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Title:

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IN-SITU MAGNETIC GAUGING TECHNIQUE USED AT LANL – METHOD AND SHOCK INFORMATION OBTAINED†

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Measuring techniques, including magnetic gauges, quartz gauges, manganin gauges, PVDF gauges, velocity interferometry, piezoelectric pins, shorting pins, flash gaps, etc., have been used over the years in shock experiments in condensed phase materials. The use of a particular technique depends on the measured parameter and the sample material properties. This paper concentrates on in-situ magnetic gauging which is particularly useful in high explosive (HE) shock initiation experiments. A short history of this technique will be given but the main discussion will concentrate on the multiple magnetic gauge technique developed at Los Alamos National Lab.(LANL). Vorthman and Wackerle[1,2] started the technique development in 1980, concentrating on particle velocity and "impulse" gauges so that Lagrange analysis could be used to map the entire reactive field. Over the years, changes to the gauge design, fabrication, and experimental focus have led to the present LANL technique. During the past two years measurements have tracked the reactive wave evolution resulting from a shock-to-detonation transition in several high explosive materials. Analysis of the data from a single experiment provides: 1) an unreacted Hugoniot point in which both the shock velocity and particle velocity are measured, 2) shock front tracking, 3) ten particle velocity profiles which measure the reactive wave evolution, 4) a "Pop-plot" distance-(time-)to-detonation point, and 5) a 3% measurement of the detonation velocity. Details of the experimental setup and information from several experiments will be discussed.

INTRODUCTION

Over the last fifty years, many different techniques have been used to make measurements in dynamic shock conditions. Early measurements were made with shorting pin techniques (later piezoelectric pins) and streak camera recordings of flash gaps and events that produced light. Gradually various gauging techniques were developed including quartz gauges, manganin gauges, magnetic gauges, lithium niobate gauges, PVDF gauges, ytterbium gauges, carbon gauges, etc. Velocity interferometry including VISAR, Fabry-Perot, ORVIS, and various modifications of them have been heavily used in the last 20 years. Each of these techniques has strengths and weaknesses so the use of a particular technique depends on the techniques available at a particular facility, the parameter or phenomena to be measured, the nature of the sample material, the shock pressure range of interest, and, probably most important, the preference and experience of the experimenter.

A new technique usually becomes available because of the need to measure something that can't be measured with the techniques available. Perhaps a particular person becomes convinced that the development is possible and worth the investment of a substantial part of his or her technical career. Nearly all the techniques we have available can be traced to one or more people who have made such an investment. This is true of magnetic gauging, particularly at LANL.

MAGNETIC GAUGES IN SHOCKS

History – Magnetic gauging was first developed in Russia and described in 1960 by Zaitzev et al.[3] A loop gauge was used to measure the particle velocity

† Work performed under the auspices of the U.S. Dept. of Energy.

in explosively driven shock experiments. Several papers were published in the early 1960's by Dremin et al.[4] (only two are listed) to measure the particle velocity in reacting/detonating HE's or non-metallic inerts at relatively high input pressures.

Although a number of researchers in the U.S. tried this technique, it was not used extensively. The first published reports of magnetic gauges being used in explosives by Americans were from Jacobs and Edwards[5] in 1970 and Cowperthwaite and Rosenberg[6] in 1976. It is interesting to note that the final comment in Ref. 5 says, "*In closing, we are strongly of the opinion that the electromagnetic velocity method is inherently a good technique which will be of considerable value as a tool for unraveling the complex problems of detonation waves and shocks in condensed media*."

The technique was developed further on gas guns at Physics International and Washington State University (WSU), largely under the direction of Fowles and coworkers[7-8] during the 1970's. Several people became acquainted with the technique at WSU and went on to implement it on guns at LANL (John Vorthman) and SRI (Yogendra Gupta). It was also used at Lawrence Livermore National Laboratory (LLNL) in the early 1980's by Leroy Erickson and coworkers.[9] Later LLNL concentrated on manganin gauges rather than magnetic gauges.

Gupta developed the first 2-D magnetic field setup that was used to measure particle velocity in two directions.[10] He has since implemented this technique at WSU.

