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Acoustic Emission from Plastic Deformation

Abstract

I would like to discuss some recent work at the University of Denver concerning acoustic emission generated during plastic deformation. I must emphasize that this is a preliminary progress report and that the investigation is still in its early stages. I would like to acknowledge two people who have been working with me on this investigation, Robert Wittman of the Denver Research Institute and Frank Higgins, a graduate student of mine at the University of Denver.

Disciplines

Materials Science and Engineering | Structures and Materials

ACOUSTIC EMISSION FROM PLASTIC DEFORMATION

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I would like to discuss some recent work at the University of Denver concerning acoustic emission generated during plastic deformation. I must emphasize that this is a preliminary progress report and that the investigation is still in its early stages. I would like to acknowledge two people who have been working with me on this investigation, Robert Wittman of the Denver Research Institute and Frank Higgins, a graduate student of mine at the University of Denver.

As previous papers have indicated, acoustic emission is defined as the pressure or stress waves generated during dynamic processes in the test material. More generally, it is possible to think of acoustic emission as the noise or low level sound given off spontaneously when there's a relaxation of stress within the test material. The most familiar example of acoustic emission generated during plastic deformation is that of the so called "tin cry". The plastic deformation of tin crystals produces a clearly audible emission which is due to twinning within the tin crystal.

Acoustic emissions occur in discrete bursts of noise which can be characterized in various ways. One can express his acoustic emission data as the number of bursts, the rate of bursts with time, the amplitude distribution of the bursts, the energy of the bursts, the rate of energy release or the frequency distribution of the bursts. The number and characteristics of the bursts generated will depend on the testing procedures used, the material being tested and the active sources of acoustic emission.

To date, acoustic emission techniques have been used as an investigative tool in three main areas:

1. Investigation of crack detection, crack propagation and crack nucleation. This area has received the most attention particularly by those people looking for detection methods.

2. The study of martensitic phase transformations. Acoustic emission techniques have been used to locate where these types of transformations occur both as a function of temperature and concentration.

3. The investigation of deformation processes during plastic deformation. It is this area of research which is discussed in this paper.

Acoustic emission bursts are generally emitted from all crystalline materials, polycrystalline or single crystals, during plastic deformation. A check of the literature to determine what authors attribute these bursts to indicates the following proposed sources. Acoustic emission from plastic deformation has been attributed to Luder's band formation, alternate slip on transient planes, slip line formation, microcrack formation, dislocation pileup relaxation, twinning, dislocation pinning, dislocation breakaway, the mobile dislocation density, slip advances and rapid source operations, i.e. dislocation multiplication. It's interesting that essentially all investigators have explained their acoustic emission data in terms of dislocation mechanisms. This is particularly interesting since Mr. Graham in the previous paper claimed that the acoustic emissions he measured coming from his aluminum alloys are not from dislocation processes but rather from the fracture of small particles in the matrix.

The difficulty in determining the actual sources of emission from the acoustic emission data is due to the fact that the data may be comprised of emissions from several sources. It is also very difficult to establish whether the sources are operating independently or cooperatively. Another problem which has hampered the interpretation of acoustic emission data is the lack of an experimental property sensitive to dislocation processes with which to compare the acoustic emission data. The majority of acoustic emission data are interpreted in terms of the stress strain curve or the load parameter, even though these properties provide very little information about microscopic processes such as acoustic emission generation.

We believe that in many cases, it is possible to overcome the difficulties discussed above and to develop acoustic emission technology into a powerful investigative tool. We believe it has the potential to be used in the investigation of deformation processes, determination of microstructural characteristics, determination of purity and the determination of defect identification and concentration.

To overcome the difficulties discussed concerning the analysis and interpretation of acoustic emission data we have implemented the following procedures:

1. A better selection of test procedures. In many cases it should be possible to effect a separation of emissions from different sources simply by a proper selection of test procedures.

2. The simultaneous measurement of the dislocation damping while measuring the acoustic emission. The damping is very sensitive to dislocation motion, dislocation mobility, dislocation multiplication, etc. and should provide valuable information if the acoustic emission is determined by dislocation processes.

The following data and discussion hopefully will illustrate what we have been trying to do and our degree of success. First, consider a plain ferritic steel, for example AISI 1018, with a microstructure as shown in Fig. 1. The structure is basically ferritic with small amounts of pearlite. If one measures the acoustic emission generated during a tensile test of this material, results as shown in Fig. 2 are obtained. Notice the excellent correlation between the peaks in the acoustic emission rate and the load drops in the stress strain curve indicating that emissions are primarily due to plastic deformation of the ferrite phase.

The structure of nodular cast iron is somewhat more complex as shown by the micrograph in Fig. 3. One still has the ferrite grains with small

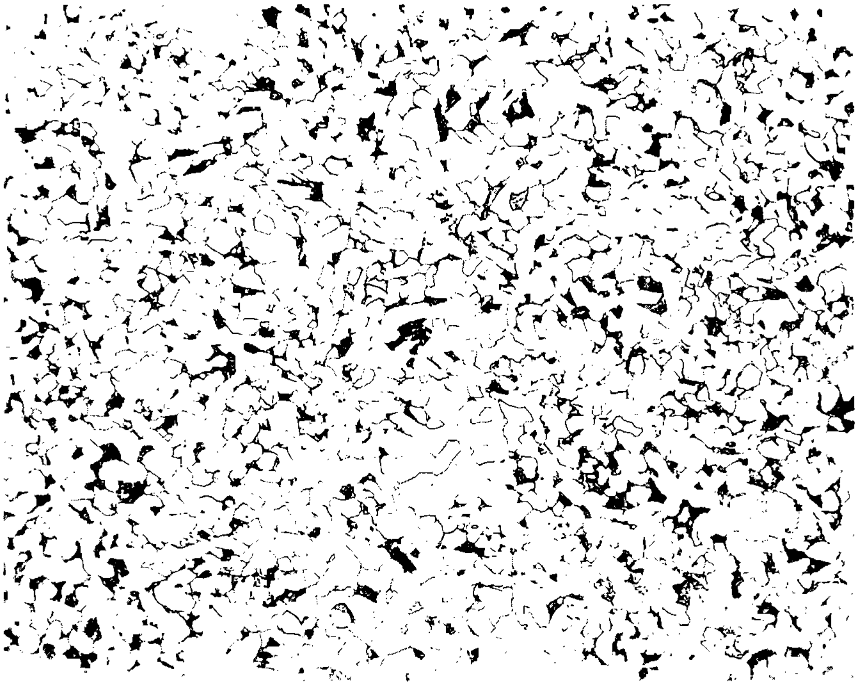

Fig. 1. Typical Microstructure of the Mild Steel Samples AISI 1018 (100X).

