Identification of mechanisms generating acoustic emission during deformation of materials is often difficult because several mechanisms may be potentially or actually operating simultaneously. Identification of sources which are actually contributing significantly to the acoustic emission can often be accomplished by testing material with different process histories, by microstructural examination before and after deformation, and by using different stress states. Mechanisms which operate simultaneously in one stress state may operate predominantly in different strain ranges in another stress state. Further confirmation of the mechanisms involved can be obtained by measurement of physical parameters, other than acoustic emission, during deformation which are sensitive to the proposed generation mechanisms for the acoustic emission.

Several examples of the use of these techniques will be shown. The sources of acoustic emission in 7075 aluminum were determined by testing in both tension and compression, and by measurement of internal friction as a function of strain. Dislocation motion was shown to be the major source of acoustic emission in beryllium by testing beryllium of different purity, heat treatment, and origin (powder metallurgy or cast and worked) in both tension and compression combined with microstructural observations. Confirmation that the source was dislocation motion and identification of the type of dislocation activity involved was made by internal friction measurements during deformation of 7075 aluminum in the T-6 temper centered at yield, as shown in Poster 1. The peak at yield is in addition to the previously reported peak at 2.5% strain. The difference between the T-6 and T-651 tempers showed no internal friction above the background level of our instrumentation throughout the entire test. Work at our laboratory and work by other investigators has shown conclusively that the second acoustic emission peak arises from the fracture of inclusions within the aluminum matrix.

7075 ALUMINUM

The mechanisms responsible for the acoustic emission generated during the plastic deformation of 7075 aluminum have been identified by testing the material in two different tempers, testing in both tension and compression, and by measuring the internal friction or damping during deformation. When the acoustic emission from 7075 aluminum was first investigated some years ago, it was proposed that the acoustic emission was generated entirely from dislocation motion. The major apparent problem with this interpretation was that the acoustic emission maximum occurs at approximately 1.5% strain. It is difficult to understand why the maximum should not occur near the onset of plastic flow if it is due to dislocation mechanisms. Testing of 7075 aluminum in the T-6 and T-651 tempers revealed a second acoustic emission peak in the T-6 temper centered at yield, as shown in Poster 1. The peak at yield is in addition to the previously reported peak at 2.5% strain. The difference between the T-6 and T-651 tempers is that the material in the T-651 condition is given a stress relief stretching of up to 3% plastic strain following solution heat treatment in order to improve flatness. This mechanical treatment suppresses the acoustic emission peak at yield but does not affect the peak occurring at higher strains. When deformed in uniaxial compression, the peak at yield (T-6 temper) is unaffected, however, the peak at higher strains disappears. Analysis of these results suggests that the acoustic emission peak at yield is due to a dislocation motion or breakaway phenomena and that the peak at higher strains originates from some other source. Confirmation of this interpretation is provided by amplitude independent internal friction measurements. The magnitude of the amplitude independent internal friction is sensitive to both the dislocation density and the average dislocation loop length. An increase in either will cause an increase in the internal friction, although the magnitude is more sensitive to the average loop length. Internal friction measurements during deformation of 7075 aluminum in the T-6 temper showed an internal friction peak which corresponded closely with the acoustic emission peak observed at yield. There was no measurable internal friction at the location of the second peak (Poster 1). Measurements of the internal friction in the T-651 temper showed no internal friction above the background level of our instrumentation throughout the entire test. Work at our laboratories and work by other investigators has shown conclusively that the second acoustic emission peak arises from the fracture of inclusions within the aluminum matrix.

