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The emission of electrons and positive ions from fracture of materials

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The emission of electrons and positive ions from materials undergoing fracture is investigated. We present a survey of charged particle emission from a number of materials including crystalline insulators, glass, graphite, polymers and composites. Particular attention is given to fibre-reinforced epoxy systems which yield unique forms of charge emission. Energy distributions of the emitted particles are given for E-glass–epoxy strands, polybutadiene filled with glass beads, and mica. Evidence is presented that interfacial failure and charge separation play important roles in the observed emission.

1. Introduction

During and following fracture of solids, the emission of charged particles [1–6], neutral particles [7] and photons [3, 8, 9] has been observed. Studies of electron emission (EE) during the tensile elongation of oxided-coated aluminium, sometimes referred to as tribo-stimulated exo-emission, have shown that fracture of the oxide coating is the initial cause of the ejected electrons [4–6]. Similarly, positive ion emission (PIE), neutral emission [6] and photon emission [3] have been observed in the same oxide–aluminium system and were shown to be due to oxide fracture. (Photon emission is most frequently referred to as triboluminescence.) These various types of emission share a number of common features, suggesting common mechanisms in their production. We refer to all forms of such emission accompanying fracture as "fracto-emission" (FE).

Basically, FE is caused by the high concentration of energy deposited into a small volume of material during crack propagation. For a short time period (microseconds or less) this can result in the following:

(1) production of highly localized heat;

(2) creation of excitations and defects in the material;

(3) production of dangling bonds and trapped electrons on or near the freshly created crack wall surface;

(4) the emission of excited and reactive species (ions and neutral particles) into the gas phase;

(5) separation of charges on the crack walls with accompanying intense electric fields for many insulating materials;

(6) production of acoustic waves.

In principle, all of the above consequences of crack growth could contribute to FE from the material. For large band-gap insulators it is doubtful that the peak localized temperatures reached are sufficient to elevate the valence band electrons thermionically into the vacuum. However, the temperature maxima reached might be quite adequate to excite and release electrons from surface traps. Likewise, thermal stimulation of the defects produced during fracture can lead to a number of de-excitations and recombinations which produce electron, ion and neutral particle emission as well as photons [10, 11].

The interaction of excited and reactive species at a surface can readily produce electrons, free ions and photons via Auger de-excitation [12], stimulated desorption [13, 14], chemi-emission [15] and chemiluminescence [16], particularly on a highly reactive surface such as the freshly created crack wall. The significant differences between a clean crystal surface and a freshly created cleavage surface on silica and quartz have been investigated by Hochtrasser and Antonni [17]. They demonstrated that a high density of dangling bonds as well as an increase in chemical reactivity occurs upon fracture. Thus, it is reasonable to assume that freshly fractured surfaces of all materials would have considerable reactivity.

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In the case of polymers, for example, electron spin resonance investigations show that fractured polymers have high radical concentrations particularly in the case of highly-crystalline oriented fibres [18]. It was suggested that cross-linkage enhances the type of fracture (presumably molecular fracture) that produces free radicals.

Clearly, fractured surfaces are potentially very reactive and could be expected to produce emission. For example, a reactive species, perhaps from the fractured material itself or from the background gases, can react with a site of high reactivity on the surface with sufficient energy release (Harris *et al.* [15] and Kasemo *et al.* [16] suggest via an excited, adsorbate-induced hole state) during de-excitation to yield electrons or photons.

The separation of charges that occurs during fracture of ionic crystals [19] is known to produce electric field intensities that can exceed $15\,000\,\mathrm{V\,cm^{-1}}$. Such fields can contribute to electron emission by providing accelerating fields; e.g. electrons having energies as great as 120 keV have been observed coming from alkali halides [20]. Ions with kinetic energies of a few hundred eV have been observed coming from granite specimens [21]. During thermally stimulated exoemission, several other substances have exhibited electron emission with energies in the range 5 eV to 10 keV [22, 23].

Other phenomena associated with the high temperatures produced at the crack tip involve thermal decomposition, diffusion of impurities and the desorption of decomposition and diffusion species into the gas phase. For example, we have found the neutral emission from thin anodized coatings on Al to be very intense and intimately related to oxide cracking [7]. The species observed (e.g. O_2, H_2O and CO_2) and their intensities were dependent on the type of anodizing electrolyte used (H_3PO_4 and ammonium tartrate) and the oxide thickness. There was strong evidence that thermal decomposition and diffusion were involved in the release of the gases. Fox and Soria-Ruiz [24] detected gases released during fracture from a number of inorganic materials. They observed intense bursts of products due to both endothermic and exothermic reactions. Urakaev *et al.* [25] saw volatile products and evidence of highly excited ions and radicals from mechanical fracture of inorganic crystals. Regel *et al.* [26] saw intense neutral emission during fracture of PMMA, observing several mass peaks. The mass spectra observed were very similar to thermal decomposition products. Andrews [18] points out that the observed material evolving from the fractured polymers may be low molecular weight species already present in the specimen which are released by stress-assisted diffusion rather than thermally-activated decomposition.

Finally we mention that the stress wave created as the crack tip moves through the material could in principle contribute to FE. Asay [27] has examined shock-induced vaporization and has seen significant amounts of mass ejected from surfaces accelerated by strong shock waves. Hayes [28] has seen electrical effects on shocked materials that suggest that charged particles might be leaving the surface. Although the shock intensity is significantly higher in these studies than created by fast crack growth, the stress-wave might contribute to part of the emission observed during fracture.

In this paper we present recent results on FE, in particular, charged particle emission from crack propagation in a wide variety of materials. We compare the properties of this emission from homogeneous materials with emission from composite materials. In all the materials tested, some form of FE was observed and was most intense in materials where interfacial failure could occur. The types of materials tested were crystalline insulators, glasses, polmers (including elastomers) and composites.

