C00-2204-02
CONF-730810--2

ACOUSTIC EMISSION AND DISCONTINUOUS YIELDING

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fly

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

William F. Hartman, Assistant Professor
Department of Mechanics and Materials Science
The Johns Hopkins University
Charles & 34th Streets
Baltimore, Maryland 21218
Telephone: (301) 366-3300, ext. 1011

ACOUSTIC EMISSION AND DISCONTINUOUS YIELDING

William F. Hartman
Department of Mechanics and Materials Science
The Johns Hopkins University
Baltimore, Maryland 21218

Abstract

The discontinuous yielding during tensile loading of many crystalline solids results in a serrated or steplike stress-strain curve and is known as the Portevin-Le Chatelier effect. In this paper the replicable features of the discontinuous yielding of dead-weight loaded annealed specimens of aluminum and brass are documented and compared with the acoustic emission accompanying such deformations. It is shown that one method of acoustic-emission monitoring provides data which is consistent with the hypothesis that the elastic energy released during a yield increment is proportional to the elastic energy stored since the last yield increment. Another method of monitoring gives a better indication of the number of acoustical events occurring and permits assessment of the frequencies of the emissions.

It is concluded that a major portion of the acoustic emission during the strain-loading of crystalline materials is primarily associated with elastic-energy release during the propagation of nonhomogeneous deformation, which is the genesis of the Portevin-Le Chatelier effect during dead-weight loading.

Introduction

Studying the acoustic emissions from solids usually has one of the two following motivations: (1) a need for innovative monitors of the structural integrity of engineering materials, (2) the desire to complement basic-research studies of material phenomena with the new perspectives obtained through acoustic emission techniques. The first of these has received considerable attention in recent years and acoustic emission techniques are now used for flaw detection (1,2). The second has not yet progressed beyond a general, qualitative correlation of acoustic emission with other mechanical properties (1,3). Thus basic research on the physics of acoustic emission from solids under stress is lagging the application of acoustic emission techniques in materials testing.

There are many aspects of material behavior which can be associated with acoustic emission (1,3). We here report on a study of the acoustic emission associated with the very important material phenomena of discontinuous slip, which is known as the Portevin-Le Chatelier (PL) effect. As discussed below, strong quantitative correlation of acoustic emission with discontinuous slip has been found.

Previous Work

The phenomena of repeating discontinuous yielding of solids was discussed as early as 1841 by Masson (4). In 1923 Portevin and Le Chatelier (5), after whom the phenomenon is now named, observed repeated momentary decreases in the load of a hard tensile machine for deformations of aluminum-copper-magnesium alloys. They also noted that each oscillation of load corresponded to the appearance of lines which propagated along the specimen, accompanied by a clearly audible, small, dry sound. These lines were first reported by Luders

(6) in 1860, and are named after him.

The first systematic attempt to determine what factors influence the occurrence and behavior of the PL effect was by McReynolds (7). He established that alloy composition, temperature of test, and rate of deformation are factors which affect repeated yielding. A major part of his investigation was devoted to showing that deformation is inhomogeneous and propagates through the specimen in wave-like fashion.

McReynolds suggested that a mechanism for sustained discontinuous yielding was rapid precipitation hardening. A similar mechanism was proposed by Cottrell (8) in 1953. That "solute atom diffusion-vacancy hypothesis" has remained a persistent basis for subsequent studies. Although Cottrell's model and many of its refinements provide some physical basis for the effect, no one existing model is capable of explaining all the features of the PL effect in crystalline metals and alloys.

