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Correlation of Mechanical and Metallurgical
Parameters with the Acoustic Emission during
Tensile Deformation of Several Metals and Alloys

Final Report

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Abstract

Acoustic emission was monitored during plastic deformation under dead-weight tensile loading of polycrystalline aluminum, brass, copper and steel. The acoustic emission data, both threshold-type and frequency-analysis type were correlated with yield strength, stored elastic energy, strain hardening parameters, loading histories, diffusion processes, slip band motion and mosaic cell size. Major results are presented under the headings: Discontinuous Yielding (Portevin-Le Chatelier Effect), Parabolic Strain Hardening and Frequency Analysis. The principal experimental techniques are also summarized.

I. Introduction

The research program, which is summarized in this final report, was originally entitled "Acoustic Emission and the Portevin-Le Chatelier Effect". Although much of the performed work was focused on studying this phenomenon of discontinuous yielding, the program included many other aspects of the acoustic emission behavior during plastic deformation under controlled dead-weight tensile loading of several materials. The materials tested consisted of polycrystalline specimens of aluminum, brass, commercially pure copper, high purity (OFHC) copper and HF-1 steel. The types of deformations monitored range from small elastic strains to plastic elongations of 30%. Typical plastic strain rates (uncontrolled) ranged from 10^{-7} to 10^{-4} sec^{-1} . Loading was administered both incrementally and continuously. Most tests were conducted at ambient room temperature, but some high temperature test (325°C) were also performed.

The acoustic emission data, both threshold-counting type and frequency-analysis type, were correlated with yield strength, stored elastic energy, several strain hardening parameters, loading history, diffusion processes, motion of Luder's bands, dislocation motion and mosaic cell size. Here, we first summarize the principal experimental techniques, then the major results are presented under three headings: Discontinuous Yielding, Parabolic Strain Hardening and Frequency Analysis.

For details of any summarized result, the reader is referred to the References, which consist of publications and papers prepared under the contract.

II. Experimental Techniques

A. Testing Apparatus

A special testing machine was constructed for the purpose of quietly applying dead-weight tensile loads to the specimens. This machine included specially designed specimen grips which permit the application of piezoelectric transducers to the polished ends of the specimen. This allows the direct placement of the transducers on the specimen without contact with the deforming region. Two types of loading procedures were used. Dead-weight increments could be applied or the load could be increased continuously by running water from a storage tank located above the testing machine into a container at the end of the lever arm (15:1 mechanical advantage). A uniform flow rate was obtained by maintaining a constant pressure head in the storage tank. Typical load increments were 0.10 kg/mm^2 , while continuous loading was achieved at 0.08 kg/mm^2 per minute. A schematic of the testing apparatus is given in (3,4,7,9).

B. Calibration Techniques

The need for a reliable transient wave calibration source led to several investigations. Impacting

devices and fracturing of glass capillaries were tried but abandoned because of the lack of repeatability. A method of utilizing spark-initiated ultrasound was then sought. After several sparking procedures were thoroughly tested, it was concluded that sparking in air, above the surface of the test part, provided the most reliable source. Finally, a commercially available spark device (Trodyne Corp. "SimCal" Type TE-706) was utilized. The ultrasonic waves that are produced by this device contain energy within the frequency range: 100-400KHz. The frequency content and the energy of the waves are reproducible, typically within 5% maximum deviation.

Using the calibration device, the coupling efficiency of the sensors to the specimen could be checked periodically during a test. Generally it was found that the sensitivity to these simulated acoustic emissions improved as the strain increased. This increase in sensitivity could be as great as 30% in OFHC Copper at 14% plastic strain, and was attributed to the hardening of the material and the corresponding decrease in ultrasonic attenuation. Without recognition of this phenomenon, more or less uniform acoustic emission activity, as a function of strain, could be mistakenly interpreted as increasing amounts of A.E. Therefore,

the A.E. data could be appropriately corrected.

C. Frequency Analysis Techniques

Amplified AE signals were recorded on video tape by a VTR (Sony Model 3650). For playback analysis, the VTR output, in the stop-action mode, was fed to a transient digitizer (Biomation Model 805). This unit has the capability of converting an analog signal into a series of 2048 points spaced at a fixed sample interval. In order to resolve the 1 MHz component of a signal, a minimum sample rate of $.5\mu$ sec was required. The digitized signal was converted into a repeatable analog signal by the transient digitizer. Using this technique, a 1.024 msec portion of the signal can be analyzed. The general procedure was to examine the recorded output at slow speed until a frame with acoustic activity was found, stop at that frame (16.7 ms in duration) and, using the gated oscilloscope output as a trigger source in conjunction with the trigger delay of the transient digitizer, capture the AE event for analysis. The analog output of the transient digitizer was finally analyzed with a spectrum analyzer.