2. Experimental procedure

In almost all cases to be described here, catastrophic fracture was produced in samples of two geometries:

(a) a rectangular parallelepiped broken in a three-point bending mode for very brittle materials, and

(b) tensile specimens, notched in the centre.

Loading was relatively slow, typically at strain rates of 1% per sec until rupture. Typical dimensions were such that the fractured surfaces had cross-sections from 5 to $20\,\mathrm{mm}^2$. In addition we also fractured a number of bare filaments, typically $10\,\mu\mathrm{m}$ in diameter, of materials such as glass, graphite and Kevlar. These were mounted so that single filaments could be broken sequentially. Also, epoxy strands of some of these materials were fractured, the strands being provided by the Lawrence Livermore Laboratory. Each strand contained approximately 250 filaments. The filament diameters were 20 μm for E-glass and 10 μm for S-glass and graphite. The filaments were untreated and the epoxy was Dow DER 332.

Most experiments were carried out in a vaccum chamber pumped by a diffusion pump with a liquid nitrogen cold trap. The background pressure was 2 to 4×10^{-6} torr and the residual gases consisted primarily of CO, H_2O and CO_2.

Some samples were also tested in an ion pumped vacuum system at a pressure of 10^{-8} torr to determine the influence of the background gases. As discussed later, no differences between the two environments were observed.

Charged particles were detected with a channel electron multiplier (CEM), a Galileo Electro-Optics Model 4039, positioned 2 cm from the sample.

The front of the CEM was biased at +300 V for efficient detection of electrons and at −2400 V for detection of positive ions [29]. For a few materials, electric and magnetic fields were introduced with grids and permanent magnets to test for the presence and energy of charged particle emission. The pulse output (10 ns pulse-width) of the CEM was amplified and fed to a 100 mHz discriminator which drove a counter, a count rate meter and a multichannel analyser (MCA) allowing counts against time to be recorded. The time domains used were usually two extremes: slow (0.8 sec per channel) or fast (1 to 1000 μsec per channel). For our survey of materials, the slow time domain was used for determining the existence of FE and relative intensities. For a few materials, the fast time domain was used to measure the decay of the emission following fracture. The time of fracture was determined either with a stress transducer on the pulling mechanism or with an acoustic emission transducer attached to the sample mount.

For all materials studied, we looked for electrons, and in some cases, positive ions. The ion species involved in the PIE have not yet been determined.

3. Results

3.1. Survey of materials

Tables I and II present a summary of the observed

TABLE I Electrons

Materials	Approximate decay times of fracto-emission	Electrons detected per cm² of crack wall
Sapphire	<1 sec, minutes	10^3
Alumina	<1 sec, minutes	10^4
Al_2O_3 anodized layer	0.1 to 20 μsec	10^5
BN	<1 sec, minutes	10^6
Quartz	<1 sec, minutes	10^6
Mica (muscovite)	<1 sec, minutes	10^6
Crystalline sugar	<1 sec, minutes	10^6
Fused silica	Several msec	10^3
Soda-lime glass	Several msec	10^3
Kevlar 49 fibres	<<0.1 sec	10^8
Graphite fibres	10 μsec	10^8
E-Glass fibres	10 μsec	10^8
S-Glass fibres	10 μsec	10^8
Epoxy (DER 332)	25 μsec	10^3
Lucite	<2 msec	10^2
Polystyrene	500 μsec, 12.3 μsec	10^3
Elastomers		
Neoprene	<1 sec	10^2
Viton	<1 sec	10^3
Buna N	<1 sec	10^2
Natural rubber	<1 sec	10^3
Natural rubber (abraded)	Minutes	10^7
Silicone rubber	<1 sec, minutes	10^5
Solithane	<0.2 sec	10^4
Vinyl rubber-filled	<1 sec, minutes	10^4
Polybutadiene	0.04 sec, minutes	10^3
Polybutadiene-filled	< sec, minutes	10^7

TABLE II Positive ions

Material	Approximate decay times of fracto-emission	Ions detected per cm^2 of crack wall
Mica (muscovite)	1 sec, minutes	10^6
Fibres		
Kevlar 49	45 μsec	10^8
Carbon	10 μsec	10^8
E-glass	10 μsec	10^7
S-glass	11 μsec	10^8
Plastics		
Epoxy (DER 332)	25 μsec	10^3
Lucite	< 2 msec	10^2
Polystyrene	35 μsec	10^4
Elastomers		
Buna N	< 1 sec, minutes	10^3
Natural rubber	< 1 sec	10^4
Natural rubber (abraded)	Minutes	10^7
Silicone rubber	< sec, minutes	10^3
Solithane	< 0.1 sec	10^6
Vinyl rubber-filled	< 1 sec, minutes	10^5
Polybudadiene	< 0.04 sec, minutes	10^5
Polybutadiene-filled	< 0.02 sec, minutes	10^6

electron and positive ion emission. It should be noted that we have not tested comprehensively for PIE. In all cases tested, EE and/or PIE have been observed, i.e. we have not as yet found a material which does not emit.

In each case, the emission intensity against time curves have a common characteristic: highest intensity at or very near fracture, followed by a decay of emission. In some materials, the decay is with time constant of the order of μsec or msec. Fig. 1a shows an example of this behaviour for the EE accompanying the fracture of polystyrene. Other materials exhibit emission that decays much slower, of the order of several seconds; this is shown for boron nitride in Fig. 1b (note the time scales). In Tables I and II, the emission intensity is measured over approximately one lifetime of the slowest decay constant. In cases where we have not measured the short decay times, we denote upper limits.