The delineation of regular features of discontinuous yielding is strongly dependent upon the type of testing, that is, whether controlled strain rate or controlled loading rate. Whereas jerky stress-strain curves can be obtained by elongation with a hard tensile testing machine, the discontinuous yielding during dead-weight loading exhibits very sharp, uniform steps. For constant rates of dead-weight loading, several general features of the PL effect have been established for annealed aluminum and brass (9,10,11,12,13). For both of these materials at room temperature the magnitude of the strain increments increases with increasing stress. For 70-30 brass the amplitude of the stress increment which precedes a strain increment increases with deformation. This is not true for aluminum; rather, the amplitude of the stress increment reaches a maximum value after about 2% deformation as shown in Fig. 1. Thereafter, the PL effect gradually disappears. Such behavior has fundamental signifi-

cance in understanding the strain-hardening process of this metal and its alloys.

Some frequently reported features of acoustic emission during plastic deformation of metals suggest a probable strong correlation with the PL effect. Figure 2 clearly shows that the emission is discontinuous. A discontinuous emission is also exhibited during crack growth. In fact, "...it is difficult to distinguish between the signals due to growth of the plastic zone and those due to small increments of crack extension. Both appear to grow in jumps and steps." (3) Therefore, it is important to characterize the discontinuous acoustic emission which results from discontinuous yielding.

A commonly used indicator of acoustic emission activity is the counts-per-second rate of the acoustic energy above a certain value impinging upon a piezoelectric transducer. Typical records are shown in Fig. 3. The similarity with the $\Delta\sigma$ vs. ϵ curve of Fig. 1 is obvious. Acoustic emission rates similar to those of Fig. 3 have been reported by Tatro (18) for aluminum and by Dunegan and Green (3) for mild steel.

The general similarity of acoustic emission rate and $\Delta\sigma$ behavior leads us to believe that a strong correlation can be obtained experimentally. There are several ways of possibly correlating the phenomena. One is that the acoustic emission can be associated with the mobile dislocation density. This was first offered as a possible model by Schofield (16) and has been recently examined by James and Carpenter (17) and found inadequate. They propose break-away of dislocations from pinning points; a model frequently used in relation to the PL effect. Another perspective, independent of any direct accounting of dislocations, assumes that the elastic energy released during a strain increment is proportional to the elastic energy stored during the preceding

stress increment. Then, when $\Delta\sigma^2$ is maximum, the released energy would be maximum and would cause stress waves of sufficient amplitude to sustain ringing of the transducer as well as to cause counting of multiple reflected pulses. Since most acoustic-emission transducers operate at resonance, increased count rate can result from simply greater amplitudes, rather than increased emission activity.

Although we will here discuss only experiments with aluminum and brass, it should be pointed out that the PL phenomenon occurs in many metals and alloys. The upper yield point phenomenon in mild steel is observed during dead-weight loadings to repeat as discontinuous yielding. This was originally reported in 1909 by Le Chatelier (17) and has been studied more recently by Wilson (20). Repeated discontinuous yielding has been studied in aluminum (7,9,10,11,21,22,23), nickel (23,24,25), copper (23), zinc (26,27), and alloys of copper-zinc (7,12,13), aluminum-magnesium (28,29), aluminum-copper (7), nickel-cobalt (30), and others (31).

Experimental Procedure

A special testing machine was constructed for the purpose of quietly applying dead-weight loads to 6-inch long tensile specimens. This machine includes specially designed specimen grips which permit the application of piezoelectric transducers to the polished ends of the specimen. These grips and a portion of the machine are shown in Fig. 4. All loads for the tests described here consisted of applying dead-weight increments to the end of a mechanical lever. The specimens were machined from 1/2-inch diameter rods to a finished thickness of 1/4 inch. Aluminum specimens were annealed at 1100°F. for two hours and allowed to furnace-cool. The brass specimens were similarly annealed at 1250°F.

Two types of transducers were employed in these tests. The first type is a standard acoustic-emission transducer having a resonant frequency of 100 KHz. This type of transducer is very sensitive to the amplitude of fast-rising pulses, in that it will begin oscillating at its resonant frequency and the ringing down takes place in a considerable time interval, resulting in a correlation between the number of cycles above a given voltage with the amplitude of the incident pulse. The second type of transducer is wide-band and heavily damped, having a center frequency of 1 MHz. Since this transducer will not ring when excited, the number of cycles above a given voltage is more indicative of the number of pulses incident upon the transducer and, in fact, good fidelity is achieved. Both types of transducer were purchased from Panametrics.

