ELECTROMAGNETIC DETECTION OF ACOUSTIC EMISSION
FROM A MARTENSITIC TRANSFORMATION

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Electromagnetic Detection of Acoustic Emission
from a Martensitic Transformation[†]

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Abstract

The acoustic emission resulting from the martensitic phase transformation in a gold-47.5at.% cadmium alloy has been observed using a purely electromagnetic means to detect the acoustic signals. This detection method eliminates transducer-related resonances which usually make a determination of the frequency spectrum associated with acoustic emission very difficult. Both the temporal and frequency response of individual acoustic emission events have been determined. For the small specimen used in this investigation the frequency response is dominated by acoustic cavity resonance effects in the specimen. This work shows that electromagnetic detection of acoustic emission may be especially useful when attempting to determine the frequency spectrum of various sources of acoustic emission.

INTRODUCTION

Acoustic emission (AE) is the spontaneous generation of elastic waves resulting from dynamical processes occurring within a solid under stress. Typically, these elastic waves are observed by using a piezoelectric transducer attached mechanically to the specimen under study. There are many sources of AE including grain boundary motion, solid-solid phase transformations and slip-line formation. A number of years ago, it was demonstrated by Schofield¹ that AE is related directly to the process of deformation in specimens subjected to a static load. From this and other recent work,² it is apparent that AE may be a useful means of obtaining practical quantitative information about dynamical processes in solids. Of particular interest is the dynamics of the process of deformation and the possible prediction of fracture.

To realize these objectives will require much more work. One area needing considerable attention is developing the ability to distinguish among the various possible sources of AE. For instance, it may be necessary to be able to distinguish AE signals produced by twinning from those produced during the formation slip lines. To this end, a study of the frequency spectrum associated with various AE sources should be valuable.

Obtaining a reliable frequency spectrum is often hampered by the presence of transducer-related resonances. These can

be eliminated rather easily if a purely electromagnetic means of detecting AE is used. Electromagnetic detection (ED) of acoustic waves has been studied extensively and is quite well understood.^{3,4} The main disadvantage of ED is that when used in a nonresonant mode, the conversion efficiency is normally lower than that which can be obtained using ideally bonded piezoelectric transducers. However, ideal bonding is seldom achieved. Since ED can eliminate resonance effects in the transducer and its mechanical mounting, it may prove to be very useful in studying AE. This paper shows that, despite the lower conversion efficiency, ED is a very feasible means of detecting AE signals.

Using a resonant piezoelectric transducer, it has been demonstrated that relatively large AE is obtained from the martensitic phase transformation in gold-47.5at.% cadmium.⁵ This material was chosen to assess the feasibility of using ED as a means of detecting AE.

THEORY

The theory for the combined processes of electromagnetic generation and detection is in good agreement with experimental evidence.³ Because it is a more difficult problem, there exists no similar exact treatment of the single process of electromagnetic detection. However, from previous work

it is possible to determine the functional dependence of ED and to make rough estimates of signal levels to be expected when using ED.

In a metal, eddy currents are generated when an acoustic wave is reflected from a surface. Only that portion of the eddy current density that is perpendicular to the polarization direction of the acoustic waves produces an appreciable electromagnetic field outside the conductor. In most materials, an eddy current density perpendicular to the acoustic polarization can only be produced by a Lorentz force on the induced currents. Therefore, a static magnetic field, H , is necessary for electromagnetic detection. The electromagnetic fields outside the conductor are proportional to this static field. The acoustically induced eddy current density is proportional to the lattice displacement, ξ . Typically, the external fields are sensed inductively; this produces a voltage at the coil terminals that is proportional to the time derivative of the external field. Consequently for an acoustic wave of angular frequency ω , one expects the coil output voltage, V_o , to be related to the above quantities by

$$V_o \propto \omega \xi B_o \quad (1)$$

The proportionality constant can be estimated from measurements using a quartz transducer to generate an acoustic wave and ED for detection. For the coil geometry and specimen size

described in the next section, and from approximate calibration measurements, we estimate that

$$V_o = 1 (\text{mV/MHz-}\text{\AA}\text{-kG}) \quad (2)$$

For a displacement of $0.01\text{\AA}$ and a magnetic field of 5 kG, this gives an output voltage of 5 μV at 100 kHz and 50 μV at 1 MHz.