For a few materials, we applied a magnetic field of 0.01 tesla to verify that the EE observed was indeed due to electrons rather than negative ions, excited neutral particles or short wavelength photons. This field was sufficiently low that negative ions with at least 1 eV energy could reach the electron multiplier, but strong enough that electrons because of their lower mass, would require over 300 eV to be detected. In the case of polystyrene, this field stopped all of the EE and approximately 80% of the EE from an E-glass–epoxy strand. The latter result suggested that

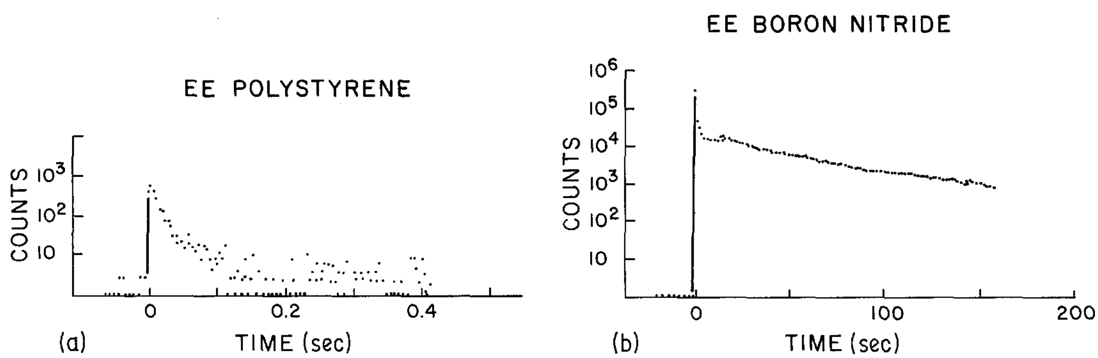

Figure 1 The time distributions of electron emission due to the fracture of (a) polystrene and (b) boron nitride.

either high energy electrons are created and/or a detectable component uninfluenced by a weak magnetic field is produced. The CEM is sensitive to ultra-violet (UV) photons with wavelengths below 120 nm and to metastable molecules with excitation energies above approximately 6 eV [29]. It appears, however, that the EE observed is principally due to electrons.

For a few materials, the samples were plated with 30 to 50 nm of gold to provide a conducting surface at ground potential. This layer dissipated static surface charges due to handling of the sample. This surface charge caused large fluctuations in the observed EE, but had little effect on the PIE. This suggested that the surface charge was deflecting the electrons away from the +300 V front cone of the CEM, but had little effect on the PIE due to the −2400 V applied to the CEM cone. It should be noted that this gold film had no influence on the charging or discharging of the fracture surface on most of the materials studied due to their high resistivity.

A significant increase in FE intensity (charge released per unit area) was observed as the sample cross-section was reduced. In Table I and II, one can see that filaments a few micrometres in diameter were relatively intense emitters of both EE and PIE. Two reasons are most plausible for this high intensity. First, when thin filaments fracture, the freshly created fracture surface quickly becomes free of the opposite crack wall. Thus, there is less chance for the particles to hit the opposite crack wall and therefore a higher probability of reaching the CEM for detection. Secondly, filaments are know to have significantly higher tensile strengths than the bulk material, thus storing more elastic strain energy prior to fracture. This could lead to an increasing amount of excitation of the material that produces FE.

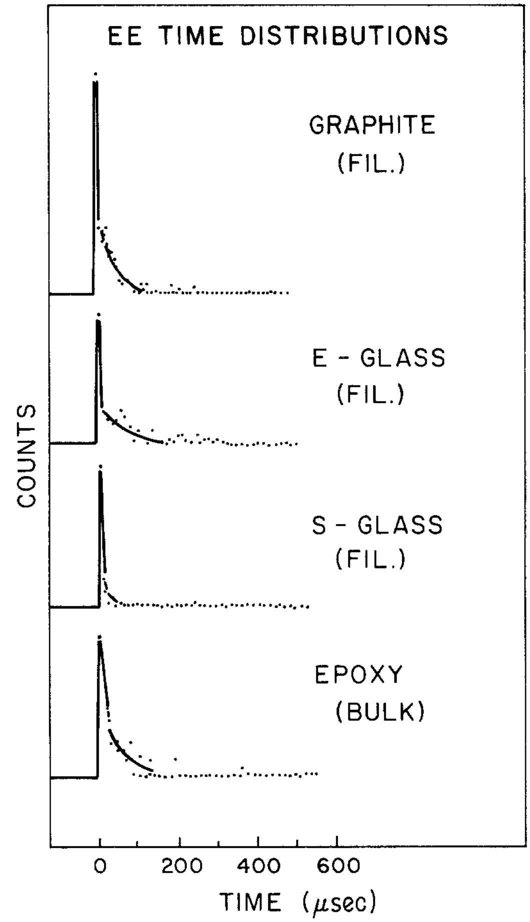

Figure 2 The time distributions of electron emission due to the fracture of graphite and glass filaments (10 μm in diameter) and bulk epoxy (Dow DER 332). Note the fast time scale.