The signals from the transducers are amplified by Tektronix 1A7A amplifiers and displayed on a Tektronix 556 oscilloscope. The outputs from the amplifiers are high-pass filtered and their excursions above a threshold amplitude are electronically counted.

Most tests are performed with considerable patience. A load increment of value 0.10 Kg/mm^2 is applied and any resulting strain or acoustic emission is recorded. No additional load increment is applied until both straining and acoustic emission have ceased for at least two minutes. With such deliberate monitoring the basic features of both discontinuous yielding and acoustic emission are dramatically delineated.

Results and Discussion

Some results of a typical aluminum test are shown in Fig. 5. The loading began one week after annealing. The acoustic emission, which is plotted as the number of counts above an arbitrary threshold, is prominent for the

region of deformation exhibiting the PL effect. In that region the increment of stress sufficient to induce the next strain increment follows the pattern of Fig. 1. Likewise, the acoustic emission occurs similarly to that portrayed in Fig. 5. The few emissions which occur at larger values of stress are not accompanied by noticeable discontinuous yielding. This behavior, or slight variations of it, has been observed in all of the aluminum tests. The emissions at larger strains suggests metallurgical or mechanical transitions are possibly occurring there. This aspect of the acoustic emission is discussed elsewhere (32). The point to be made here is that the acoustical activity persists only where the deformation is discontinuous. By testing an aluminum specimen within a day or two after annealing, the region of the distinct PL effect is extended and so also that of the acoustic emission.

Since the PL effect is very dramatic in brass, many tests have been conducted with both α -brass and leaded, yellow brass. Since, during these tests, the load is not increased until straining and acoustic emissions cease, the resulting strain histories are very interesting. Figure 6 shows a typical strain history for a test which required 11 hours of monitoring. During a strain increment the average rate of straining is approximately $7 \times 10^{-6} \text{ sec}^{-1}$, until a strain of value .018 is achieved, then it decreases to $1.3 \times 10^{-6} \text{ sec}^{-1}$. Following a strain of .045 the straining rate remains fairly constant, averaging about 10^{-4} sec^{-1} . The acoustic emission also changes following this last strain (see Fig. 7). All the values of strain and strain rate pertain to those measured over the 15 cm gage length.

In order to indicate the degree of reproducibility in these tests,

three identical tests, using the wide-band transducers, are shown in Fig. 7 along with Test 7206 which used the standard resonant transducer.

It is obvious that the wide-band transducer gives more indications of acoustic activity between yield increments, while the resonant transducer responds primarily during the yield increment. This means that the output of the former correlates with the number of events or stress waves while that of the latter is more indicative of the amplitude or energy of these events.

If we assume that the energy which is released as ultrasonic waves during each PL step is associated with the total elastic energy stored in the specimen, then, since that energy is monotonically increasing with load, so also should the acoustic emission. But this is not the case. Normally a small or large acoustic emission follows a correspondingly small or large stress increment which precedes a yield increment. Therefore, let's consider the elastic energy stored since the last strain increment. If σ_0 is the stress at which the last strain increment occurred and if $\Delta\sigma$ is the increase necessary to produce the next unit of plastic deformation, then the elastic energy, ΔW , stored between these strainings is:

$$\Delta W = \left(\sigma_0 + \frac{\Delta\sigma}{2} \right) \frac{\Delta\sigma}{E} \quad (1)$$

where E is Young's modulus. If σ_0 is considered large in comparison with $\Delta\sigma$ (this is true for the brass tests since the initial yield stress is appreciable), then eqn. (1) can be approximated as

$$\Delta W \approx \frac{\sigma_0 \Delta\sigma}{E} \approx \frac{\Delta(\sigma^2)}{2E} \quad (2)$$