BERYLLIUM

There are many potential sources of acoustic emission during deformation of beryllium. Dislocation motion, twinning, grain cleavage, inclusion (primarily BeO) fracture or decohesion, and precipitate fracture or decohesion are all reasonable possibilities. The general characteristics of acoustic emission from beryllium are shown in the top figure of Poster 2. Beryllium from powder metallurgy stock, from rolled ingot, and from special high purity powder metallurgy stock was tested. Material was tested after several different heat treatments, and measurements were made in both tension and compression. Details of the heat treatments used are given in Reference 5. The response of the magnitude of the two peaks to these experimental parameters is summarized on
measurements indicate that the acoustic emission environments were similar, as shown in 6, although a major shift in amplitude of emission from a sample loaded biaxially was observed (Poster 5). The presence of cracks or voids in a test sample will cause a decrease in the measured elastic modulus when compared to a defect-free sample. A simple first-order theory showing that the apparent or effective elastic modulus is dependent on the volume of cracks in the material is given in Poster 7, i.e. $Y_{\text{eff}} = Y(1 - \alpha V/V)$. The variation in modulus change is greater than that predicted from typical load deflection curves. In order to effectively use modulus change measurements as a tool to study crack initiation, growth, etc., it is necessary that techniques be used which can detect small changes in the modulus to a very high degree of accuracy and precision.

**Stainless Steels in a Hydrogen Environment**

Acoustic emission is a potential technique for monitoring stainless steels for hydrogen-assisted crack growth. Acoustic emission was monitored from 21-6-9 stainless steel (nominally 21% Cr, 6% Ni, 9% Mn, 0.25% N) stressed biaxially in hydrogen and inert environments. The first observation was that the amount of acoustic emission during loading was substantially greater than in uniaxial tension, as shown in Poster 3. The sample volumes and strain rates were different for the two tests, so the rms has been normalized to the same volume and strain rate using the well established proportionality between rms and the square root of strain rate or sample volume. No detectable difference in the amount or strain dependence of acoustic emission during loading was seen between hydrogen and inert environments, although hydrogen-assisted crack growth clearly occurred in a hydrogen environment. A typical surface crack and a fracture surface from a sample tested in a hydrogen environment are compared with a surface and fracture occurring in an inert environment in Posters 3 and 4. Furthermore, the amplitude distributions of acoustic emission bursts from samples tested in hydrogen and inert environments were similar, as shown in Posters 5 and 6, although a major shift in amplitude occurred from loading to holding at constant load (beyond the yield stress). Acoustic emission from hydrogen-assisted crack growth can be distinguished from other sources of emission by holding the sample at constant load and measuring the emission as a function of time. Acoustic emission associated with plastic flow should decline rapidly with time at constant load as plastic deformation producing stress relaxation ceases. Hydrogen-assisted crack growth, however, should not decrease significantly with time and will provide an acoustic emission source after stress relaxation has ended. The predicted difference in acoustic emission versus time between samples stressed and held in hydrogen or helium was observed (Poster 5).

Acoustic emission was monitored from samples loaded biaxially in hydrogen and inert environments. A typical surface crack and fracture surfaces from samples tested in hydrogen and inert environments are compared with a surface and fracture occurring in an inert environment in Posters 3 and 4. Furthermore, the amplitude distributions of acoustic emission bursts from samples tested in hydrogen and inert environments were similar, as shown in Posters 5 and 6, although a major shift in amplitude occurred from loading to holding at constant load (beyond the yield stress). Acoustic emission from hydrogen-assisted crack growth can be distinguished from other sources of emission by holding the sample at constant load and measuring the emission as a function of time. Acoustic emission associated with plastic flow should decline rapidly with time at constant load as plastic deformation producing stress relaxation ceases. Hydrogen-assisted crack growth, however, should not decrease significantly with time and will provide an acoustic emission source after stress relaxation has ended. The predicted difference in acoustic emission versus time between samples stressed and held in hydrogen or helium was observed (Poster 5).

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REFERENCES


ACOUSTIC EMISSION COUNT RATE VS TIME FOR 7075 ALUMINUM IN TENSION

ACOUSTIC EMISSION COUNT RATE VS TIME FOR 7075 ALUMINUM IN COMPRESSION

THE ONLY DIFFERENCE BETWEEN T6 AND T651 TEMPER IS THAT THE T651 MATERIAL IS GIVEN A STRESS RELIEF STRETCHING OF UP TO 1% PLASTIC STRAIN FOLLOWING THE SOLUTION TREATMENT IN ORDER TO IMPROVE FLATNESS. THIS PLASTIC STRAIN REMAINS IN Effect during THE ACYUSTIC EMISSION MEASUREMENT PERIOD BUT IS NOT AFFECTED BY THE PEAK OBSERVED AT ABOUT 1% PLASTIC STRAIN.

