figure 5 A typical example of acoustic emission characteristics and stress as a function of strain for epoxy matrix with 100 phr hardener (MNA) content.

for checking the dependence of the AE signals recorded on the position of the source of emission relative to that of the transducer. Fig. 7 shows the relationship between the AE amplitude of debonding and distance of the transducer from the glass bead. The amplitude of emission obtained from a brittle matrix is larger than that obtained from a ductile matrix, but attenuation of the elastic waves during propagation through the matrix can be neglected within the experimental differences of the transducer location.

3.3. AE characteristics of carbon fibre composites

Fig. 8 shows a typical example of AE characteristics together with a stress–strain curve of the specimen composed of a single carbon filament. Reinforcement with a single carbon fibre can have little effect on the gross stress–strain relations of the composite, but a general feature of the AE activity was quite different from that of the epoxy matrix, i.e. a sharp increase of emission occurred between 4 to 5% strain. As the emission produced by matrix cracking occurs near the yield point, the emission at 4% strain is generated by fracture of the carbon fibre. The carbon fibre begins to fracture at this strain level and continues to fracture successive up to 5% strain, depending on the strength distribution of the fibre along its length. Fig. 9 shows a polarized micrograph of the fibre when the emissions occurred. The bright bands along the boundary of the fibre and matrix are related to shear fracture at the interface, which was caused by shrinking and sliding of the fibre near broken ends. Fig. 10 shows the relationship between the total AE counts and the number of broken fibres obtained from microscopic counting along the fibre length. The AE bursts have one to one correspondence with the fibre fracture. About two times as many as the total

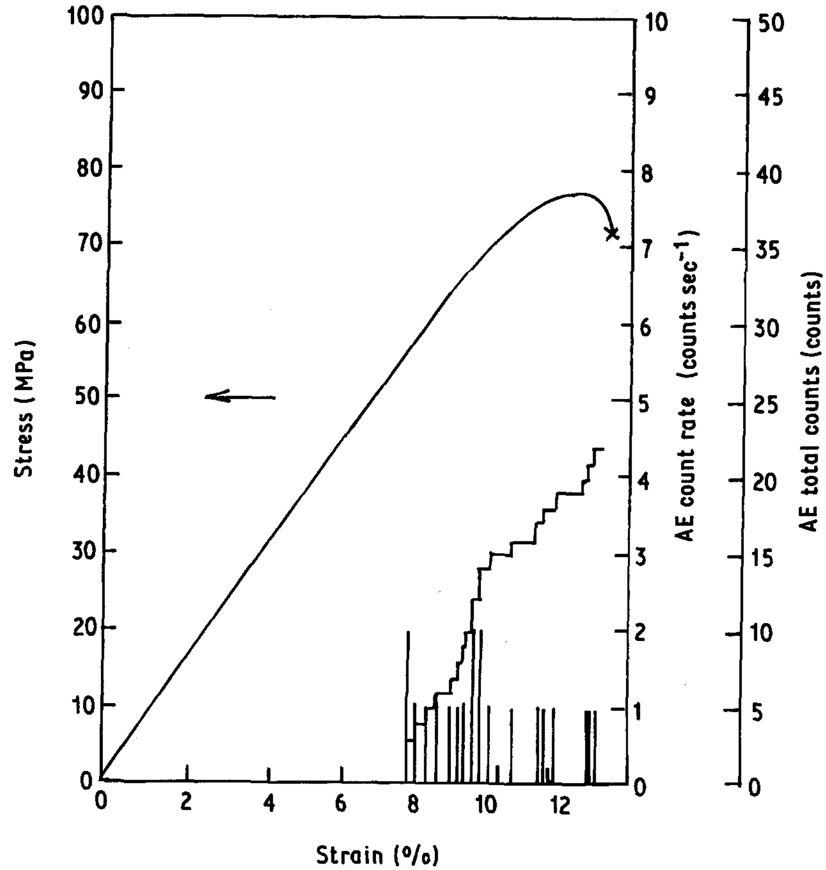

Figure 6 A typical example of acoustic emission characteristics and stress as a function of strain for a single glass bead filled composite with hardener (MNA) content of 40 phr.

number of emissions were observed for the specimen in which two filaments were embedded.