Figure 8 shows two brass tests for which the acoustic emission, ΔC , is very similar to the changes in $\Delta \sigma^2$. In order to facilitate visual comparisons, the curves were fabricated by connecting the discrete data points. The agreement should be greater in 7206 since in this test the acoustic emission was monitored with a resonant transducer. Test 7217 of that same figure also shows the effect of allowing the specimen to remain dormant under load overnight. When loading is resumed after such an interruption, a large stress increment is required to produce the first straining which is accompanied by a correspondingly large amount of acoustic emission. Such behavior is indicative of very slow diffusion processes which modify the yield criteria following plastic deformation.

The different responses of the two types of transducers can be seen from the examples of the acoustic signals shown in Fig. 9. All of these signals are displayed with a vertical sensitivity of 50 microvolts per division. The signals shown in (a) are from a resonant transducer. The frequency of the displayed signal is approximately the same as the resonant frequency of the transducer, and persistent ringing is evident. Each of the two signals in (b), (c) and (d) are simultaneous displays of the amplified outputs from wide-band transducers placed at the end of the specimen. These signals are not ringing. In fact, even in the case of large background noise ^(b)~~(a)~~, single pulses can be easily detected. The time separation of the signals at the two ends of the specimen, such as in (c), delineates the wave-propagation feature of the emission. Since the time difference is less than the time for a wave to travel the gage length of the specimen, we are assured that the emission originated within the deforming region of the specimen.

Closure

Previous studies of the acoustic emission from deforming metals have led investigators to confirm that plastic deformation is discontinuous (3,33). It is also nonuniform; both on the microscopic and the macroscopic levels. Intermittent localized slip band formation has been clearly documented by Pond and Harrison (34). They show that individual slip lines in the early stages of single crystal deformation can be separated by as much as 30 microns and that when a slip line forms the amount of slip is not equivalent to several Burger's vectors but several hundred, even several thousand Burger's vectors. As straining progresses, the lines become regularly spaced at closer intervals, thus local uniform but nonhomogeneous deformation is eventually obtained on a microscopic level. Similar observations, using electron microscopy, have been reported by Fourie (35). On the macroscopic level the deformation propagates from local slipped areas across the specimen, achieving momentary uniformity until the initiation of more slip bands. The manifestation of this behavior in a deforming polycrystal is the delineation of propagating slip bands, Luder's lines, on the surface of the specimen. Again such behavior, especially the features of slowly propagating deformation, can be most vividly observed in face-centered cubic metals and alloys undergoing dead-weight extension. It is clear then that the PL effect is intimately associated with the basic work-hardening mechanisms of crystalline materials.

We have shown that, during discontinuous yielding, the energy of the acoustic emission correlates qualitatively with the elastic energy stored since the last strain increment. The basic sources of acoustic emission

in crystalline solids are considered to be various dislocation mechanisms (36). The correlation of the acoustic emission with an incremental elastic energy makes it appropriate to examine the mechanisms which are potentially consistent with this observation. On a continuum scale, the incremental elastic energy can be associated with the local yield criteria. Future considerations, from both of these perspectives, of the acoustic-emission phenomena, should result in a clearer understanding of plastic deformation and work-hardening of crystalline solids.

Acknowledgments

The assistance of Mr. Ronald A. Kline, graduate student, is sincerely appreciated. The support of this work by the United States Atomic Energy Commission is gratefully acknowledged. AEC Report Number C00-2204-2.