EXPERIMENTAL METHOD AND RESULTS

All studies were done using the same specimen and coil. The experimental setup that was used is shown in Fig. 1. A 300 turn coil of #40 copper wire containing the 6 mm diameter by 5 mm long gold-cadmium specimen was immersed in a heat dispersing fluid. This allowed the specimen to be heated uniformly (the phase transformation occurs near 72°C on heating and in the vicinity of 60°C on cooling) using a $30\ \Omega$ noninductively wound resistance heater that was driven from a dc power supply (a power dissipation of 10 watts produced a heating rate of about 8°C/min). The temperature in the vicinity of the specimen was determined using a copper-constantan thermocouple. Temperature gradients near the specimen were estimated to be less than 2°C/cm .

The coil was connected via about six feet of coaxial cable to the input of an amplifier chain having a maximum gain of 120 db and an upper -3 db frequency of 1 MHz. Normally about

105 db gain was used. The amplifier output was ac coupled to a Schmitt trigger which served as a level discriminator. Each time the input signal exceeded a preset threshold, the Schmitt trigger circuit produced an output voltage pulse of about 0.1 μ sec duration. The number of pulses in each one second interval was determined continuously by a frequency counter. A printer was used to give a permanent record. The counter dead time must be taken into account when determining the total count by summing the printer output.

The discriminator threshold was set to give very nearly zero counts per second with the specimen in the coil, at room temperature and in zero applied field. For the measurements reported here, a field strength of about 10 kG and a gain of 106 db was used but with higher gain and a stable Schmitt trigger, essentially the same results were obtained using fields as low as 4 kG. Figures 2 and 3 show the AE count rate (in counts per sec) as a function of time when the specimen is either heated (Fig. 2) or cooled (Fig. 3) through the martensitic phase transformation. The horizontal scale for the heating curve is almost linear in temperature; it begins near 50°C and goes up to about 110°C. At least part of the high temperature tail on the heating curve is due to the lack of thermal equilibrium rather than any intrinsic specimen behavior.

The horizontal (time) scale of the cooling curve is not

nearly linear in temperature. The extreme right hand side corresponds to about 70°C and the left hand side to about 25°C. As observed previously, the maximum in the AE rate on cooling occurs at a lower temperature than on heating. This is likely due to supercooling of the phase transformation. Also notice that the vertical scales for heating and cooling differ by more than an order of magnitude. Heating through the phase transformation produces a much larger integrated count than does cooling through it (23,000 on heating vs. 3,300 on cooling). The actual total count and count rate depends upon the heating or cooling rate and the discriminator threshold level. These results agree qualitatively with those reported recently.^{5,6}

The AE signals as sensed by the coil were considerably smaller than those encountered in previous piezoelectric studies; this required using higher amplification. However, the larger gain did not introduce any serious experimental problems as long as normal precautions were taken with respect to the shielding of spurious electromagnetic pickup.

A Biomation Model 610 transient recorder was used to record individual AE signals so that their characteristics could be investigated in more detail. The recorder is supplied with both slow and fast analog outputs; the slow output was used to plot the temporal response on a strip chart recorder and the fast output was used to determine simultaneously the

frequency spectrum (using a spectrum analyzer).

As expected, AE signals of widely varying amplitude and time course were observed. However, as shown in Fig. 4, they could be separated into two main groups. Note that these signals contain very little random noise (the system bandwidth is 1 MHz) showing that many individual AE signals are well above the amplifier noise level. The low frequency signals in Fig. 4a were most common when the specimen was cooling while the high frequency signals in Fig. 4b were most common while heating through the high count rate region shown in Fig. 2. However, both types of response could be observed during almost any portion of the heating or cooling cycle.