3.4. AE characteristics of glass fibre composites

The AE events against strain curves for the specimen with 40 phr MNA in which a bundle of glass fibres is composed of 90 filaments are shown in Fig. 11. In this case, the stress–strain relation of the composite was affected by incorporation of the glass fibres. Note that there is marked AE activity beyond 6% strain to final fracture strain. The final fracture of the specimen was initiated by crack initiation at one of the fracture ends of the fibre and crack propagation occurred through the matrix between fibres before gross yielding was reached.

4. Discussion

4.1. AE waveform and amplitude distribution

As a wide band transducer was used in this experiment, the electrical signal is a comparatively exact analogue of the original stress wave. In addition, it was shown that, although reflections and interference may be expected, the mechanical losses due to viscoelastic processes of the matrix have little effect on the position of the transducer within the present measuring techniques. Therefore, the extensive data analysis of AE events with respect to waveform and amplitude distribution can give reliable information on the origin of AE generation. Unfortunately, the frequency analysis has not been carried out in the present investigation, but one can find a clear distinction between matrix cracking and fractures of the carbon and glass fibres by checking amplitude and time duration of the AE signals as shown in Fig. 12.

Amplitude distributions are shown in Fig. 13. The epoxy matrix shows most of emission with relatively small amplitude below 1.4 V (80 dB), but the emission generated by fracture of the carbon fibre has a large amplitude distribution between 1.2 and 2.0 V. The fracture of the glass

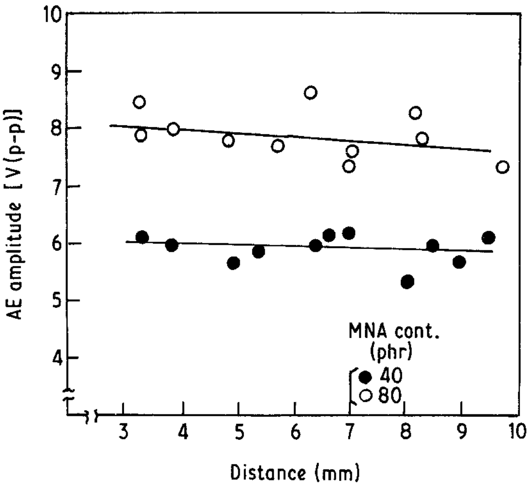

Figure 7 Relation between amplitude of acoustic emissions (80 dB) and distance of a transducer from a glass bead particle.

fibres shows complex distributions with small and large amplitudes.

4.2. Evaluation of interfacial shear strength between fibre and matrix

When a composite with a continuous fibre is subjected to external loads, the fibre and matrix deform together and the stress distribution in each of the two components is equally uniform. As the external load is increased, the stress in the fibre will be built up to fracture at the weakest point along its length. For a material reinforced with fractured and discontinuous fibres the load can be transmitted to the fibre by means of shear stresses at the fibre/matrix interface. When the external load is further increased, the subsequent fibre fracture occurs at the second weakest point. Thus, the fibre continues to fracture in turn with