BIBLIOGRAPHY

1. Liptai, R. G., Harris, D. O., Engle, R. B., and Tatro, C. A., "Acoustic Emission Techniques in Materials Research," Proceedings of Symposium on Advanced Experimental Techniques in the Mechanics of Materials, San Antonio, Texas, 1970.
2. Hutton, P. H. and Parry, D. L., "Assessment of Structural Integrity by Acoustic Emission," Materials Research and Standards, Vol. 11, 1971, pp. 25-32.
3. Dunegan, H. C. and Green, A. T., "Factors Affecting Acoustic Emission Response from Materials," Materials Research and Standards, Vol. 11, 1971, pp. 21-24.
4. Masson, A., "Sur l'Elasticite des Corps Solides," Annales de Chimie et de Physique, Ser. 3, Vol. 3, 1841, p. 451.
5. Portevin, A. and Le Chatelier, M. A., "Sur un Phenomene Observe lors de l'Essai de Traction d'Alliages en Cours de Transformation," Comptes Rendus, Vol. 176, 1923, pp. 507-510.
6. Lüders, W., "Über die Äusserung der Elasticität an Stahlartigen Eisenstäben und Stahlstäben, und über eine beim Biegen solcher Stäbe beobachtete Molecularbewegung," Dingler's Polytechnisches Journal, 4th series, Vol. 5, 1860, pp. 18-22.
7. McReynolds, A. W., "Plastic Deformation Waves in Aluminum," Transactions of the American Institute of Mining and Metallurgical Engineers, Vol. 185, 1949, p. 232.
8. Cottrell, A. H., "A Note on the Portevin-Le Chatelier Effect," Philosophical Magazine, Vol. 44, 1953, p. 829.
9. Sharpe, W. N., Jr., "The Portevin-Le Chatelier Effect in Aluminum Single Crystals and Polycrystals," Ph.D. dissertation, Baltimore: The Johns

- Hopkins University, 1966.
10. Sharpe, W. N., Jr., "The Portevin-Le Chatelier Effect in Aluminum Single Crystals and Polycrystals," *Journal of the Mechanics and Physics of Solids*, Vol. 14, 1966, p. 187.
 11. Bell, J. F., The Physics of Large Deformation of Crystalline Solids, Springer Tracts in Natural Philosophy, Vol. 14, Springer-Verlag, New York, 1968,
 12. Hartman, W. F., "The Applicability of the Generalized Parabolic Deformation Law to a Binary Alloy," Ph.D. dissertation, Baltimore: The Johns Hopkins University, 1967.
 13. Hartman, W. F., "Generalized Parabolic Work-Hardening during Tensile Deformation of Brass," *Journal of Materials*, Vol. 4, 1969, p. 104.
 14. Tetelman, A. S., "Acoustic Emission Testing and Microfracture Processes," *Materials Research and Standards*, Vol. 11, 1971, p. 13.
 15. Engle, R. B. and Dunegan, H. C., "Acoustic Emission: Stress Wave Detection as a Tool for Nondestructive Testing and Material Evolution," *International Journal for Nondestructive Testing*, Vol. 1, 1969, pp. 109-125.
 16. Schofield, B. H., "Acoustic Emission under Applied Stress," U.S. Air Force Report, Wright Patterson, OAR, ARL, R-150, 1961.
 17. James, D. R. and Carpenter, S. H., "Relationship between Acoustic Emission and Dislocation Kinetics in Crystalline Solids," *Journal of Applied Physics*, Vol. 42, No. 12, 1971, pp. 4685-4697.
 18. Tatro, C. A., "Experimental Considerations for Acoustic Emission Testing," *Materials Research and Standards*, Vol. 11, 1971, p. 17.
 19. Le Chatelier, M. A., *Revue de Metallurgie*, Vol. 6, 1909, p. 914.