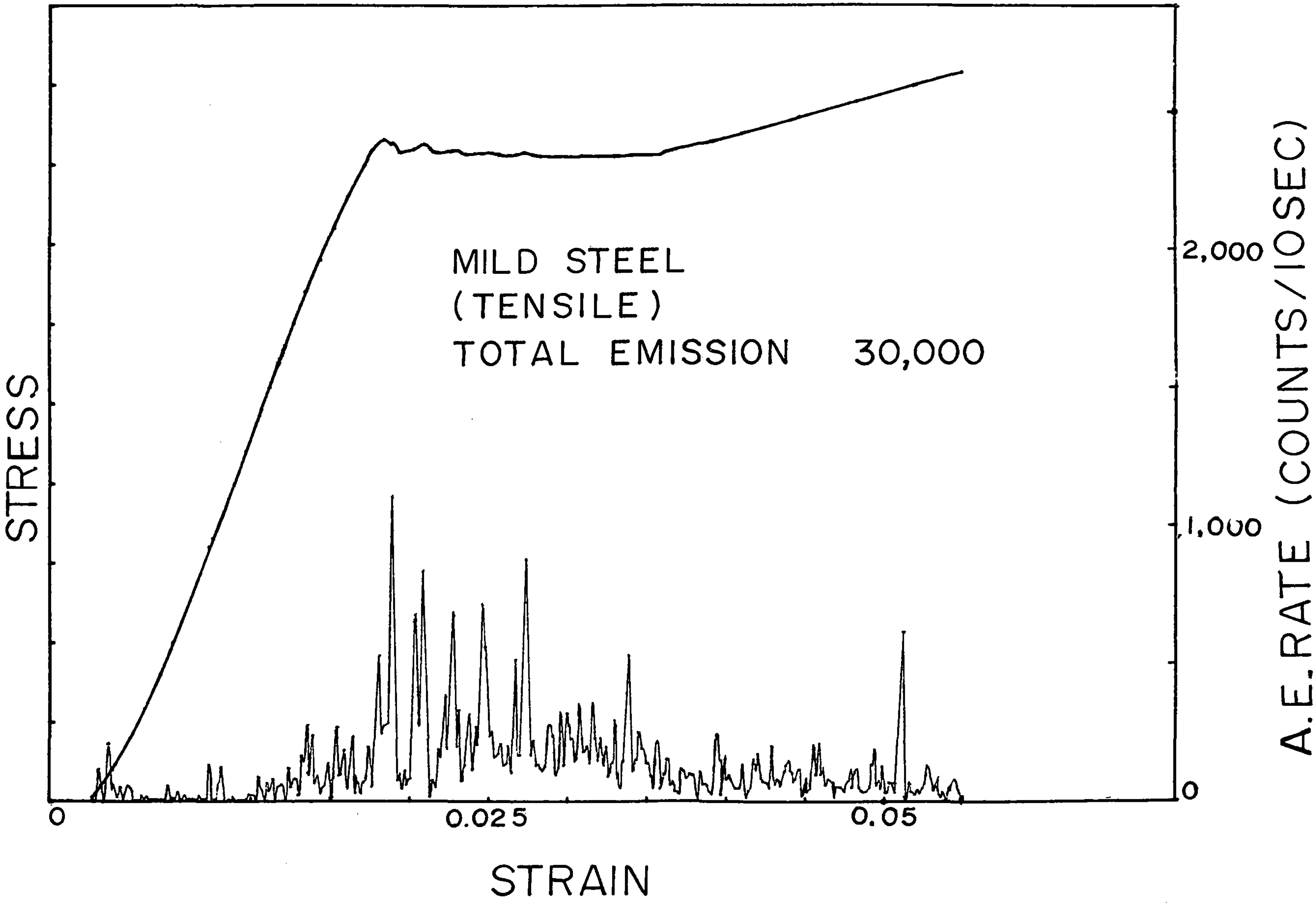

Fig. 2. Acoustic Emission Data from a Tensile Test of Mild Steel

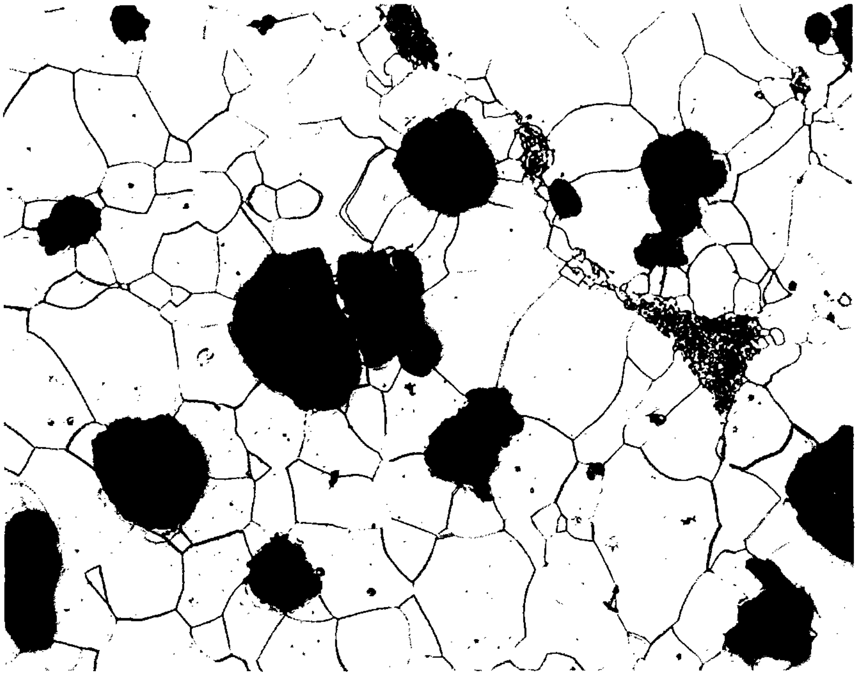

Fig. 3. Typical Microstructure of the Nodular Cast Iron Samples (100X)

amounts of pearlite, but in addition there are large nodules of graphite within the matrix. Looking at the structure one would expect at least two types of emission during plastic deformation: 1) emissions generated during deformation of the ferrite and 2) emissions generated due to fracture of the graphite nodules. Figure 4 shows acoustic emission data generated during a tensile test of nodular cast iron. A comparison of Fig. 2 and 4 show that it would be essentially impossible to separate the emissions from ferrite deformation from those due to fracturing of the graphite nodules.

However, a thoughtful study of the structures indicates that with proper selection of test procedures it might be possible to separate the emissions from these two sources into different regions of the stress strain curve. If one considers a spherical nodule, the stress necessary for fracture is considerably less in tension than that required in compression. Hence, if the materials are tested in compression the emissions due to deformation of the ferrite should still occur at yield while the emission due to fracturing of the graphite nodules will occur at higher stress levels. That this is indeed what happens is shown in Fig. 5, which gives the acoustic emission data generated while testing the same grade of mild steel in compression. Notice,there is a very nice peak in the acoustic emission count rate right at yield. We believe that this is due to deformation of the ferrite and our damping experiments, when completed, should either confirm or rule this assumption out.

Testing of the nodular cast iron in compression gives data like that shown in Fig. 6. Notice that the acoustic emissions do indeed separate into two regions. A peak like that observed in the mild steels at yield and then a large amount of emission at a higher stress. We believe the emissions at yield are due to dislocation processes during deformation of the ferrite, while the emissions at higher stresses are due to fracture of the graphite nodules. We are presently trying to confirm this by determining the number of fractured nodules at different points along the stress strain curve using the scanning electron microscope. We also hope to do spectral analysis of the two types of emissions much like that described by Lloyd Graham in the previous paper. This example hopefully demonstrates how a considerable amount of information can be gained simply by a more careful selection of testing procedures.

Now let me discuss the other problem--that of not having a sensitive experimental parameter with which to compare the acoustic emission data. The aluminum alloy 7075-T6 has been widely and extensively studied with regard to the acoustic emission generated during plastic deformation. While all of the previous authors, with the exception of Lloyd Graham, have explained their results in terms of dislocation processes, no one can actually prove what the mechanism is which is responsible for the acoustic emission. Work at Lawrence Livermore has shown that the RMS amplitude of this acoustic emission signal increases approximately linearly with strain rate, and that the slope of the linear dependence decreased with increased plastic strain. Work on this alloy by Darrell James and myself is shown in Fig. 7 and 8. In this study we tested a large number of tensile samples, all cut from one plate, with large differences in gauge volume. The samples were all pulled at a constant strain rate to a constant predetermined strain value. The sum of the count rate and the RMS