3.2. The fracture of fibre reinforced epoxy

We note that single filaments and pure epoxy produce FE with a simple decay curve with time constants of a few microseconds. Fig. 2 shows emission against time curves for the filaments as well as for pure Dow DER 332 epoxy. If we then examine the FE accompanying the fracture of fibre reinforced epoxy strands made from the same filaments and epoxy, we find emission curves that differ considerably from the pure materials. Figs 3 and 4 show typical emission curves for a number of fibre–epoxy systems on a time scale which is very slow compared to the emission from pure materials. First we see a rapid rise reaching a peak near the instant of rupture, then a decay with a complicated time dependence. For all cases, the emission lasts far longer than for the pure materials. If we assign time constants to portions of the decay curve, they vary from msec to 5 min or longer. If we examine the initial portion of the curve on a faster time scale (Figs 3b and 4b), we see events prior to catastrophic fracture of the sample, sometimes with decay constants associated with fracture of the pure samples. In Fig. 3b the strand itself has not yet ruptured, but some filament and matrix failure has occurred. We note that the different fibre–epoxy systems presented here have different FE curves. For example, the emission from E-glass is considerably more intense and longer lasting than for S-glass. Examination under a microscope of the samples following

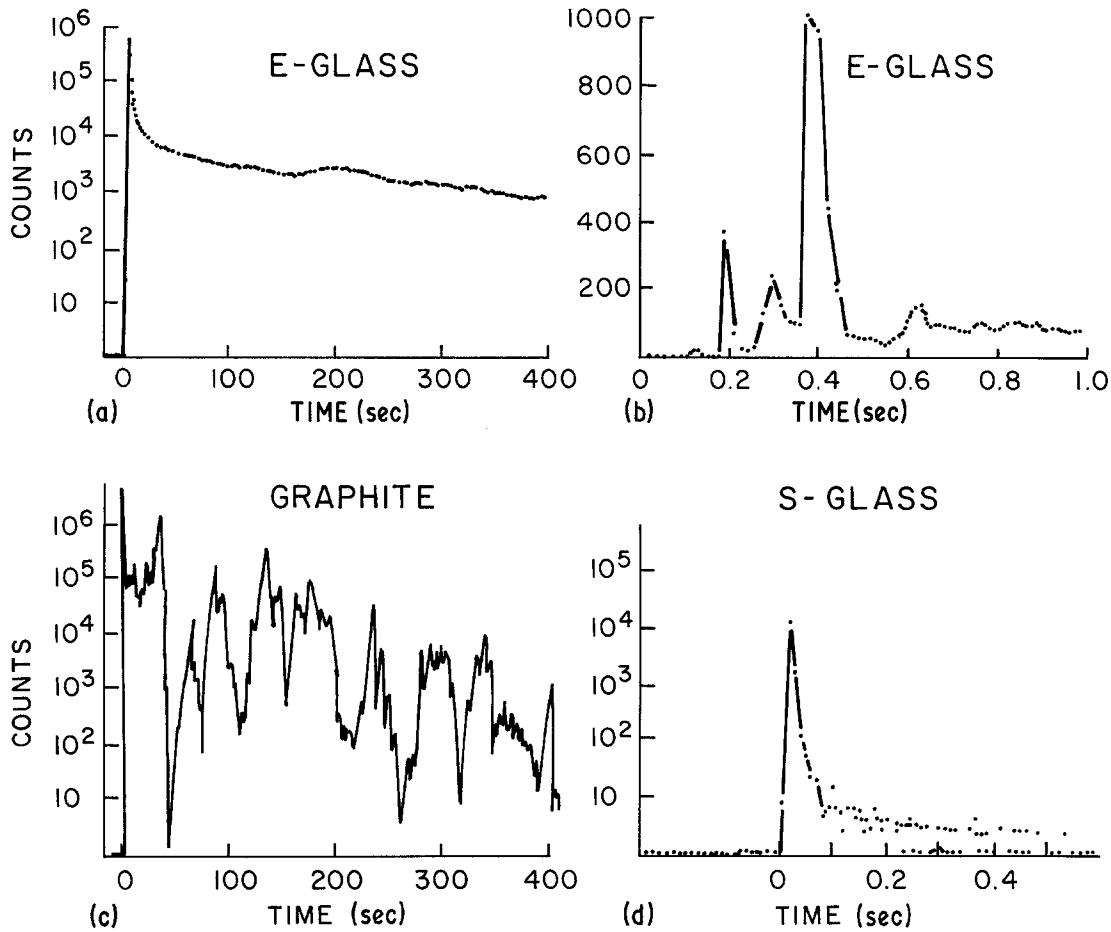

Figure 3 Electron emission during and following fracture of fibre–epoxy strands. Note the range of time scales.

rupture shows that there is considerably more delamination and separation of the filaments in the case of E-glass and graphite than for S-glass, S-glass showing very few clean fibres. The larger diameter E-glass filaments (20 μm compared to 10 μm) could contribute to the degree of interfacial failure.

Thus, our interpretation is as follows. Prior to rupture, the sample under tension suffers minor failures. These failures consist primarily of fibre breakage and epoxy failure and produce EF similar to that of pure materials. Finally, as these minor failures accumulate, the entire strand fails, producing a large amount of delamination or interfacial failure between the filaments and epoxy. It is the latter form of failure which we believe is responsible for the major FE component with the slow decay and is possibly an indicator of the extent of interfacial failure that has occurred. Occasionally, during the decay, smaller additional peaks in FE are observed due to further instances of minor failure because of creep of the differentially stretched materials near the broken ends of the strands. By far the predominant emission appears to be coming from the surfaces created by separation of the filaments from the matrix.