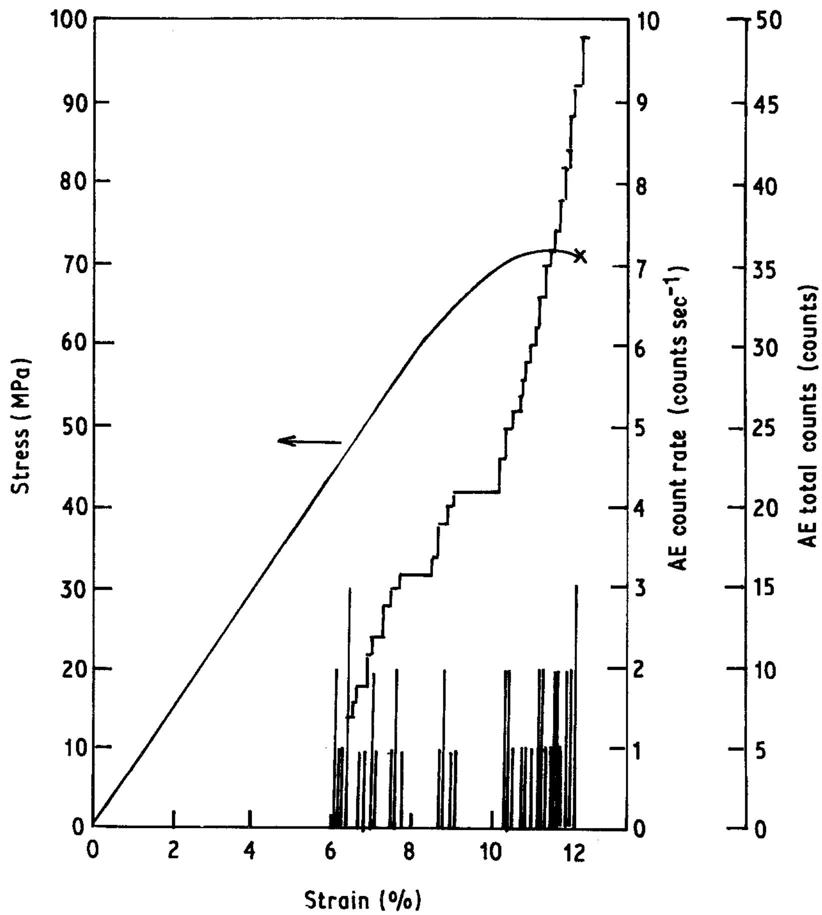

Figure 8 A typical example of acoustic emission characteristics and stress as a function of strain for a single carbon-reinforced composite with hardener (MNA) content of 40 phr.

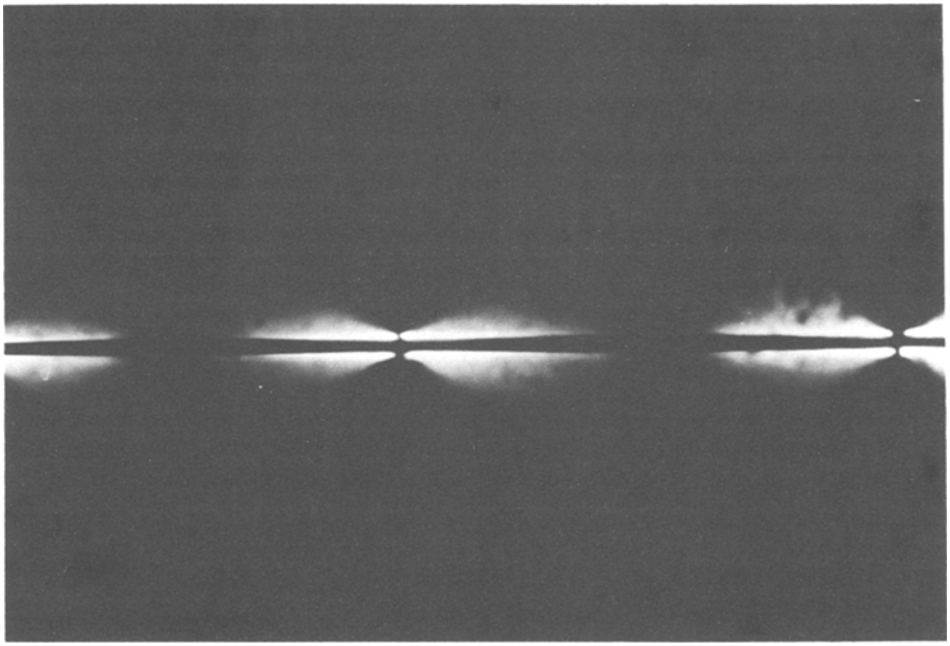

Figure 9 A polarized microphotograph of fractured carbon fibres.

an increasing external load until the fibre reaches a critical length given by [4]

$$L_c = r\sigma_f/\tau \qquad (1)$$

where σ_f is the average fracture strength of the fibre, r is the radius of the fibre and τ is the shear strength at the fibre/matrix interface. If the fibre is longer than the critical length the shear stresses build up sufficient tensile stress to fracture the fibre. As the AE events have one to one correspondence with the number of fracture of the fibre, the average critical length can be calculated from the total AE counts obtained. Fig. 14 shows the relation between interface obtained from the AE results. Based upon the well known experimental evidence that the shear fracture