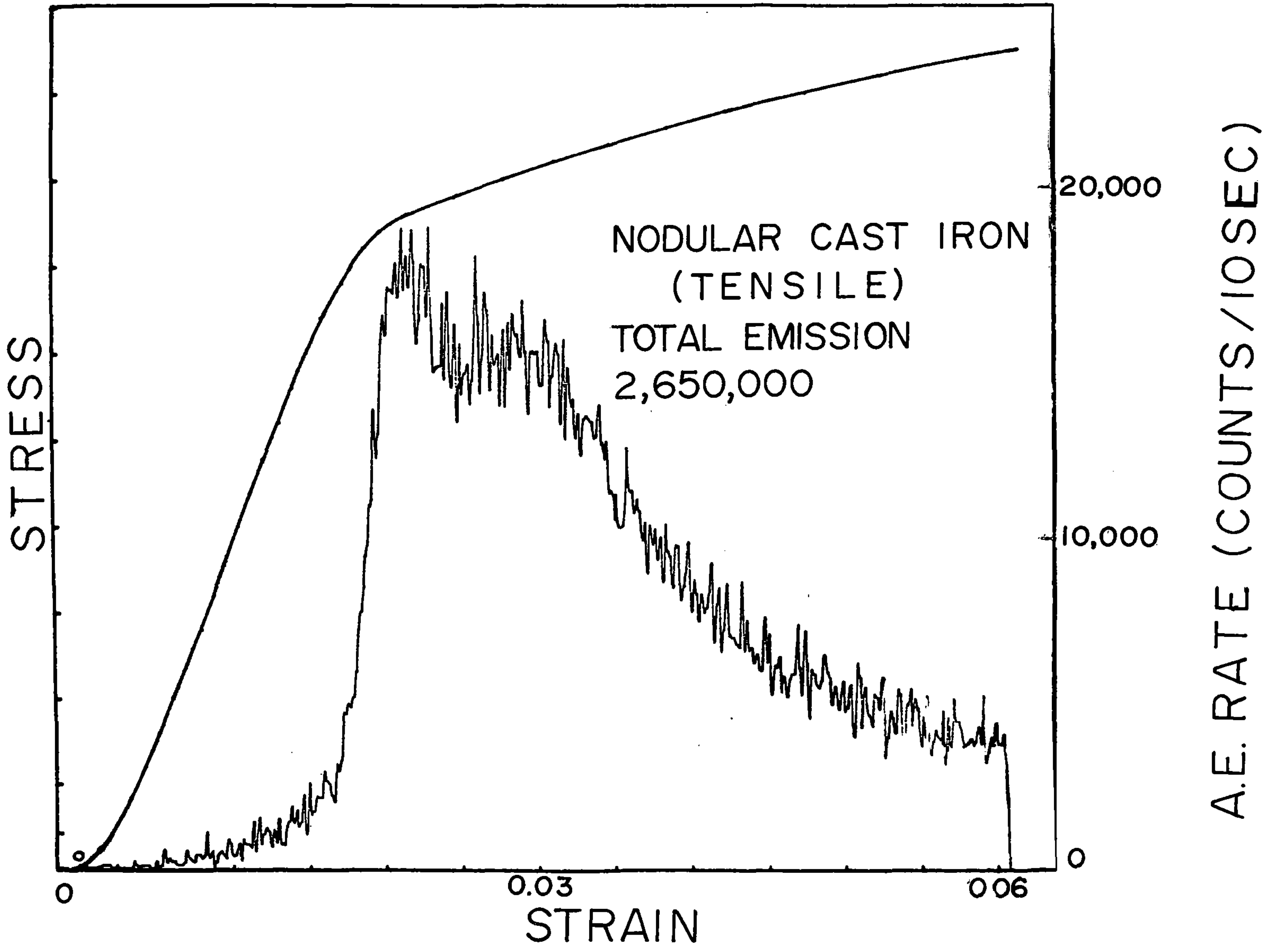

Fig. 4. Acoustic Emission Data from a Tensile Test of Nodular Cast Iron

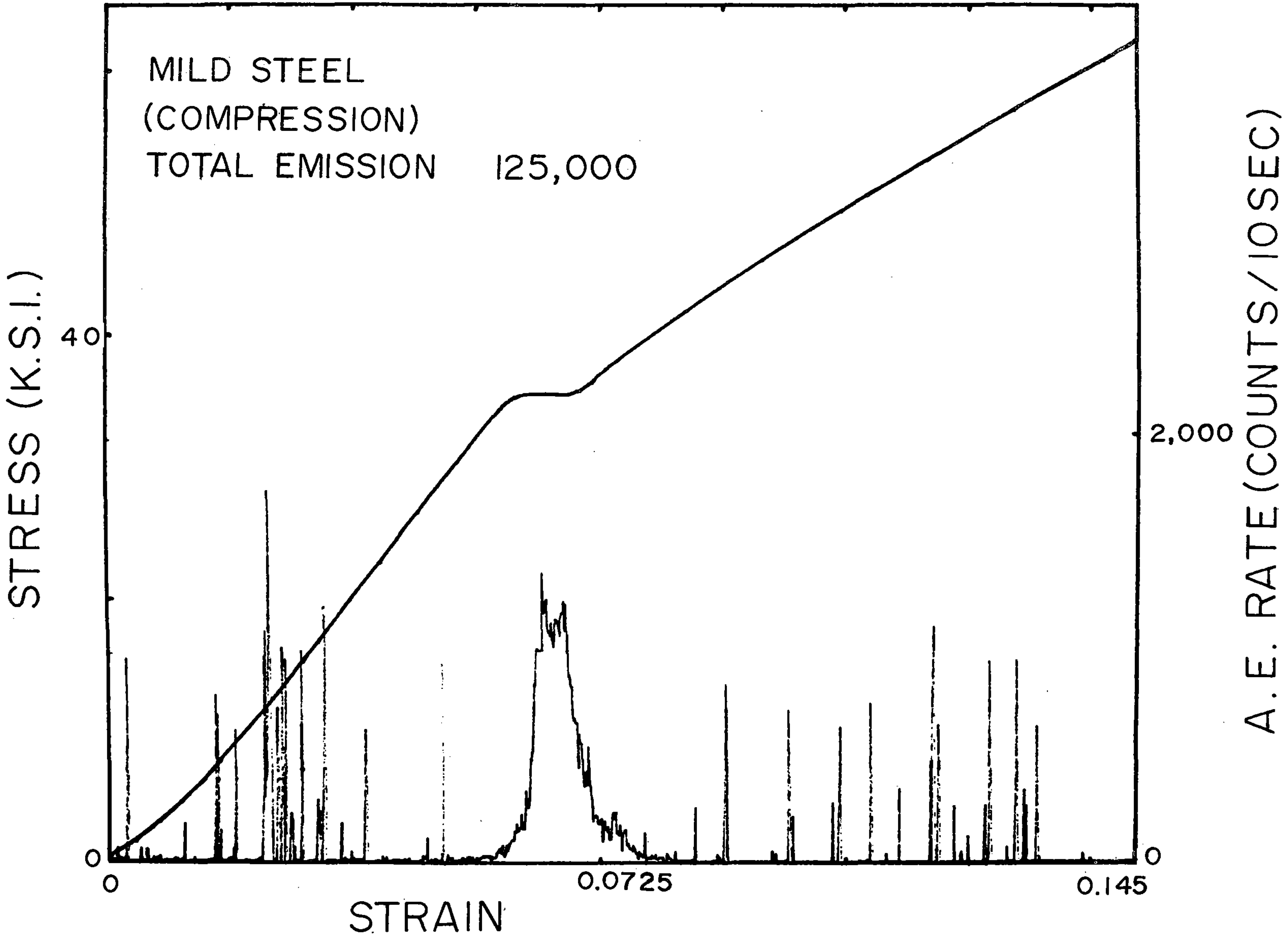

Fig. 5. Acoustic Emission Data from a Compression Test of Mild Steel

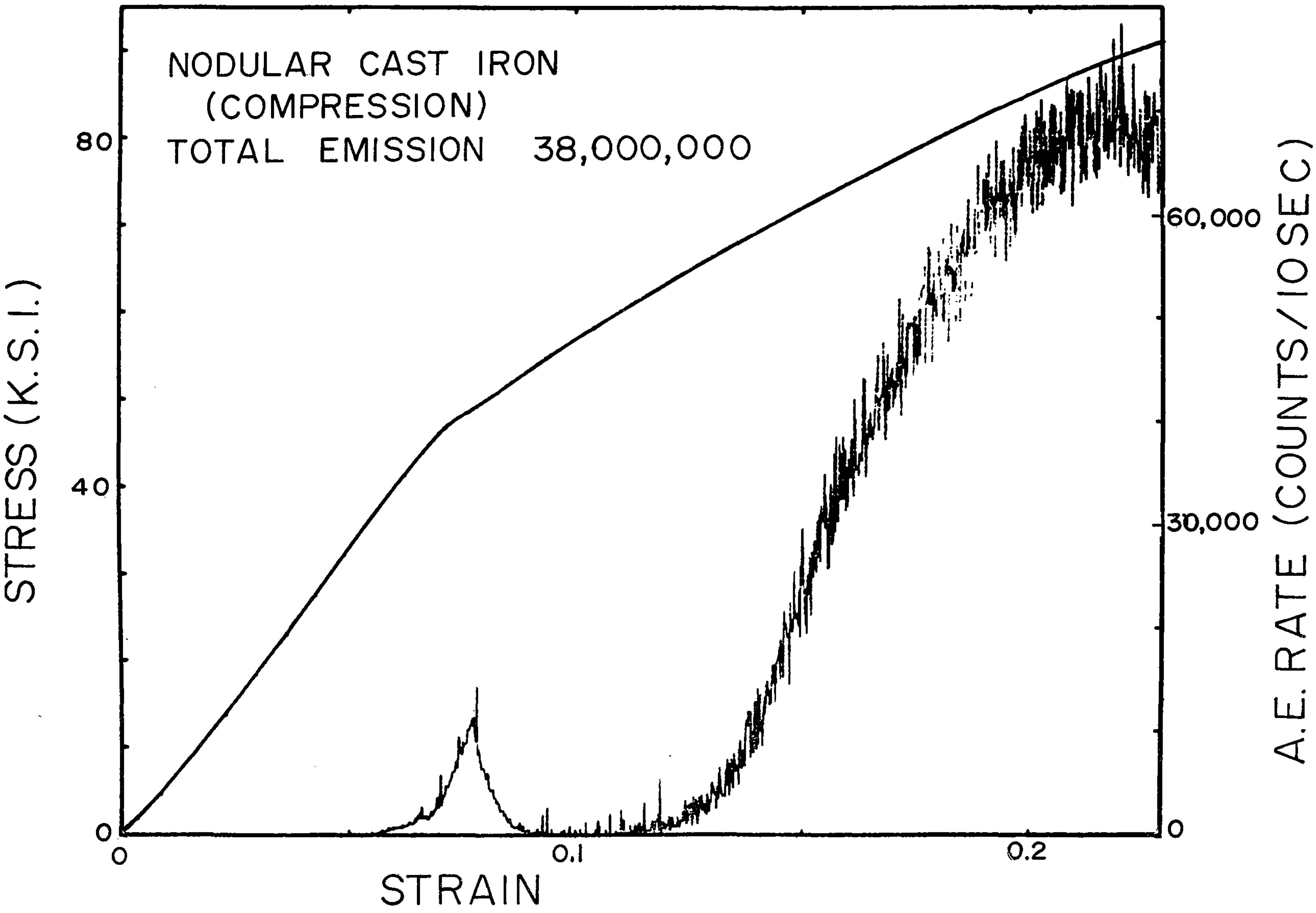

Fig. 6. Acoustic Emission Data from a Compression Test of Nodular Cast Iron

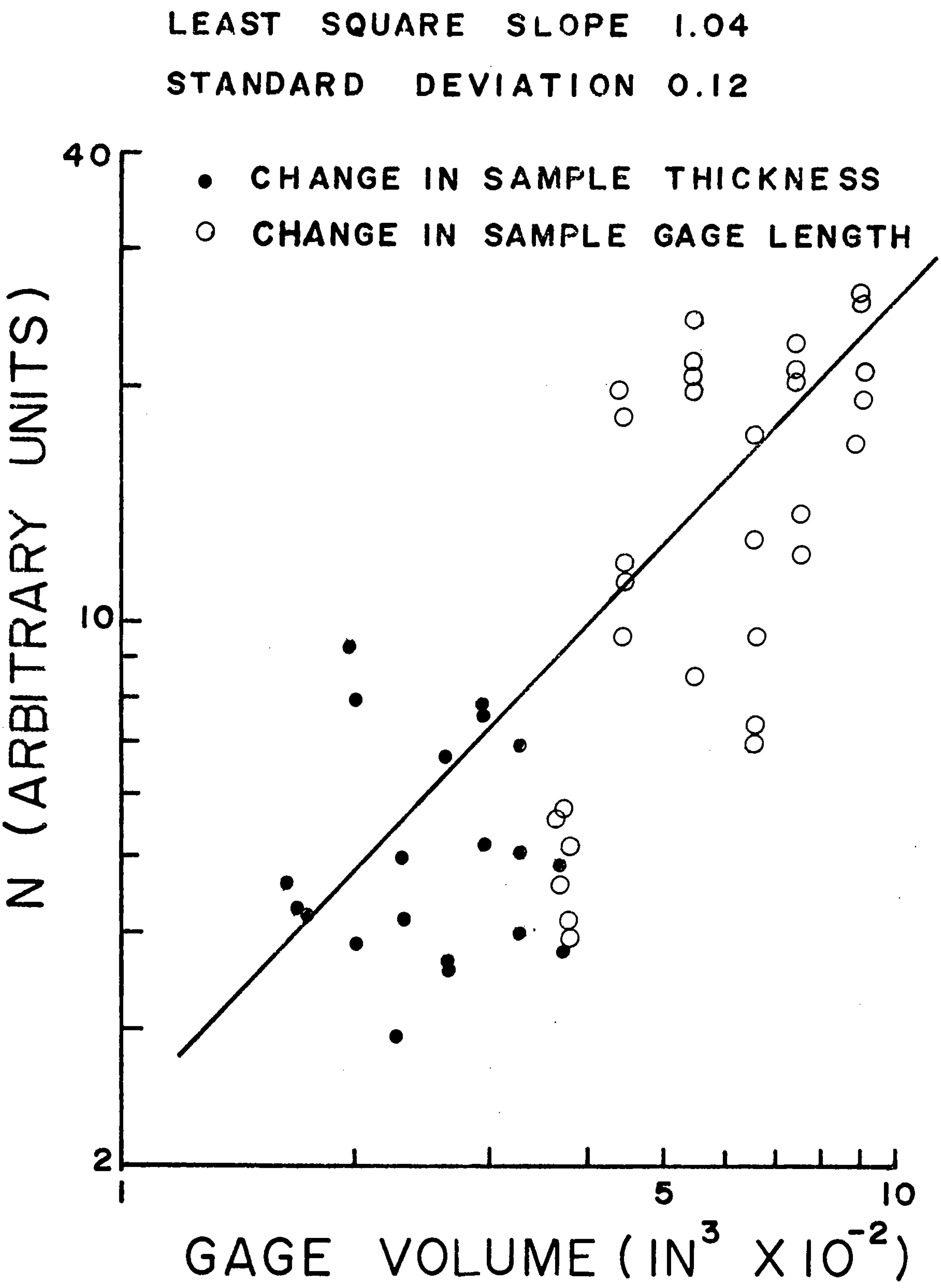

Fig. 7. Data showing the relationship between Total Acoustic Emission Counts and the Gauge Volume for the Aluminum Alloy 7075-T6.

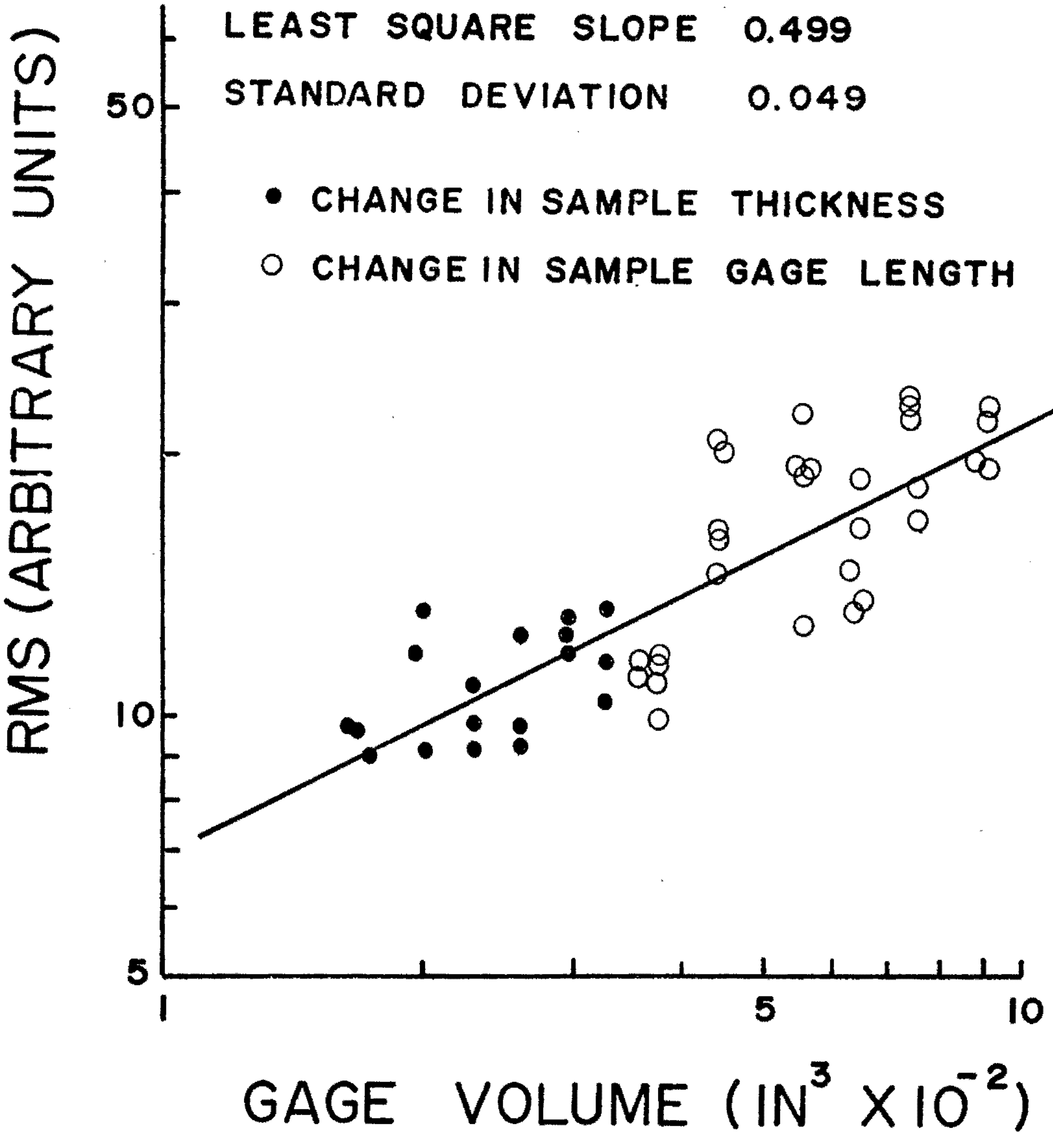

Fig. 8. Data showing the relationship between the RMS Value of the Acoustic Emission Amplitude and the Gauge Volume for the Aluminum Alloy 7075-T6.

amplitude were then plotted versus the sample gauge volume. The results shown in Fig. 7 and 8 show that the total number of counts is proportional to the gauge volume while the RMS amplitude is proportional to the square root of the gauge volume.

I've included these data to try to convince you that indeed we do know a good deal about the acoustic emission from 7075-T6 aluminum. Even so, as mentioned earlier, we still do not know the sources and mechanisms producing the emissions. Since all of the previous investigators, (again with the exception of Lloyd Graham at this meeting) have explained their data in terms of dislocation processes, a simultaneous measurement of the dislocation damping should provide helpful information in trying to identify the sources.