The EE from E-glass and S-glass–epoxy strands following rupture were relatively smooth curves, as were the PIE curves for all three composites. However, as seen in Fig. 3c, the EE curve from a graphite–epoxy strand is intense, but very erratic. In the case of some samples, the emission would

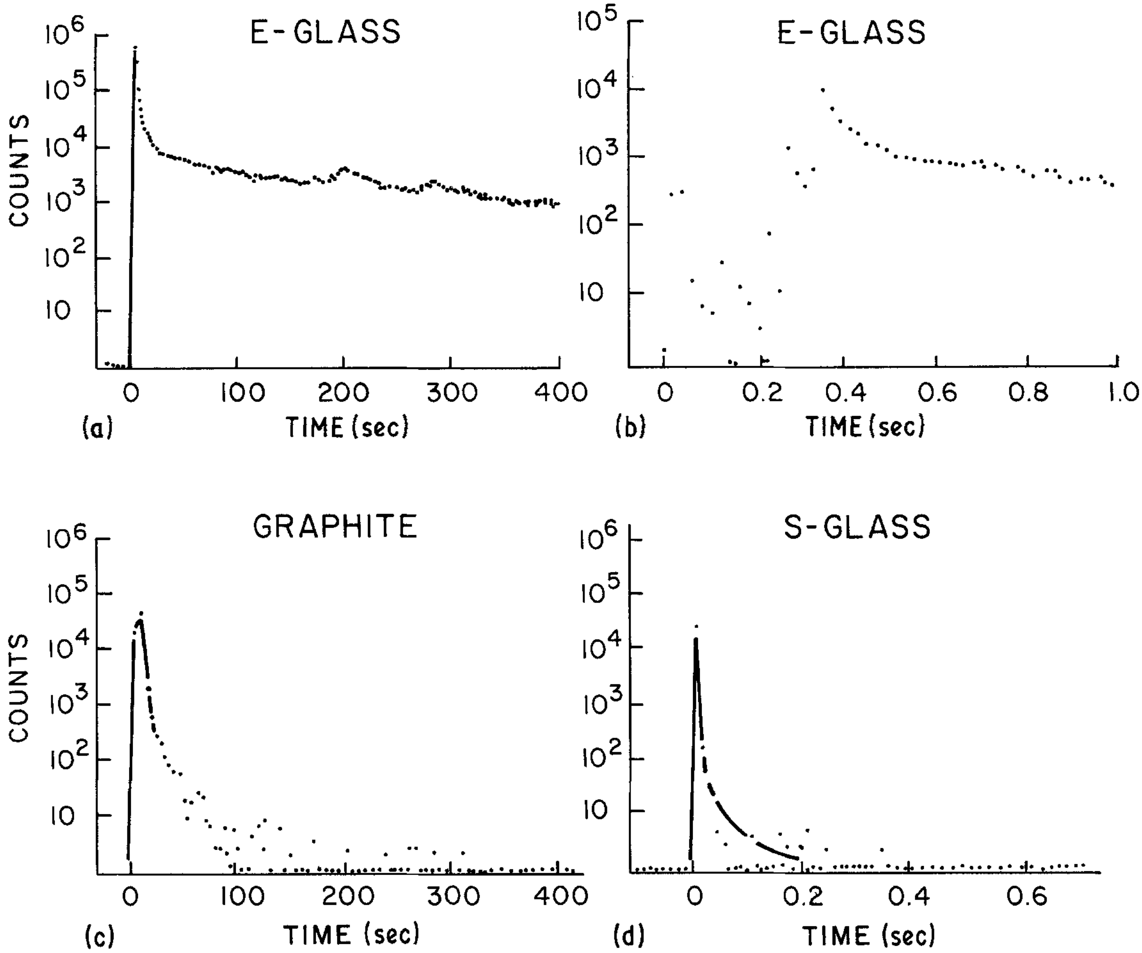

Figure 4 Positive ion emission accompanying and following fracture of fibre–epoxy strands.

actually drop to zero counts for a few seconds and then jump to several thousand counts per sec. Of course, one significant distinction of graphite is its high conductivity. We believe that this erratic behaviour is due to surface charging and discharging that tends to alter the electron emission (but has no effect on the positive ion emission). This could occur at the interface of the graphite filament and the thin residual layer of material from the matrix [30]. Strong positive charging that occasionally discharged would explain the erratic EE and relatively smooth PIE.

E-glass–epoxy strands were also fractured in the ultra high vacuum system to determine whether the long lasting emission observed was due to chemi-emission from reaction of the fracture surfaces with background gases. A reduction of the background pressure by two orders of magnitude had no influence on either the EE or PIE.

When EE and PIE are compared over several samples we find that the total emission, on the average, is nearly the same. When the emission from two different samples are normalized, as shown in Fig. 5, we see that within the fluctuations of the observed particle counts, the two curves are indistinguishable. This suggests that a common rate-limiting step is occurring in EE and PIE.

By placing fine mesh grids in the regions between the sample and the CEM it is possible to make a retarding potential energy analysis [31] of the EE and PIE accompanying fracture of materials. The derivative of the count rate against retarding grid potential is the energy distribution

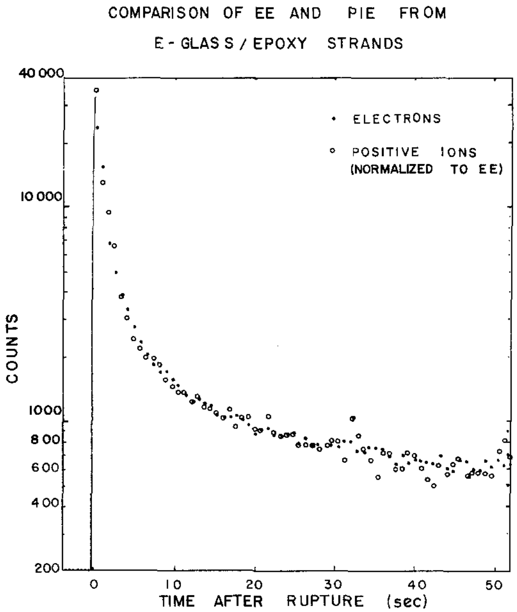

Figure 5 Comparison of electron emission and positive ion emission due to fracture of E-glass–epoxy strands. The PIE data has been normalized to the EE data.

of the emitted particles. Fig. 6 shows the results for both EE and PIE from the fracture of two different E-glass–epoxy strands. Both charges seem to have very similar energy distributions peaking near 0 eV, with a significant quantity of higher energy particles tailing off in the range of a few hundred eV. Although this derivative curve does not show it, approximately 15% of the particles could not be stopped by potentials in the 500 to 1000 V range. The presence of these higher energy particles suggests that charging of the fracture surface (due to separation of charges) is playing a role in the ejection of these particles from the surface. The similarity of the EE and PIE energy distributions again suggests that they share a crucial mechanistic step.

