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ON THE PROBLEM OF DEVELOPING ACOUSTIC EMISSION AS A QUANTITATIVE TECHNIQUE

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ABSTRACT

Several aspects of the problem of developing acoustic emission into a quantitative technique are considered briefly. These include: the relation between acoustic emission and the energy dissipated in thermodynamically irreversible processes, the relation between acoustic emission and the stress fields involved in dynamic theories of crack propagation, and the distinction between near and far fields for acoustic emission sources.

INTRODUCTION

The characteristic feature of acoustic emission is the generation of high frequency stress waves whose energy is derived from a quasi-static strain field. The energy conversion process is associated with a mechanical instability, as in crack growth (1). The general problem falls into two parts, namely the calibration of the "chain of detection" (source-specimen-transducer-electronics) and the establishment of a relation between the conversion process and a practically useful measure of "damage". The second part is considered in the following.

ACOUSTIC EMISSION AND IRREVERSIBLE THERMODYNAMIC PROCESSES

There are strong arguments for taking the energy or power within a given bandwidth as the measure of acoustic emission. The measure of damage is likely to be an irrecoverable deformation, e.g. plastic strain and hence, according to the scheme of Fig. 1, to involve irreversible thermodynamic processes.

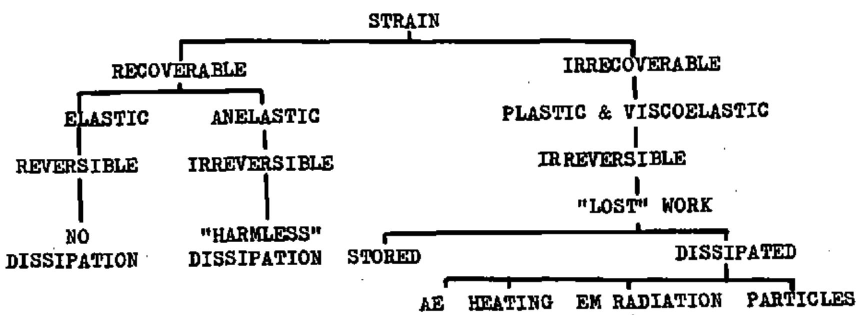

Fig. 1 Acoustic emission and irreversible processes

Thus acoustic emission may be one manifestation of the energy dissipated in irreversible processes, e.g. dislocation motion. In such cases there exists a possibility of using acoustic emission to measure, say, the volume of a plastic zone. The practical realization of this possibility requires a knowledge of what has been called the Partition Function, i.e. the relation between the energy detected as acoustic emission and the energy emitted outside the detection bandwidth and, in particular, as thermal phonons. An experimental method for making a direct measurement of the partition function in a special case has been suggested by the author (2).

Mechanisms for the generation of acoustic emission by moving dislocations have received much attention (3-5). This process seems to fit into the scheme of Fig. 1. However, acoustic emission from brittle materials seems not to fit this scheme. Such materials are copious emitters, but in them dissipative processes are relatively unimportant. This apparent paradox leads one to ask whether acoustic emission from brittle materials is a different phenomenon from acoustic emission from ductile materials, what sort of partition function operates for brittle materials, and whether it is possible in principle to obtain quantitative measurements of damage in brittle materials via acoustic emission. In the following sections features of the theories of fracture mechanics and of acoustic transients which are relevant to these questions are examined.

ACOUSTIC EMISSION AND DYNAMIC THEORIES OF FRACTURE

There is no provision for acoustic emission in quasi-static theories of fracture, i.e. theories of the equilibrium crack. Dynamic theories must be considered. Setting aside any doubts about the surface energies of moving cracks, the problem in such theories is to incorporate the energy of the moving displacement field about the crack into an energy balance equation. Mott (6) treated the case of a crack advancing at steady speed by assuming the displacements to have the static form uniformly translated. Hence the rate of increase of kinetic energy, U_k, with crack area, A, could be found in terms of the quasi-static strain energy release rate, G_s, and the surface energy term 2Γ: $dU_k/dA = G_s - 2\Gamma$, where $G_s - 2\Gamma = 0$ is the static equilibrium condition. Eshelby (7) says the moving displacement field should be scaled by a velocity-dependent factor and distorted as by a Lorentz Contraction. Recent treatments of moving cracks by Broberg (8) and Freund (9) have been formulated in terms of a dynamic strain energy release rate, G_d. Freund has derived G_d for uniformly advancing and for stepwise accelerating cracks. G_d provides a means of retaining the form $G - 2\Gamma = 0$ for the equation of motion by incorporating the kinetic energy effects as a reduction in G from its static value G_s: $G_d = G_s$ at zero crack velocity, v_c but decreases almost linearly with increasing v_c and is zero when v_c reaches the Rayleigh wave velocity.