We are able to make these measurements using a system shown in Fig. 9. The sample is cut to three half wavelengths of a resonant frequency (usually between 40-80 KHz). Two piezoelectric quartz crystals are then placed on the sample as shown. The quartz crystals are cut to one half wavelength for the resonant frequency. An oscillating voltage of frequency equal to the resonant frequency is applied to one of the quartz crystals (driver crystal). This produces a standing wave in the sample. However, the enlarged portions of the sample are at nodes, hence one can grasp hold of the sample at these points and not disturb the standing wave. Making grips as shown it is possible to mechanically deform the sample. The second quartz crystal serves as a gauge. The voltage developed across it is directly proportional to the strain amplitude of the standing wave. The log decrement (a measure of the dislocation damping) is directly proportional to the ratio of the driver voltage to the gauge voltage.

It is instructive to compare the acoustic emission data from a tensile sample of 7075-T6 with the dislocation damping data for a similar test. Figure 10 shows the acoustic emission data. Notice that there is a considerable amount of emission (approximately seven million counts). Compare these data with the dislocation damping measured in 7075-T6 and shown in Fig. 11. The difference is quite astounding. There is essentially no damping in this material and no detectable change in the damping at yield. These data were obtained using a vibratory strain amplitude of 10^{-7}, however, increasing the strain amplitude to 1×10^{-4} (fracture strain of the quartz crystals) still produced no measurable damping. These damping results, although surprising, give very strong support to the conclusions of the previous paper by Lloyd Graham, where it is stated that the majority of acoustic emission generated in the alloy 7075-T6, when plastically deformed, is from the fracture of small intermetallic particles.

If this hypothesis is correct, compressive deformation of 7075-T6 should greatly reduce the amount of acoustic emission. Figure 12 shows the acoustic emission from a compression test. Indeed the amount of emission is less, 9,000 total counts compared to 6,700,000 total counts when tested in tension.

The measurement of dislocation damping as well as acoustic emission in fairly pure molybdenum, contrary to the results obtained in 7075-T6 aluminum,

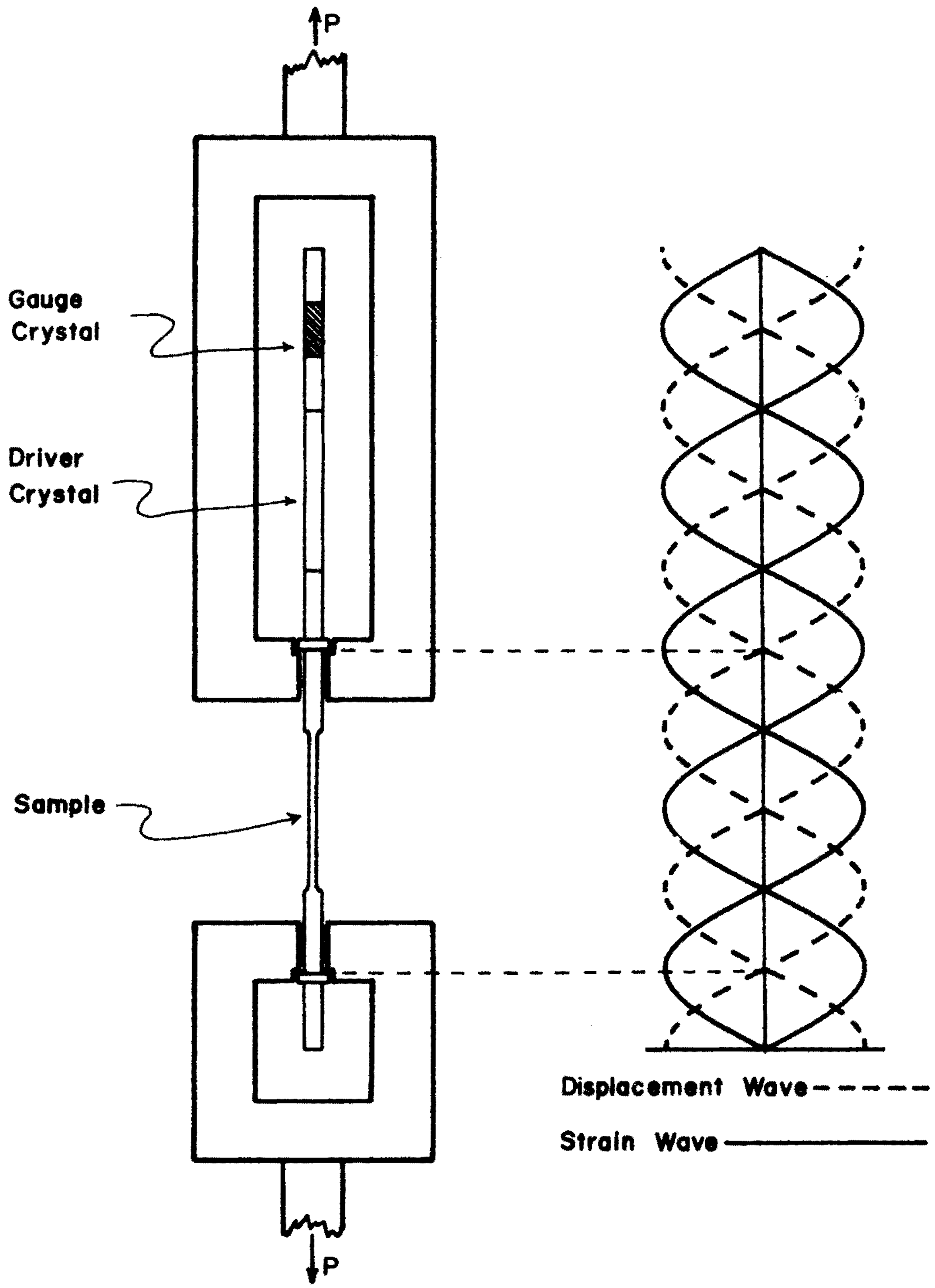

Fig. 9. Schematic of the Apparatus Used to Simultaneously Measure the Acoustic Emission and the Dislocation Damping.

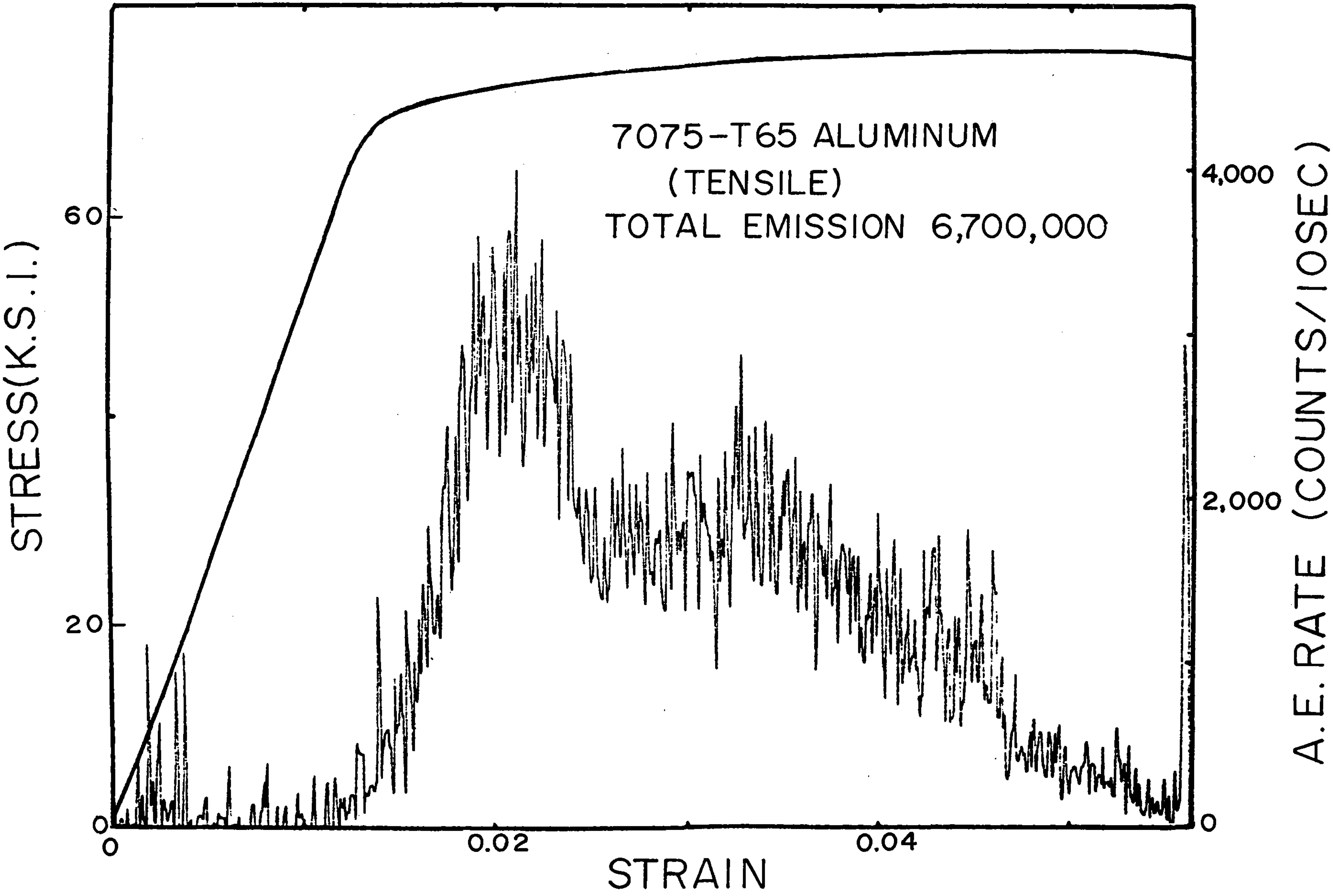

Fig. 10. Acoustic Emission Data from a Tensile Test of 7075-T6 Aluminum.