A comparison of EE and PIE from the E-glass–epoxy system was made by placing an ion and electron detector on opposite sides of the sample. First, simultaneous emission of both charges was observed upon fracture. Second, the pulses coming from these detectors were tested for coincidence; i.e. within two time windows (0.5 and 100 μsec). The pulses were tested in this way to discover if electrons and ions occur correlated in time, in order to determine whether a portion of the electrons were produced by ionization of molecules which in turn were observed as positive ions. The results were unambiguously negative. No coincidence of any statistical significance was observed in either time frame. We thus conclude that there is no evidence of simultaneous creation of electrons and ions via ionization of neutral species in the EE and PIE observed from the E-glass–epoxy system.

3.3. Other long time-constant emitters

As a test of the correlation between interfacial failure and the long lasting FE, we examined a number of systems which would tend to involve failure of an adhesive-like bond. First, E-glass–epoxy strands were split along their length (see Fig. 7a) causing extensive delamination with only minor fibre and epoxy fracture (as determined by optical microscopy). This splitting by delamination produced the emission observed in Fig. 7a, yielding the same long time-constant emission seen in rupture of the fibre strands each time the splitting occurred (vertical arrows).

Another test involved samples of bulk epoxy bonded to glass, lucite and aluminium in such a way that they failed in shear along the interface.

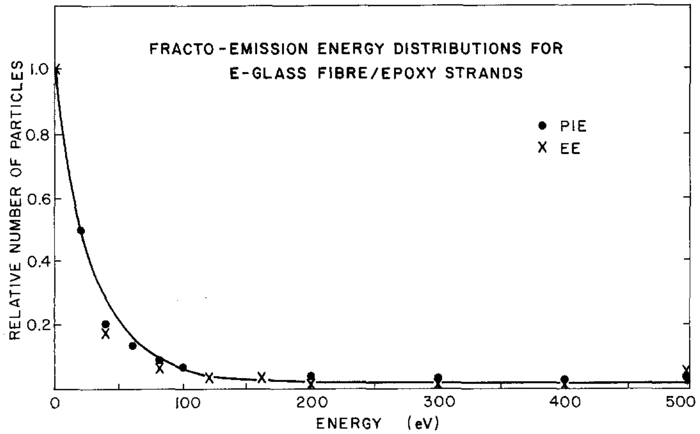

Figure 6 Energy distributions of electrons and ions from fracture of E-glass–epoxy strands. Obtained by differentiation of retarding potential analysis of the emitted particles.