The energy of the moving displacement field is related to the energy of acoustic emission. It has been suggested (10) that they are identical, but the relationship is probably more complicated, for reasons indicated below. However, it is tempting to regard the diminution of G_d with increasing v_c as an effect of the radiation impedance seen by the newly created surfaces.

ACOUSTIC EMISSION AS A QUANTITATIVE TECHNIQUE

The dependence of G_d on v_c has been confirmed by Doll (11) in experiments on PMMA, in which about 60% of the kinetic energy was detected as heat. Such experiments are clearly relevant to the determination of the Partition Function mentioned above.

IMPULSIVE ACOUSTIC SOURCES

Some insight into the likely properties of the newly created surfaces as sources of ultrasonic radiation may be gained by considering the general properties of impulsive acoustic sources. It is instructive to take the simplest case, namely a piston radiating into a fluid of density ρ. The "near" and "far" fields must be distinguished. The far field criteria, $a/R \ll 1$, $ka^2/R \ll 1$, $kR \gg 1$ with $k = 2\pi/\lambda$, at distance R from a continuous source of radius "a" may be extended to the case of an impulsive source. It is shown in (12) that:

a) The work done in accelerating a piston to velocity V is divided between the kinetic energy of the near field and the energy of an acoustic pulse radiated into the far field.

b) For instantaneous acceleration, equal amounts of energy, $4\rho a^3V^2/3$, go into the near and far fields.

c) The energy of the far field pulse is roughly proportional to the product of the acceleration and the near field kinetic energy.

d) If the piston stops instantaneously the near field kinetic energy is radiated into the far field.

e) If the piston stops slowly the near field kinetic energy is re-absorbed by the piston.

It is suggested that acoustic emission is the analogue of the far field pulse, and that the kinetic energy term arising in the fracture mechanics theories is the analogue of the near field kinetic energy in the piston-in-fluid model. The necessary addition of shear waves to the model for a solid represents a major complication and, in particular, destroys the simple picture of the near field kinetic energy being due to an entrained mass. It should be noted that the formula for near field length used in NDT ultrasonics applies to the case $2a \gg \lambda$. Here the case $a \ll \lambda$ is of interest and the distinction is between quasi-static, essentially un-phase-shifted low frequency components and phase-shifted high frequency components. It is made by means of the criterion $kR \lessgtr 1$, where k is the wavenumber. In this sense many acoustic emission experiments have been made in the near field, e.g. those of Bodner (13) on the fracture of glass rods, and good agreement between the observed pulses and predictions based on calculations of the static fields is to be expected. But, as is shown below, far field effects should be important for emission from the fracture of small particles.

ACOUSTIC EMISSION FROM THE BRITTLE FRACTURE OF SMALL PARTICLES

"Heavy alloy", a tungsten-copper-nickel alloy containing about 95% tungsten as particles of about 50u size, may be used to illustrate the points raised in the preceding sections. Taking the longitudinal wave velocity as 5110m/s R as 10 mm and $a \sim 25u$, the frequency independent far field criterion $a/R \ll 1$ is easily satisfied, as is $ka^2/R \ll 1$ for frequencies of practical interest.

$kR > 1$ is satisfied for frequencies above 80 kHz. The energy released from the static strain field if such a particle is fractured may be estimated from G_s for a penny-shaped crack to be $\sim 8.10^{-4}$ J. It remains to be shown that such fractures actually occur in preference to processes at the matrix-particle interface, but if they do then the energy released into the dynamic strain field will be of the order given above, since the surface energy and dissipative terms will be relatively insignificant. It is not yet possible to calculate the partition function which would determine the amount of acoustic emission resulting from such an event, but such a calculation would contain the following ingredients. Firstly, an estimate of the frequency distribution of the energy released into the dynamic strain field is required: the higher frequency components will appear as heat. Secondly the fraction of the stress wave energy falling in the far field is required. Thirdly, the angular distribution of intensities and the relative weighting of longitudinal and shear waves in the far field are needed. These are determined by the symmetry of the static field and by Poisson's ratio.

SUMMARY

It seems that the strength of the detected acoustic emission from some types of brittle fracture may be strongly dependent on the size and geometry of the sample, and on its gross mechanical properties, as well as on the rate of increase of new fracture surface, i.e. "damage". It also appears that the determination of those factors which govern the energy of the far field pulse should have a high priority. For example, if the V in the piston-in-fluid model can be associated with the velocity to which newly created surfaces are "instantaneously" accelerated, then V should depend on material constants such as strength, modulus and density. Finally, although it may never be practicable to predict the acoustic emission resulting from failure processes of practical interest, consideration of the problems involved in so doing may assist in the optimization of detection methods.

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