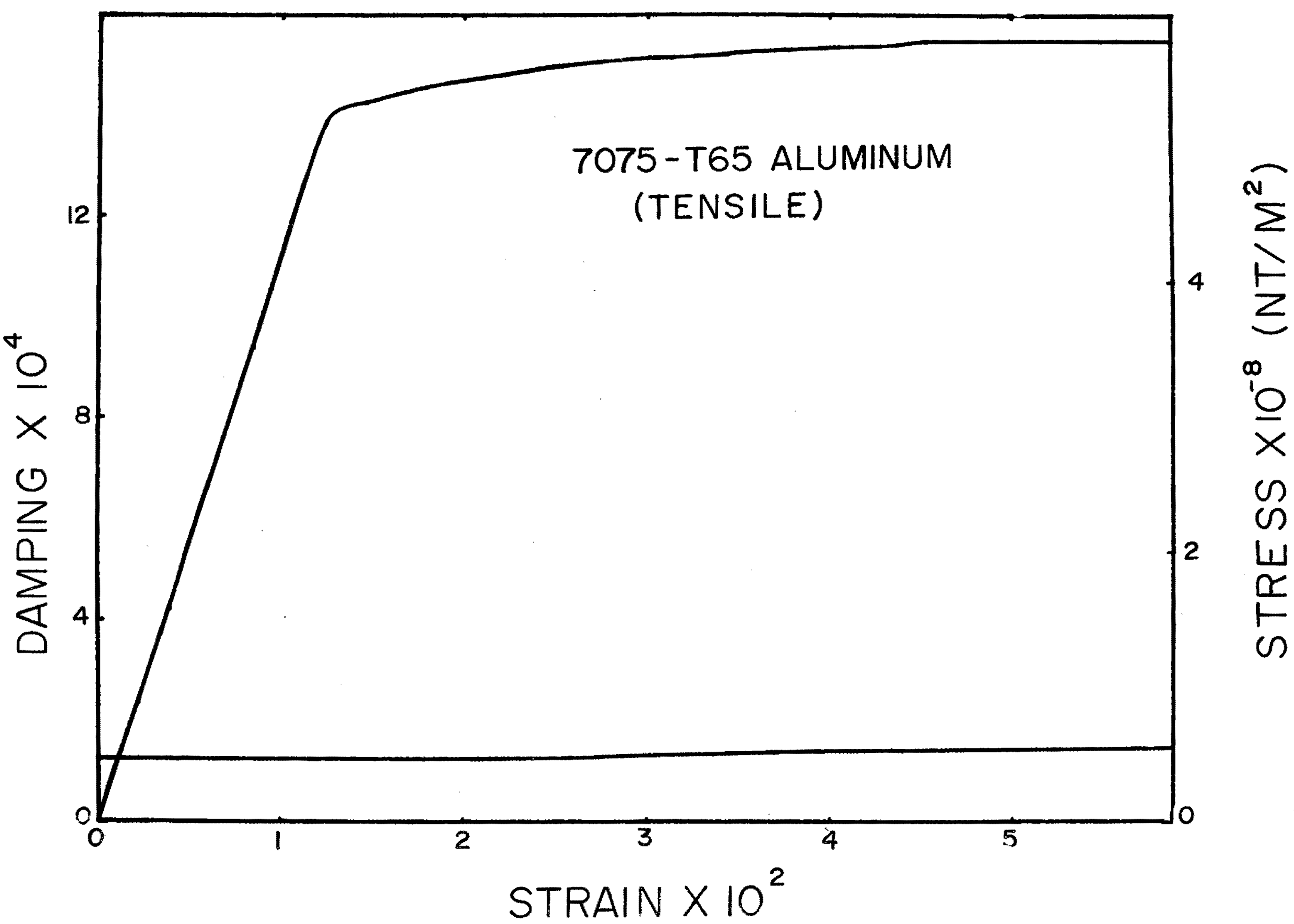

Fig. 11. Dislocation Damping Data from a Tensile Test of 7075-T6 Aluminum.

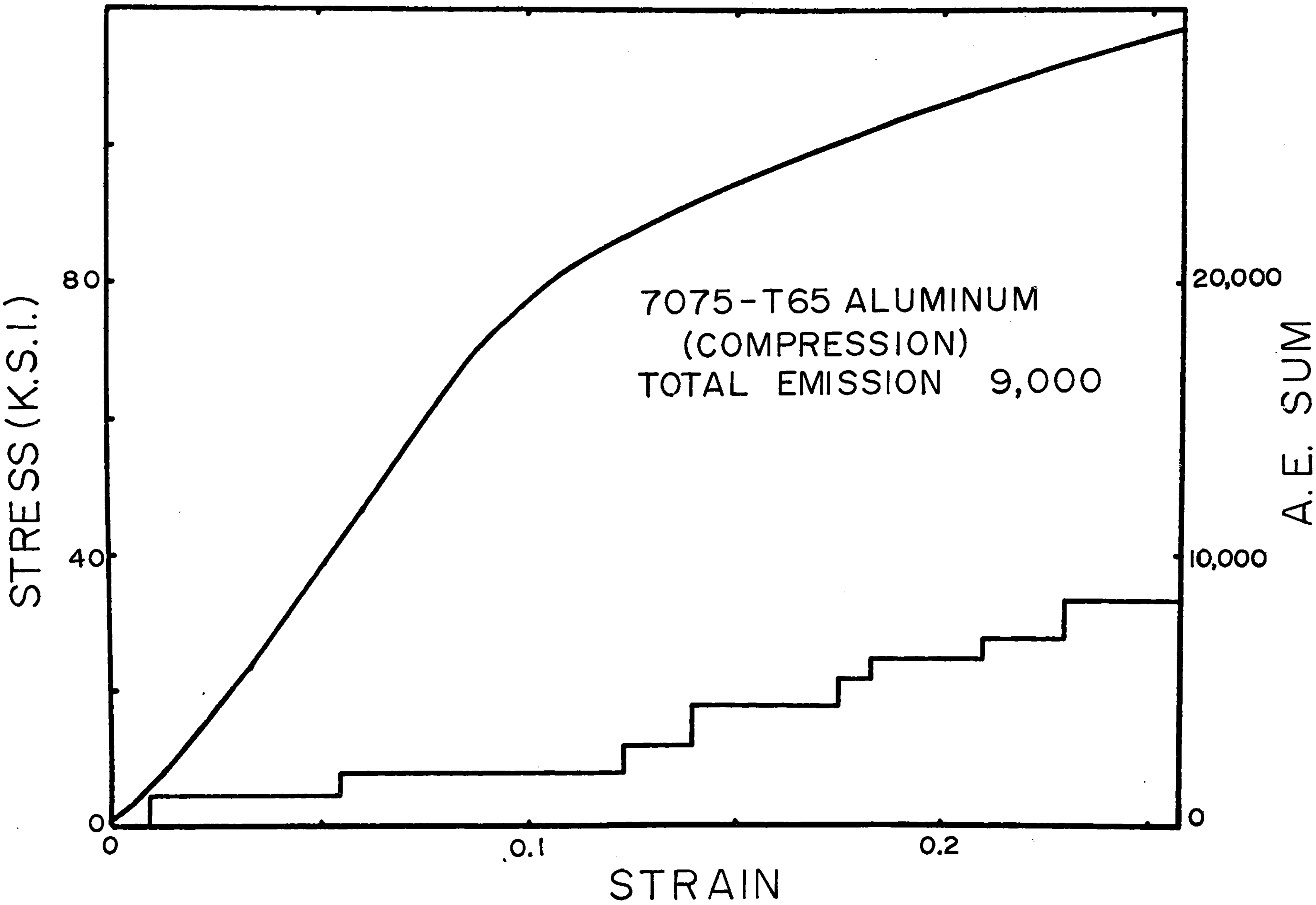

Fig. 12. Acoustic Emission Data from a Compression Test of 7075-T6 Aluminum.

indicates that the acoustic emission is indeed due to dislocation breakaway and/or multiplication. Figure 13 shows the data. Aside from the very beginning of the test, where some of the acoustic emission is from grip noise, the acoustic emission and the damping match very well; both show a large increase at yield and a linear increase with increasing strain. Compressional acoustic emission data shown in Fig. 14 are consistent with a dislocation mechanism as the source of emission. Notice there is a drastic increase at yield and then little emission as the material work hardens.