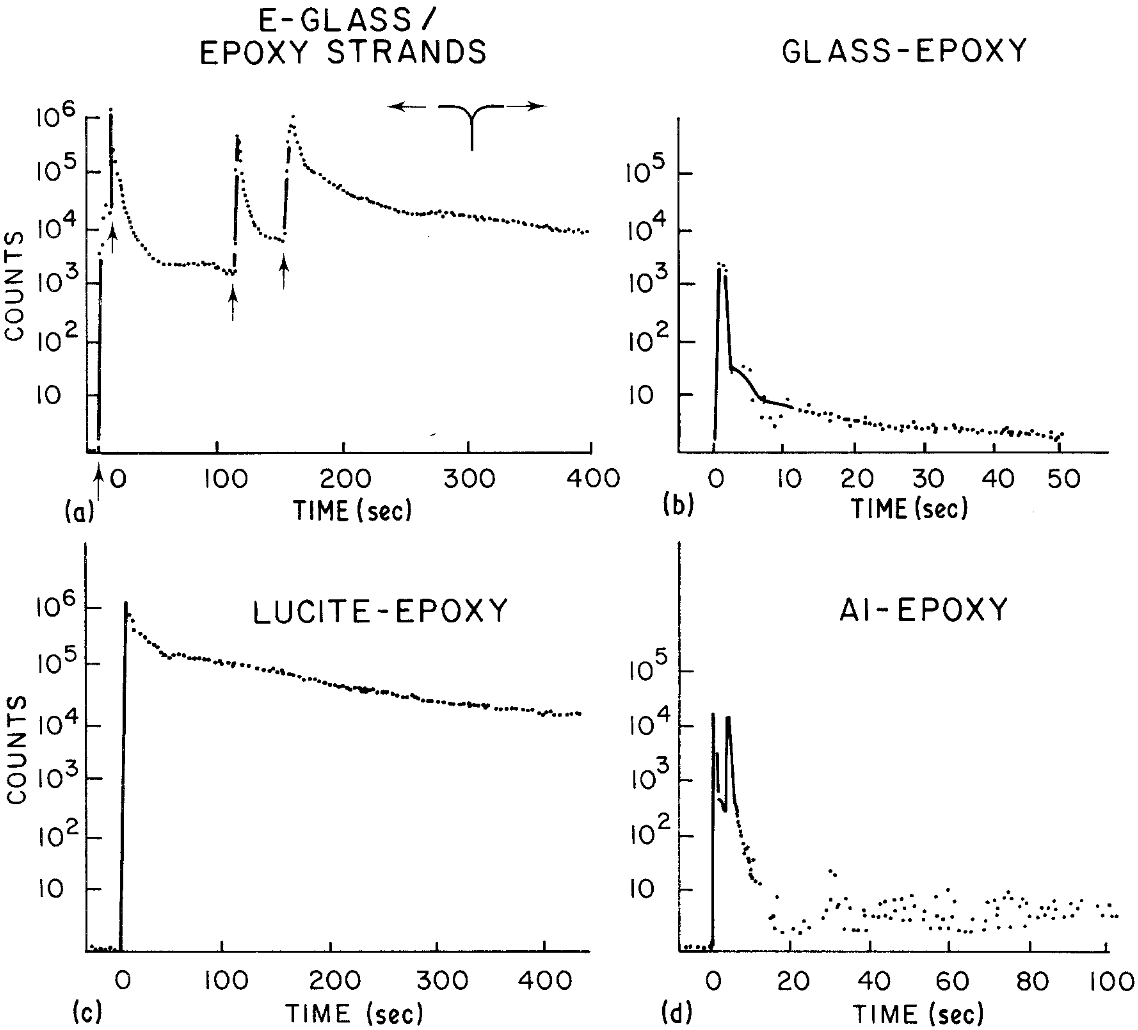

Figure 7 Electron emission during and following interfacial failure between epoxy and other materials: (a) split E-glass–epoxy strands, (b) soda-lime glass (c) lucite and (d) aluminium.

The bonded area was approximately 1 cm^2. Fig. 7b, c and d show the resulting EE curves for these interfaces all exhibiting the long lasting emission.

Another type of system tested was the elastomer, polybutadiene, with and without the presence of 34 vol% untreated glass beads 30 to 95 μm in diameter. The samples were provided by The University of Akron Institute of Polmer Science. EE and PIE curves for samples with identical cross-sections are shown in Fig. 8. Although the rubber alone has relatively long lasting emission, we see that the sample containing the glass beads emits considerably more strongly. Interestingly, the slow rise in emission corresponds to the relatively slow propagation of the crack in the elastomer. Gent [32] has shown that the beads become detached during straining of the material. Most likely this type of failure is responsible for the enhanced emission. The energy distribution curve for polybutadiene containing glass beads is shown in Fig. 9 and is similar to that obtained for E-glass.

Since we suspect that charge separation is involved in the release of particles when this long time-constant emission is observed, we examined a system that is know to leave highly charged surfaces following cleavage, namely mica (muscovite). Fig. 10 is the EE and PIE accompanying the fracture (cleavage) of mica, both showing the long

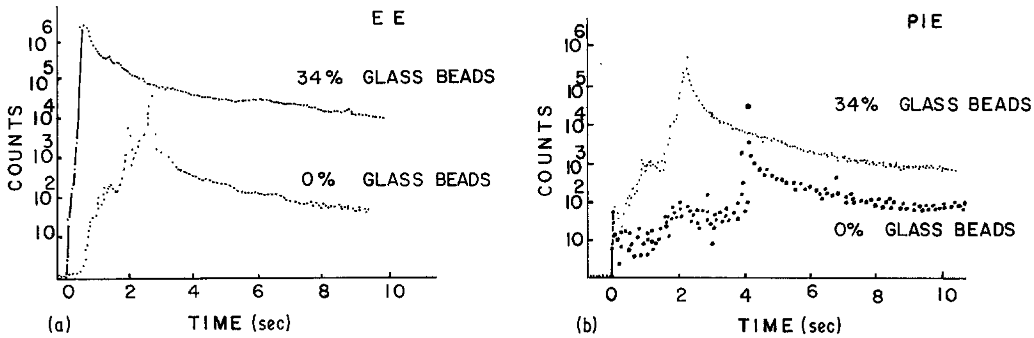

Figure 8 The emission curves for (a) electrons and (b) positive ions from the fracture of polybutadiene filled and unfilled with small glass beads.

lasting emission. Fig. 11 contains the EE and PIE energy distributions from retarding potential energy analysis and they are seen to be similar to E-glass–epoxy fracture except that they are more energetic. Although not entirely conclusive, the similarities between the mica FE and the FE from other systems suggest that charge separation may be significant.

4. Discussion

Our results show that FE is indeed a widespread phenomenon; we have not yet found a material that does not produce some form of FE. The magnitude of the emission per unit area varies considerably as does the time dependence. For all materials, the emission accompanying the motion of the crack tip appears to be most intense. The creation of excited states would occur during this time when the energy density is the highest and the resulting emission appears to begin immediately [4, 6]. In many materials we see a fast decay with submicrosecond time-constants followed by a slower decay of microseconds, milliseconds or even many seconds. The mechanisms for the very fast and very slow emissions are likely to be quite different and need to be investigated in depth.

The results involving the fracture of epoxy–fibre systems suggest that different filament materials can alter the FE, possibly due to differences in the filament–epoxy bond and the degree of delamination that occurs. We have shown that when separation of the filament from the matrix occurs it is accompanied by a unique type of FE involving very long time-constants and relatively high energy particles (a few hundred eV). Most likely, the production of such high energy particles involves the electric fields due to charge separation that occurs when adhesive bonds are broken. Vladikina *et al.* [33] observe high energy electron emission from a number of systems that exhibit surface charging due to friction of dielectrics in a vacuum and by fracture. They also observe very

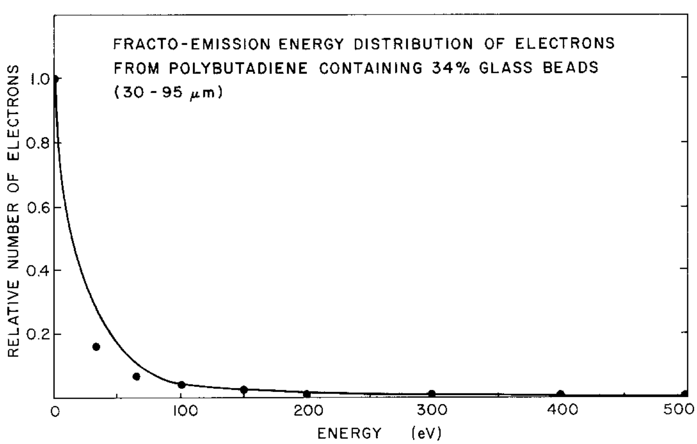

Figure 9 The energy distribution of electrons produced by fracture of polybutadiene containing glass beads.