Another AE signal and the resulting frequency spectrum is shown in Fig. 5. It is obvious that the spectrum is not a continuous distribution of frequencies as might be expected for a simple transient excitation of an acoustic wave. Instead there are several peaks in the frequency response. The transient response of the combined coil-amplifier system was a strongly damped, 1 MHz oscillation lasting about 3 μ sec. This may account for one or both of the highest frequency peaks in Fig. 5b. Other possible system related effects including finite channel width and amplifier saturation were investigated. The very prominent peak near 80 kHz was frequently present. Most tests showed the 80 kHz component to be related to the presence

of AE but occasionally spurious electromagnetic noise pickup would also produce an output having a large 80 kHz component. The only reasonable explanation that we can offer is that this 80 kHz peak is somehow associated with a short duration overload of the amplifier but evidence on this score is far from conclusive. This 80 kHz component is clearly giving a large contribution to the signals in Figs. 4a and 5a.

The remaining peaks in Fig. 5b exhibited many of the characteristics expected of AE signals. Their relative amplitude varied from one event to the next. Some frequency response curves showed fewer peaks, some more. It seems reasonable that these peaks could be due to an acoustic cavity resonance effect. In a specimen of the size used here, many acoustic modes are possible within the frequency range studied. Very roughly, the various sets of acoustic modes will be determined by the condition $d = n\lambda/2$, where d is some characteristic dimension and $\lambda = v_s/f$ is the acoustic wavelength (v_s being the acoustic velocity and f the fundamental frequency for any given set of modes). Using the transverse sound velocity of gold, $v_s = 1 \times 10^5$ cm/sec, and a characteristic dimension of 5 mm gives a fundamental frequency of 100 kHz or a fundamental period of 10 μ sec. This agrees reasonably well with the location of peaks in Fig. 5b (the fundamental resonance could be masked by the large 80 kHz response).

Depending upon the location of the AE within the specimen, some modes would be excited more efficiently than others. Therefore, the event-to-event variation in amplitude of the various harmonics is not surprising.

In Fig. 5b, the 350 kHz peak has the smallest amplitude; this is contrary to the behavior expected from Eq. (1). However, Eq. (1) does not include the possibility of resonant acoustic modes. In general the amplitude of the fundamental resonant mode will be larger than the harmonics. That is, an acoustic cavity resonance effect tends to enhance the low frequency response. The generally smaller amplitude of the higher frequency peaks reinforces the interpretation that these peaks arise from acoustic resonance effects.

DISCUSSION AND CONCLUSIONS

The experimental results reported here show that AE signals can be observed by ED, a purely electromagnetic means of detecting acoustic waves. Using ED to detect AE from the martensitic transformation in gold-47.5at.% cadmium gives a count rate curve having a shape similar to that observed using piezoelectric detection.

It is quite easy to have a critically damped coil and amplifier system so that multiple counting due to transducer ringing can be reduced drastically. This should then help to

reduce the dependence of total count on the discriminator threshold level, a problem encountered in many piezoelectric measurement systems. Because of the simple frequency response of ED and the freedom from transducer resonance problems, it is rather easy to determine the frequency spectrum of individual AE signals. It has been demonstrated that acoustic resonance effects can play an important role in determining the frequency spectrum. This should be especially true in materials having at least one small dimension. Although much more work is needed in this area, ED may offer a new means of detecting and studying AE in conducting materials;⁷ it should be especially useful in circumstances where one wishes to determine the frequency spectrum associated with the emission of stress waves.

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- * Alfred P. Sloan Foundation Research Fellow.
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7. Insulating materials can be studied using ED if a conducting foil is bonded to the insulator surface.

Figure Captions

- Figure 1: The experimental setup used to determine the acoustic emission count rate, total acoustic emission count and the temporal and frequency characteristics of typical acoustic emission signals. The transient recorder is a Biomation Model 610.
- Figure 2: The acoustic emission count rate as a function of time obtained when heating through the martensitic phase transformation. A total of about 23,000 counts were obtained in this run but the total count and maximum count rate depended to some extent on the heating rate and discriminator threshold level.
- Figure 3: The acoustic emission count rate as a function of time obtained when cooling through the martensitic phase transformation.
- Figure 4: Two typical types of temporal response: (a) a signal with a large low frequency component, and (b) a signal containing many different frequency components (but definitely not having the characteristics of random noise).

Figure 5: (a) The output voltage from a single acoustic emission event, and (b) the corresponding frequency response. As mentioned in the text, the two frequency components near 1 MHz may be instrument related.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.