Hopefully, these examples of preliminary data have demonstrated that a considerable amount of valuable information can be derived from acoustic emission data if: 1) proper test procedures are carefully selected and 2) an additional sensitive experimental variable is measured in addition to the acoustic emission.

In closing, let me relate to you one very practical application involving acoustic emission. At the Lawrence Livermore Lab they have been looking at acoustic emission of 7075-T6 aluminum for sometime. They had secured several plates from different suppliers and were making comparison tests of acoustic emission as a qualification procedure. The RMS acoustic emission amplitude of one of these plates is shown in Fig. 15. While all of the other RMS amplitude curves were smooth, this one had the very large bursts shown in Fig. 15. Investigating the metallurgy and microstructure of that plate, they found large 40 to 60 μm chromium rich particles as shown in Fig. 16. These were due to poor heat treatment of the material, and that material was rejected. It could have been rejected simply on the basis of an acoustic emission evaluation.

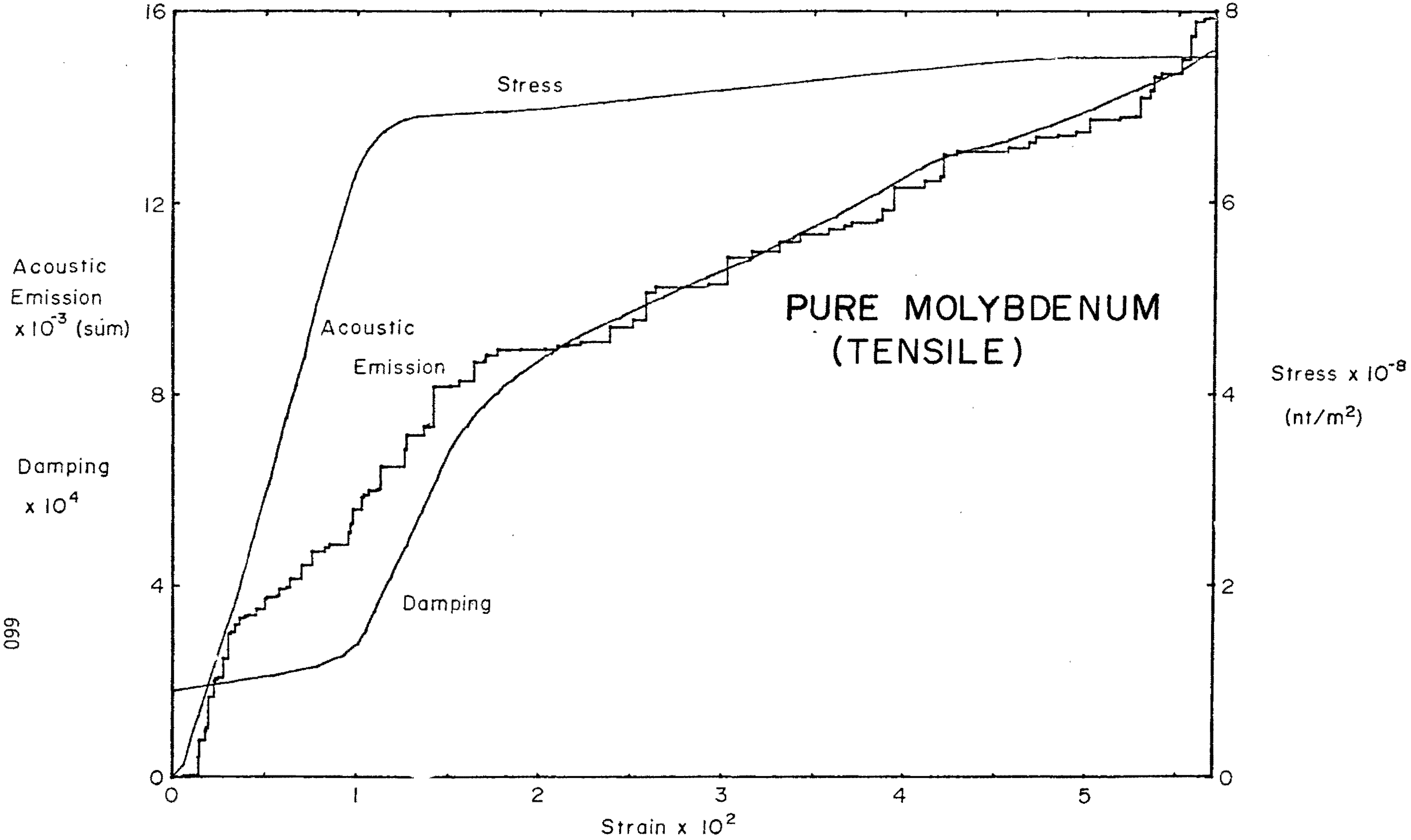

Fig. 13. Acoustic Emission and Dislocation Damping Data from a Tensile Test of Pure Molybdenum.

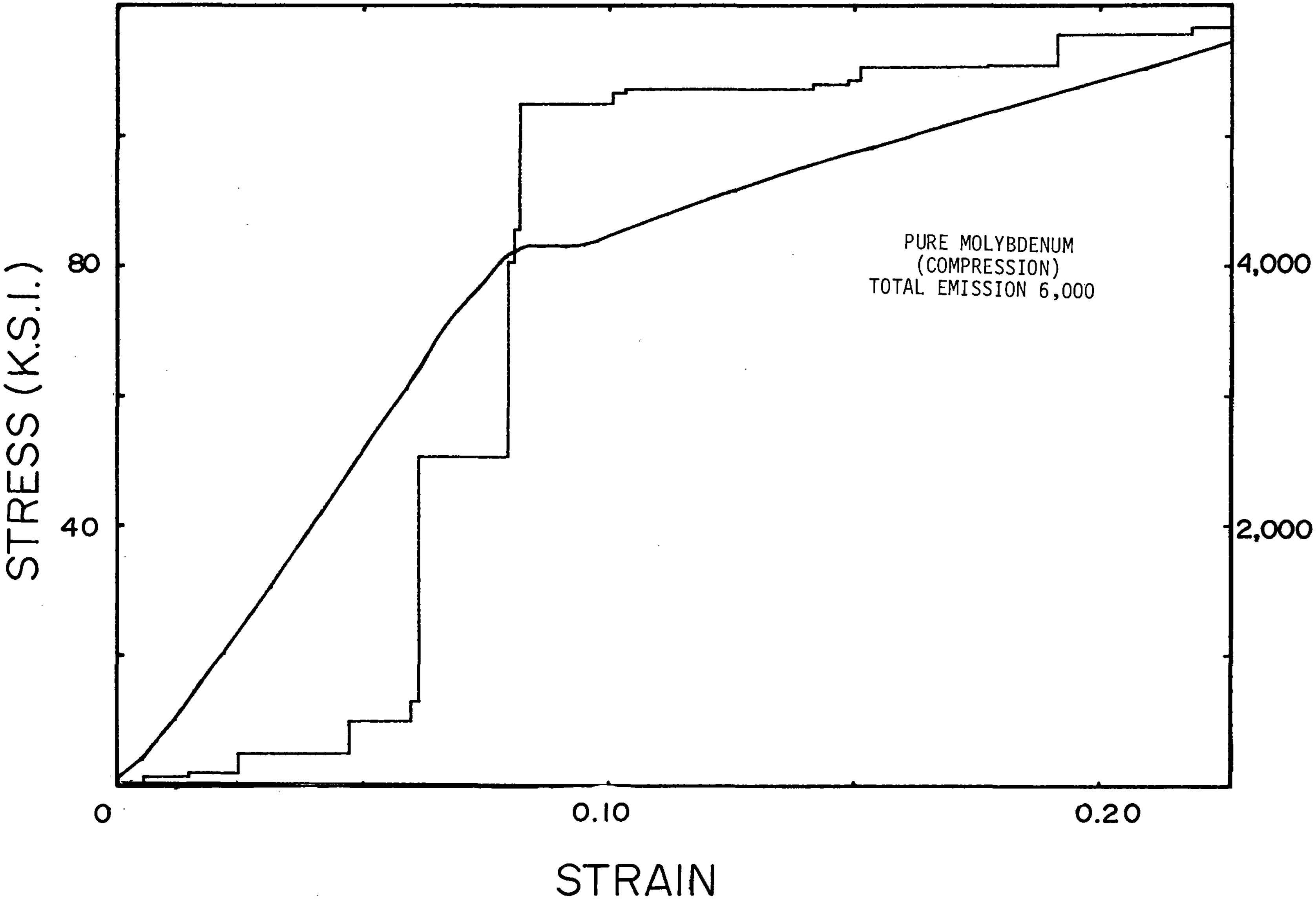

Fig. 14. Acoustic Emission Data from a Compression Test of Pure Molybdenum.