20. Wilson, D. V., "Grain Size Dependence of Discontinuous Yielding in Strain-Aged Steels," *Acta Metallurgica*, Vol. 16, 1968, p. 743.
21. Dillon, O. W., Jr., "Experimental Data on Aluminum as a Mechanically Unstable Solid," *Journal of the Mechanics and Physics of Solids*, Vol. 11, 1963, p. 289.
22. Bodner, S. R. and Rosen, A., "Discontinuous Yielding of Commercially-Pure Aluminum," *Journal of the Mechanics and Physics of Solids*, Vol. 15, 1967, p. 63.
23. Appleton, A. S. and Waddington, J. S., "Some Observations of Discontinuous Yielding Phenomena in Copper, Nickel and Aluminum after Shock Loading," *Philosophical Magazine*, Vol. 12, 1965, p. 273.
24. Wilcox, B. A. and Smith, G. C., "The Portevin-Le Chatelier Effect in Hydrogen-Charged Nickel," *Acta Metallurgica*, Vol. 12, 1964, p. 371.
25. Blakemore, J. S., "The Portevin-Le Chatelier Effect in Hydrogenated Nickel," *Metallurgical Transactions*, Vol. 1, 1970, p. 145.
26. Rosenhain, W. and S. L. Archbutt, "On the Alloys of Aluminum and Zinc," *Proceedings of the Institution of Mechanical Engineers*, 1912, p. 333.
27. Bullen, F. P., "Discontinuous Yielding in Zinc Single Crystals," *Philosophical Magazine*, Vol. 7, 1962, p. 133.
28. Brindley, B. J. and Worthington, P. J., "Serrated Yielding in Aluminum-3% Magnesium," *Acta Metallurgica*, Vol. 17, 1969, p. 1357.
29. Thomas, A. T., "The Tensile Deformation Behavior of an Aluminum-Magnesium Alloy," *Acta Metallurgica*, Vol. 14, 1966, p. 1363.
30. Blakemore, J. S., "The Portevin-Le Chatelier Effect in Hydrogenated Nickel Alloys," *Metallurgical Transactions*, Vol. 1, 1970, pp. 151-156.
31. Worthington, P. J. and Brindley, B. J., "Serrated Yielding in Substitutional Alloys," *Philosophical Magazine*, Vol. 19, 1969, p. 1175.

32. Hartman, W. F., "Towards Correlating Acoustic Emission with Strain-Hardening Transitions," submitted for publication.
33. Fisher, R. M. and Lally, J. S., "Microplasticity Detected by an Acoustic Technique," Canadian Journal of Physics, Vol. 45, 1967, p. 1147.
34. Pond, R. B. and Harrison, E., "Slip Velocities in Several Metals as Measured by Interferometric Cinemicrography," AFOSR Report No. TR58-96, Baltimore: The Johns Hopkins University, 1958.
35. Fourie, J. T., "The Life History of Individual Slip Lines During the Plastic Deformation of α -Brass Single Crystals," Acta Metallurgica, Vol. 8, 1960, pp. 88-96.
36. Gillis, P. P., "Dislocation Mechanisms as Possible Sources of Acoustic Emission," Materials Research and Standards, Vol. 11, 1971, pp. 11-13.

List of Captions

- Fig. 1 Averaged Data from 4 Aluminum Tests (Ref. 9)
- Fig. 2 Acoustic Emission during Tension Testing of Steel at 321°C. (Ref. 14)
- Fig. 3 Stress and Acoustic-Emission Rate for 7075-T6 Aluminum (above) and Beryllium (Ref. 15)
- Fig. 4 Specimen and Tension Grips
- Fig. 5 Strain and Acoustic Emission for Dead-Weight Extension of Aluminum
- Fig. 6 A Typical History of Strain for a Brass Test
- Fig. 7 Strain (bold line) and Acoustic Emission Plotted Against the Applied Stress
- Fig. 8 The Acoustic Emission (ΔC) is Similar to the Increment of the Squared Stress ($\Delta \sigma^2$)
- Fig. 9 Examples of the Acoustic Signals During Dead-Weight Extensions of Brass

Figure 1

Figure 2

figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Test 7206

Figure 8

a. $10\mu\text{s}/\text{div.}$

b. $20\mu\text{s}/\text{div.}$

c. $20\mu\text{s}/\text{div.}$

d. $20\mu\text{s}/\text{div.}$

Figure 9