THESE OBSERVATIONS ARE IN THE ACYUSTIC EMISSION BEHAVIOR IN TENSION AND COMPRESSION. PARTIAL OBSERVATION AT ALLOYS IN TENSION AND COMPRESSION AT HIGH STRESSES SHOWS THAT A MINIMAL DETERMINANT FOR THE T6 TEMPER IS THAT IN BOTH TREATMENT AND COMPRESSION, THE PEAK AT 1% PLASTIC STRAIN IS NOT OBSERVED IN THE T6 TEMPER. THIS RESULT IS CONSISTENT WITH A DISLOCATION ORIGIN FOR THE SECOND PEAK. IN BOTH T6 AND T651 TEMPER, THE PEAK AT YIELD IS OBSERVED IN THE T6 TEMPER BUT NOT IN THE T651 TEMPER. THIS RESULT IS CONSISTENT WITH A DISLOCATION MECHANISM FOR THE SOURCE OF THE FIRST ACYUSTIC EMISSION PEAK.

RECENT WORK BY THE AUTHORS AND OTHERS HAS SHOWN THAT THE SECOND PEAK ARISES FROM THE FRACTURE OF INCLUSIONS.

Poster 1

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BERYLLIUM

- **Characteristics of the Acoustic Emission Peak at the Onset of Plastic Flow**
  - Small in the solutionized and unannealed condition
  - Larger after the metal has been aged to form A1FeBe, or FeBe precipitates
  - Larger when slowly cooled rather than fast cooled from the aging temperature
  - Larger when a yield point is observed
  - Sensitive to material origin (powder metallurgy or wrought ingot)
  - Disappears in high purity metal
  - Similar in tension and compression

- **Characteristics of the Acoustic Emission Peak Centered at One Percent Plastic Strain**
  - Independent of heat treatment
  - Independent of material origin
  - Independent of purity
  - Similar in tension and compression

- **Possible Mechanisms**
  1. Grain cleavage and/or twinning. Rejected because of the small number of bursts in tension and compression, and also because the size of the grain cleavage and twin formation is too small to account for the number of bursts observed.
  2. BeO fracture. Rejected because there are substantial BeO peaks in ingot Be, which has a negligible BeO content.
  3. Fracture of A1FeBe, or FeBe, precipitates. Rejected because of the very small size of these precipitates and because of the similarity of results in tension and compression.

- **Internal Friction Measurements Confirm Postulated Mechanisms**
  - The peak at the onset of plastic flow is from the generation of new dislocations.
  - The corresponding internal friction change is small.
  - The peak at one percent plastic strain is from breakaway of dislocations from pins. The pins are presumably generated by the plastic flow process itself. (The corresponding internal friction change is large.)

- **Confirmation of the Validity of the Interpretation of the Internal Friction Results**
  - The yield point in iron is known from other experiments to arise from breakaway of dislocations from carbon interstitial atmospheres. The internal friction peak expected from the breakaway process is observed.

Poster 2
1. **Stress vs. Load for 21-6-9 Stainless Steel Loaded in Tension in Air.**

RMS acoustic emission vs. load for 21-6-9 stainless steel loaded in tension in air. Measured RMS values scaled to approximately the same sample volume and strain rate as the biaxial tests. Measured at approximately the same location on the fracture surface.

2. **Surface Cracks Commonly Found Originating at Inclusions for Steel Loaded in Hydrogen Environment.**

Surface cracks commonly found originating at inclusions for steel loaded in a hydrogen environment.

3. **No Surface Cracks in Steel Loaded in an Inert Environment.**

No surface cracks in steel loaded in an inert environment.