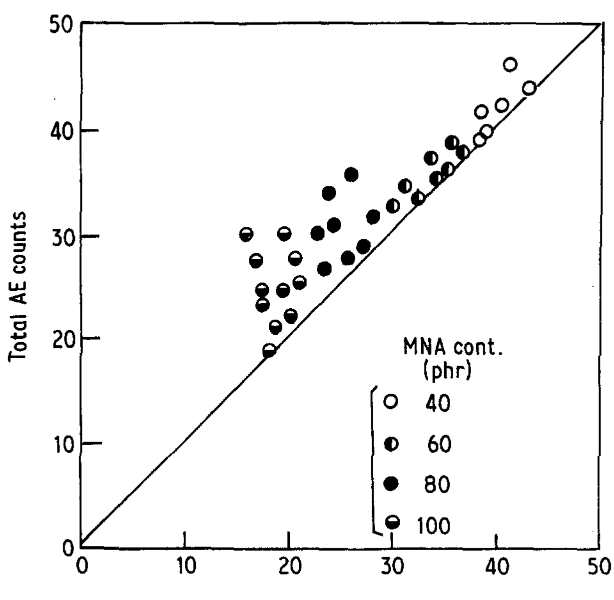

Figure 10 Relation between total counts of acoustic emissions and the number of fractured fibres along the fibre direction.

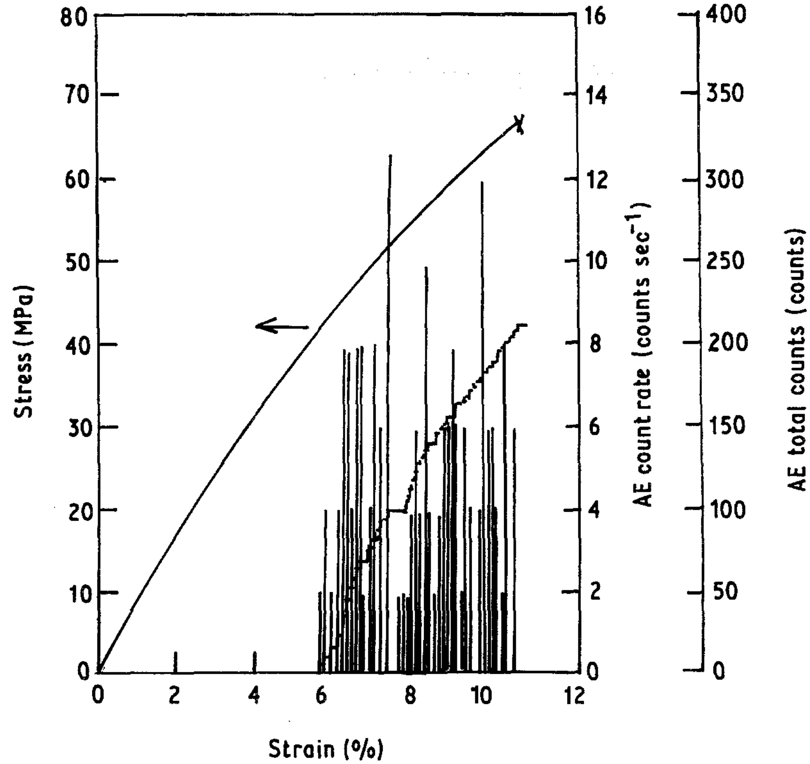

Figure 11 A typical example of acoustic emission characteristics and stress as a function of a bundle of glass fibre-reinforced composite with hardener (MNA) content of 40 phr.