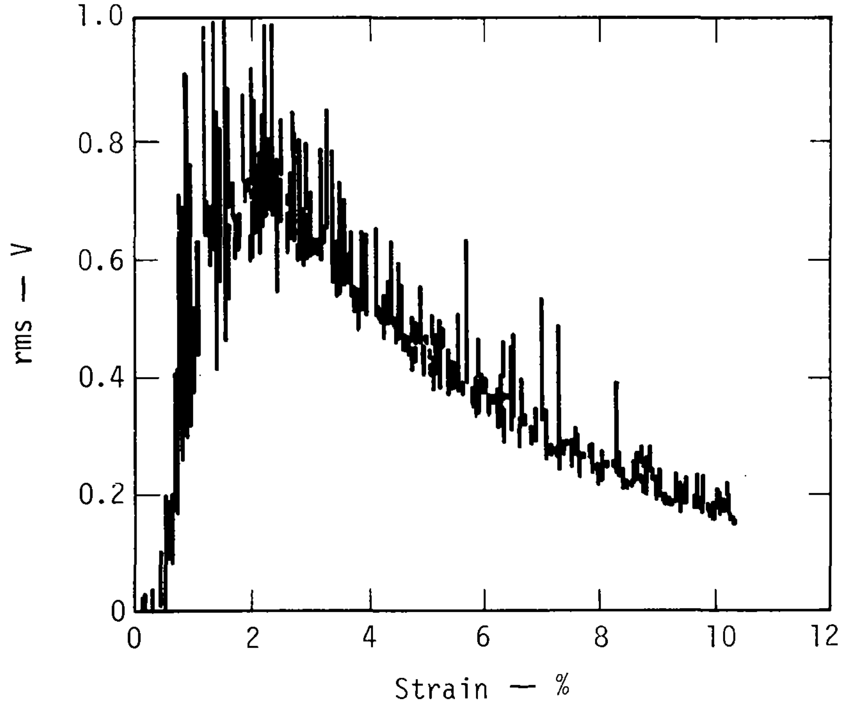

Fig. 15. RMS Acoustic Emission Data from a Tensile Test of 7075-T6 Aluminum.

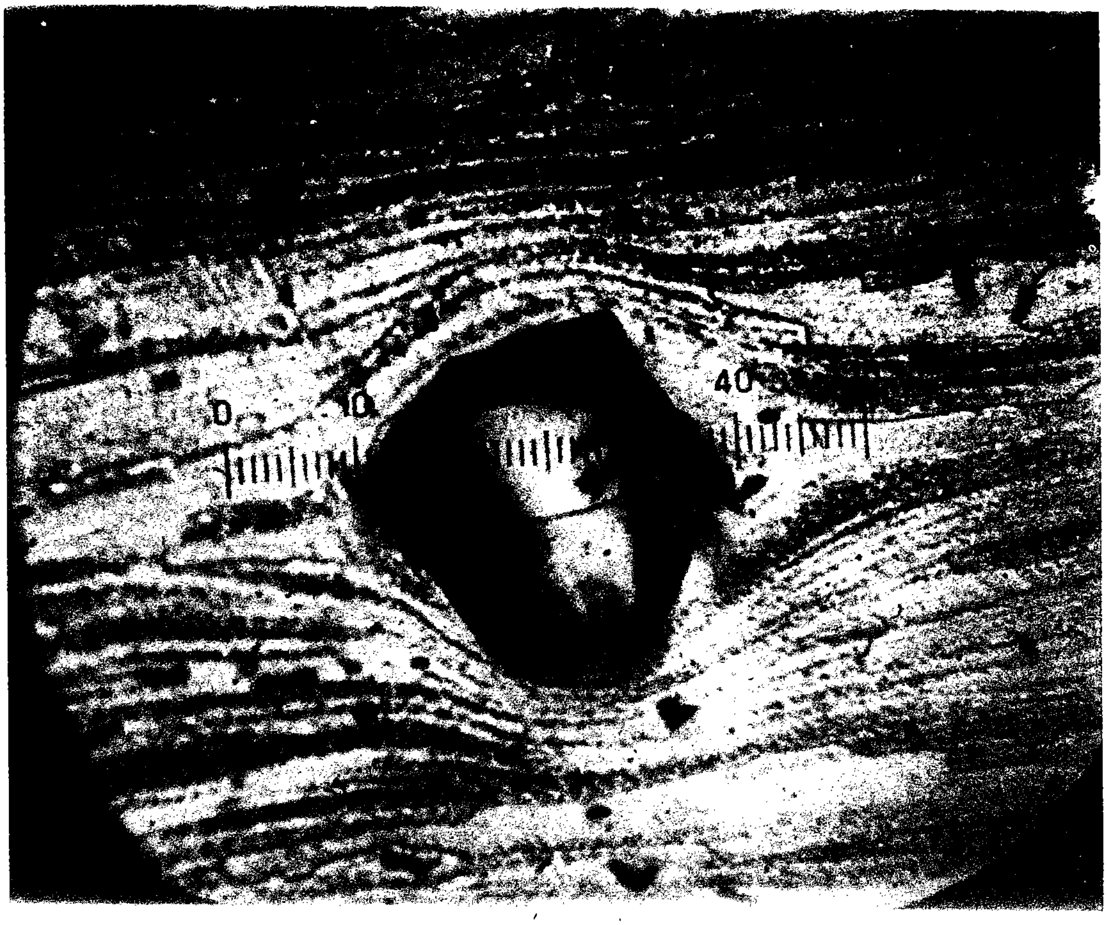

Fig. 16. Intermetallic Particles found in the Plate giving the Acoustic Emission shown in Fig. 15.

DISCUSSION

DR. TIEN: Thank you very much. Dr. Green?

DR. R. E. GREEN(Johns Hopkins University): I'd like to report some measurements that we made using ultrasonic pulse echo methods for measuring attenuation in the 1 to 10 MHz frequency range simultaneously with acoustic emission measurements also in tensile tests of some of the materials. Now, I always find a large amount of dislocation damping during the course of the whole stress strain curve. Quite conversely if I go to a high purity aluminum, and especially aluminum with single crystals, I find lots of dislocation damping but no acoustic emission that I can discern above the background level of my testing system. So, I suspect maybe the difference may be different frequencies or different strains or something, but I don't think that as a matter of general principle that plastic deformation of any aluminum alloy is independent of dislocation motion.

PROF. CARPENTER: I certainly agree and I don't mean to imply that there is no dislocation motion in all aluminum alloys. We've done some work on 6061, which I didn't report, which has different characteristics from the 7075, and it's clear that there is dislocation motion in this alloy. However, as nearly as we can tell in 7075-T6, and this is really a T-651, to the best of our ability we cannot measure any dislocation motion or damping in that material.

DR. GREEN: Steve, what's the highest frequency you can go to?

PROF. CARPENTER: Highest frequency? That's strictly determined by the quartz bars used. Our system will go to about 200 KHz, but if you go that high you can't get a very high strain amplitude.

MR. ALEX GARY (NASA-Lewis): Would not your observations and those of Mr. Graham depend on the band pass of the transducer? Typically acoustic emission from dislocation motions would be in the near gigahertz range while those from particle cracking might well be in the 100 MHz range, so that what you can actually see might just depend on your crack.

PROF. CARPENTER: Yes. What you say is true, but I should make my point clear, that when I'm talking about emissions from dislocations, I'm not talking about the resonance of the dislocation line. I'm talking about if I have a dislocation, for example, in molybdenum, that is pinned by interstitial carbon or oxygen or something along it, as it bows out and breaks away under stress, it will send out a pulse through the material. This is what we measure and it shouldn't be at the gigahertz range.

DR. TIEN: How do you know that?

PROF. CARPENTER: I would guess the best answer to that question would be in terms of the good correlation of our damping data and acoustic emission data. It is very well established that the changes in the damping are due to dislocation breakaway and/or multiplication and the increased length of the dislocation line. The good correlation of the acoustic emission with damping in molybdenum indicates that this also is the source of the acoustic emission. In fact, damping studies led us into this. We were studying dislocation breakaway and wanted to know if we could hear it. Since we were measuring in a 100-300 KHz window we wouldn't see it if it were in the gigahertz range.

DR. LARRY KESSLER (Sonoscan, Inc.): Your principal source was from intermetallic particles. Would you explain your intermetallic particles? Were they exclusively breaks between materials a and b, or were there also breaks between particles of the same kind of material?

PROF. CARPENTER: I really can't answer that because we haven't gotten into that. I think Lloyd could answer that much better than I. What we're pointing out is, particularly in the cast iron, that we can separate what we think is breakage within the graphite nodule itself from the deformation of the ferrite grain.

DR. HARRY SCHWARTZBACH (Rockwell International, Utility Products Group): Did you see that?

PROF. CARPENTER: No, not yet. The investigation is looking into that now.

DR. SCHWARTZBACH: You haven't seen it then?

PROF. CARPENTER: No, but then we haven't been on this program long.

DR. KESSLER: One further clarification. Can particles be considered grains, or not?

PROF. CARPENTER: You wouldn't think so, no.

DR. KESSLER: A particle would be larger than a grain?

PROF. CARPENTER: No, smaller. If you go back and look at the microstructure of the 7075-T6 you see the grains and I would guess the particles are on the order of, oh, a hundredth or less the size of a grain.