**Poster 3**

- Biaxial stress increases amount of observed acoustic emission.

- Material cracks when loaded in a hydrogen environment, but does not crack in an inert environment. There is no apparent difference in acoustic emission during loading in the two environments.

**Poster 4**
ACOUSTIC EMISSION BURST RATE AS A FUNCTION OF TIME AT CONSTANT LOAD FOR SAMPLES LOADED IN HELIUM AND HYDROGEN.

BURST AMPLITUDE DISTRIBUTION WHILE STRESSING SAMPLES IN HELIUM.

BURST AMPLITUDE DISTRIBUTION WHILE STRESSING SAMPLES IN HYDROGEN.

BURST AMPLITUDE DISTRIBUTION DURING HOLDING AT CONSTANT LOAD FOR SAMPLES LOADED IN HELIUM AND HYDROGEN.

BURST AMPLITUDE DISTRIBUTION DURING HOLDING AT CONSTANT LOAD FOR SAMPLES LOADED IN HYDROGEN.

BURST AMPLITUDE DISTRIBUTIONS ARE DIFFERENT DURING LOADING AND HOLDING AT CONSTANT LOAD, BUT THE BEHAVIOR IN HYDROGEN AND HELIUM ENVIRONMENTS IS SIMILAR.

CRACKING CAN BE DETECTED BY MEASURING THE TIME DEPENDENCE OF THE ACOUSTIC EMISSION BURST RATE AT CONSTANT LOAD.

THE PROBABLE MECHANISM INCLUSIONS FRACTURE DURING PLASTIC DEFORMATION AND CRACK GROWTH, IF PRESENT, DOES NOT DECREASE WITH TIME AND PROVIDES A SOURCE OF ACOUSTIC EMISSION AT LONG TIMES. AS OBSERVED.

POSTER 5

POSTER 6
DERIVATION BELOW

A FIRST ORDER APPROXIMATION TO THE RELATIONSHIP BETWEEN THE APPARENT ELASTIC MODULUS AND THE VOLUME OF CRACKS IN A TEST SAMPLE

\[ E_{\text{app}} = E_0 (1 - V_{\text{crack}}) \]

For rods in longitudinal vibrations (length of rod equals one half wave length),

\[ v = \frac{2\pi f}{L} \]

Cracks in pure iron developed during electrolytic charging. No cracks were found in the 304 stainless steel.

ACKNOWLEDGMENTS

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MODULUS CAN BE DETERMINED WITH HIGH PRECISION BY MEASURING THE LONGITUDINAL RESONANT FREQUENCY OF THE TEST BAR. A MARX COMPOSITE PIEZOELECTRIC OSCILLATOR FOR PERFORMING SUCH MEASUREMENTS IS ShOWN BELOW.

The center of the sample is a displacement node. Hence an electric contact can be placed there without disturbing the standing wave.

THE WORK INVOLVING FOLLOWING CRACKING WITH APPARENT MODULUS CHANGE MEASUREMENTS IS EXPLORATORY IN NATURE. THE CHANGE IN APPARENT MODULUS IS MUCH LARGER THAN PREDICTED FROM THE FIRST ORDER THEORY OUTLINED ABOVE GIVEN THE VOLUME OF CRACKS MEASURED METALLOGRAPHICALLY. HYDROGEN APPARENTLY PRODUCES CHANGES OTHER THAN CRACKING IN THE SAMPLE WHICH SUBSTANTIALLY ALTER THE ELASTIC MODULUS. WORK IS CONTINUING TO EXPLORE THE NATURE OF THESE OTHER EFFECTS AND TO DETERMINE IF MODULUS CHANGE MEASUREMENTS CAN BE USED TO QUANTITATIVELY MEASURE THE AMOUNT OF CRACKING IN A SAMPLE.

Changes in the resonant frequency and hence changes in the apparent elastic modulus for pure iron and type 304 stainless during electrolytic charging with hydrogen. As expected, no change was observed in the stainless steel since the samples were not stressed statically.