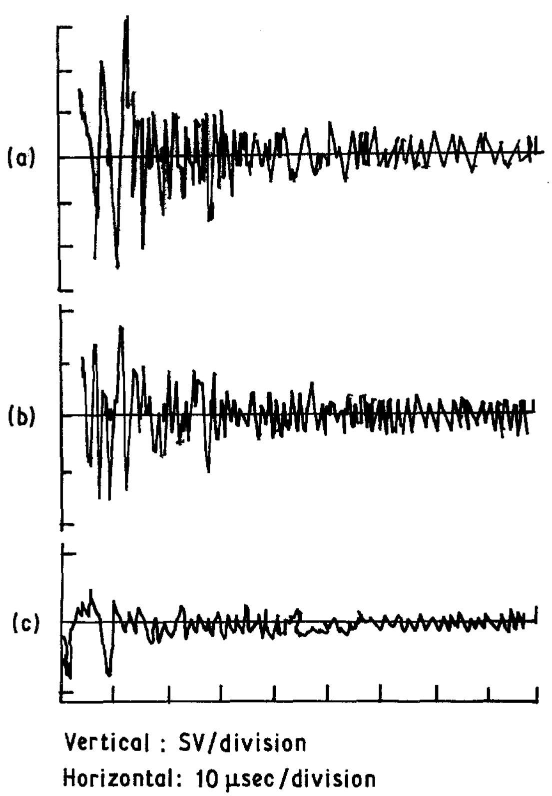

Figure 12 Waveforms of matrix, carbon and glass fibres.

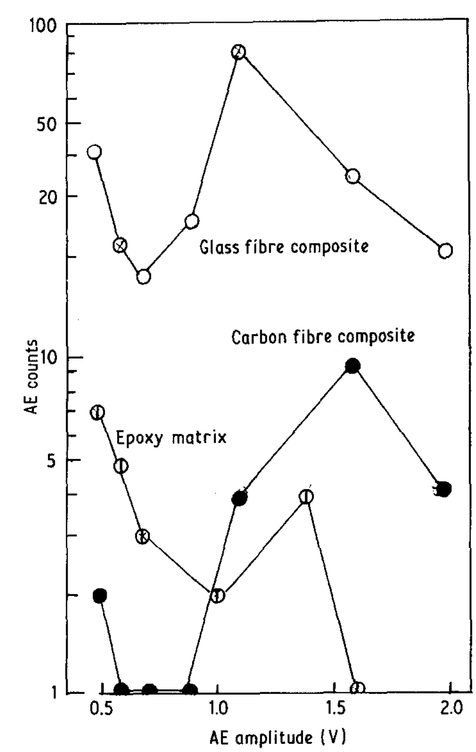

Figure 13 Amplitude distributions (80 dB) for matrix cracking, carbon and glass fibre fractures.

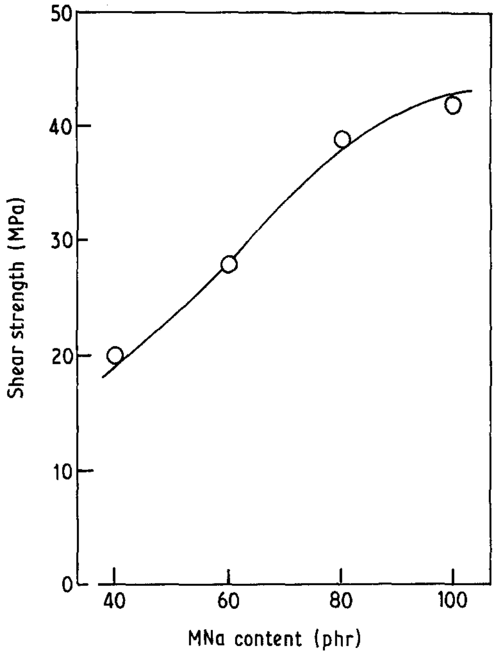

Figure 14 Variation of shear strength at carbon/epoxy interface with hardener (MNA) content.

strength of adhesive joints increases with increasing modulus of the adhesives, the result shown in Fig. 14 is quite reasonable. A value of 3 MPa was calculated for the shear strength of the glass fibre and epoxy composite, but this value may be much underestimated because the specimen fracture occurs by crack initiation at one of the broken ends of the fibre before a critical length is reached.

Concludingly, it is pointed out that AE monitoring in a uniaxial model composite composed of a single or few continuous fibres provides useful information on a quantitative evaluation of the shear fracture strength of the fibre/matrix boundary.

Acknowledgement

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