Additional details of this technique are given in (8,9).

III. Results - Discontinuous Yielding

Many metals and alloys which exhibit repeated discontinuous yielding (Portevin-Le Chatelier effect) also emit rather interesting acoustic energy during work hardening. Both phenomena are dramatic in dead-weight extensions of annealed specimens of brass or aluminum. The acoustic emission from such specimens was monitored and correlated with the features of the Portevin-Le Chatelier effect. When the discontinuous yielding subsides in aluminum, so does the acoustic emission; in fact, smooth continuous flow can occur in these materials with no detectable acoustic emission. Data were shown to be consistent with the hypothesis that, at room temperature, elastic energy released during a yield increment is proportional to the elastic energy stored since the last yield increment. On a continuum scale, the incremental elastic energy can be associated with the local yield criteria. However, at elevated temperature, the AE occurs irregularly and there is no obvious correspondence with stored elastic energy.

The PL effect is a macroscopic result of the inhomogeneous, discontinuous slip which occurs in the individual crystalline grains. The propagation of Luders' bands during a PL strain increment was observed. The physical mechanisms governing such phenomenon are temperature dependent. When the testing temperature is high enough to cause creep, the AE differs from

that occurring at room temperature. At high temperature, the PL effect does not appear as truly discontinuous yielding but rather as a significant increase in the rate of the persistent, creep-like straining. At high temperature, the AE occurs irregularly; much of it between the PL yield increments, with some yield increments having little or no AE at all.

The energy, which is released during a PL strain increment, is gradually and irregularly released during the high-temperature tests. This is reasonable because of the existence of the continuous straining taking place in the high-temperature test. The stored energy, rather than being released all at once and in a uniform way, is released in small amounts continuously and in larger amounts at irregular times.

Details can be found in (1,2,4).

IV. Results - Parabolic Strain Hardening

Many ductile polycrystalline metals and alloys exhibit quantized parabolic strain hardening, known as Bell's parabolic law.

During tensile testing, a change from one parabolic region to another appears as a discrete second-order transition.

The genesis of the parabolic hardening transitions, especially as it relates to metallurgical properties, is still unknown. Mode transitions and other variations in the hardening behavior, when considered as material transitions in a general sense, can be expected to be accompanied by measurable variations in physical observables other than stress and strain. The hardening transitions originate in the plasticity of the microscope structure, and therefore, the AE characteristics, which are known to vary with plastic deformation, should be one such observable.

Three crystalline solids, having various metallurgical properties, including large differences in purity, stacking-fault energies, grain sizes, annealing histories and yield strengths were studied. All three specimens strain-hardened according to Bell's law, and all exhibited similar variations in AE. Local AE increases occurred at the strains where parabolic hardening transitions were observed. This result strongly supports the overall significance of Bell's law and suggests that microstructural changes occur during the transitions. For details, see (3,5,10).

V. Results - Frequency Analysis

Observations of different characteristic AE frequencies during AE inspection of welds (6), as well as during the Portevin-Le Chatelier effect, motivated the pursuit of AE frequency analysis. Some Results are:

A. HF-1 Steel (7,9)

The ability to extract information about the deformation process from the concomitant acoustic emission signals is of basic importance for both research and applications. This research has demonstrated that frequency-analysis techniques yield information about mechanical deformation mechanisms that cannot be obtained by conventional amplitude counting techniques. It was shown that the acoustic emissions from the tensile loading of HF-1 steel, exhibit three different frequency spectra, corresponding to microplasticity, plasticity and deformation after recovery.

This sensitivity to the mechanism of deformation suggests several possible applications. Once a material has been fully investigated with respect to frequency behavior, suitable spectral monitoring techniques can be devised to determine the exact nature of the material's state of deformation. Such procedures could be applied

where present amplitude counting techniques fail. For example, HF-1 steel does not exhibit appreciable AE in the plastic region until immediately prior to failure. By simply examining the number and size of the signals produced, warning of material failure would not be observed until immediately prior to failure. However, by examining the relative contributions to the acoustic emission the the 100-200 kHz region and the 200-300 kHz region, a more sensitive evaluation of structural integrity can be achieved. This can also be applied to determine the maximum load previously experienced by a material that does not exhibit an appreciable Kaiser effect.

B. Brass (8,9)

During all stages of plastic straining of brass, the maximum frequency content of the detected AE signals is less than 1 MHz. Higher frequency components of the AE signal occur more often at larger strains. The acoustic emissions observed during the plastic strain increment exhibit higher frequencies than those detected during the elastic portion of the Portevin-Le Chatelier step. Uniformly impeded slip-band motion can account for the frequencies of the AE, as well as the increase of frequency with increasing strain. Mosaic cell size is a good candidate for a microstructural parameter that can be related to the intermittent motion of slip bands.

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