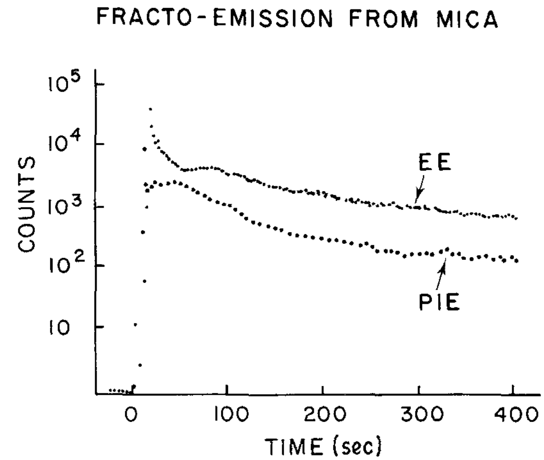

Figure 10 Fracto-emission curves for mica showing time dependence of both electrons and positive ions.

long decay constants for friction-induced EE from polymers, an effect accompanied by intense surface charging. They attribute the observed electron emission to field emission which requires electric fields of the order of 10^6 to 10^7 Vcm^{-1} and surface charge densities of 10^{-8} to 10^{-7} Coulomb cm^{-2}. Although it is very probable that charging is involved we are reluctant at this point to attribute the emission we observe to field emission. The main reason for this is that our energy distributions peak at or near 0 eV. One would expect the most intense EE from the highest potential points on the surface which would then produce electrons with high energy. Very low energy electrons are not likely to accompany field emission. Secondly, we find many similarities between the EE and PIE from the same type of samples, e.g. the time dependence of the emission curves and energy distributions. This suggests a common mechanism yet it is difficult to see how field emission and the production of free ions could be related.

One possible role of the electric field is the following: imagine that charge patches of varying sign and charge density are created on the surface due to separation of the crack walls. We then assume that the excitations that can produce FE, e.g. energetic defects of chemically reactive species, are able to locate in the region above the charge layer; for simplicity we would expect this to be near or at the surface of the material. Then, when de-excitation occurs, free electrons or ions are produced and depending on the sign of the charge area over which they are created, they may be attracted into the surface, and thereby lost, or repelled into the vacuum with kinetic energy determined by the potential at the position where they were created. Then, the energy distributions we observed are simply a function of the distribution of charge density on the surface. The energy distribution may also be influenced by a dependence on charge density of the de-excitation probability and/or the probability of an FE-producing excitation reaching a given region. Since the charge density for good insulators has decay constants of several minutes to hours in a vacuum, the more rapid decay observed would imply that it is a measure of the supply of excited species rather than due to charge leakage. Consistent with this, we see no change in the energy distribution of either EE or PIE with time over a period of 2 min. Finally we note that the loss of charge due to leakage would be exponential, whereas the initial FE decay is much more complicated.

5. Conclusion

Considerably more work needs to be done to

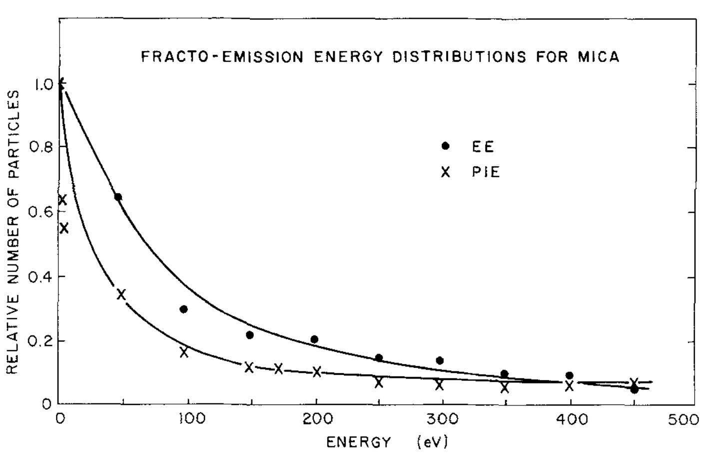

Figure 11 Energy distributions of electrons and positive ions arising from the fracture of mica.

clearly define the various mechanisms involved in the FE observed. We are also interested in pursuing possible applications of FE to understanding fracture phenomena. For example, it is feasible that the intense emission observed during crack propagation is related to crack velocity and/or fracture mechanics parameters such as surface energy of the instantaneous stress intensity factor.

In composites or multiphase systems FE may indicate precisely where fracture is occurring, e.g. intra- versus inter-granular fracture, delamination, etc. FE may be a useful monitor of the mechanochemistry accompanying fracture, e.g. in stress corrosion. It may also be sensitive to sub-critical crack growth. Certainly it would be an effective way to distinguish between surface cracking from internal micro-fracture in materials like ceramics since FE is a surface effect. Although still speculative at this point, it is conceivable that FE could contribute to our understanding of a wide variety of fracture phenomena.

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