Principle of Operation – Electromagnetic particle velocity gauging is based on Faraday's law of induction. For a conductor of length **L** moving with velocity **u** in a steady uniform magnetic field of strength **B**, the induced voltage is,

$$V = \mathbf{L} \bullet \mathbf{u} \times \mathbf{B}\,. \qquad (1)$$

In Eq. 1, all quantities but the induced voltage V are vector quantities. If, by design, the vectors **L**, **u**, and **B** are everywhere mutually orthogonal, this reduces to the scalar equation,

$$V = LuB. \qquad (2)$$

Furthermore, electrical leads to sense the voltage in the conductor **L** can be made to have zero induced voltage by placing them parallel to the plane defined by the vectors **B** and **u**. The experiments are designed so that this is the case.

Fowles and coworkers described a modification to the velocity gauge in which the end was shaped like a triangle rather than a rectangle.[7] They showed that this gauge would measure a voltage related to the impulse rather than the particle velocity. This gauge was used in early LANL experiments.

Magnetic gauges are useful for measurements in non-metallic materials only. Experiments must be designed to eliminate or minimize the movement of metallic objects which will perturb the magnetic field. However, the use of these gauges in initiating and detonating HEs, which are somewhat conductive, has been amply demonstrated.

MAGNETIC GAUGING AT LANL

At LANL in the 1970's, experiments to measure the shock initiation of HEs used manganin gauges.[11] In the early 1980's John Vorthman changed the direction of the measurements to magnetic gauges. We now refer to our method as the Vorthman technique. One of the important contributions Vorthman made was to recognize that the gauges could be in the form of a membrane that was embedded at an angle in a sample HE piece. This led to several advantages which will be discussed later. Many of the aspects of the LANL technique are discussed in Ref. 12 in more detail.

Gauge Design – The gauge is a membrane consisting of a 25 μm thick FEP Teflon layer with a layer of 5 μm of aluminum glued to it. It is then coated, exposed, and etched with the desired pattern. Then another layer of 25 μm thick FEP Teflon is glued on top. A completed membrane is about 60 μm thick. These gauges are made by RdF Corporation of Hudson, NH. We supply them a mask of the gauge pattern. An early gauge pattern is shown in Fig. 1.

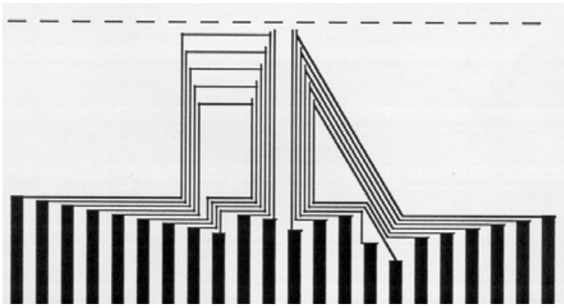

FIGURE 1. Early gauge design with five particle velocity gauges and five impulse gauges. The two leads down the center were often used to estimate conductivity during the experiment.

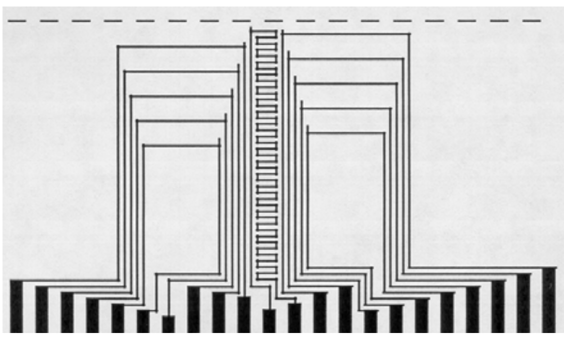

FIGURE 2. Gauge design with ten particle velocity gauges and a shock tracker down the center.

The gauge package shown in Fig. 1 has both a velocity and an impulse gauge at each of five different positions spaced 2 mm apart on the membrane. Wave profiles measured with this gauge package were used to provide input to a Lagrange analysis process developed by Chuck Forest.[13] Unfortunately, this process was difficult to do, involved large amounts of time, and required some estimates of unavailable data. Lately we have abandoned the impulse gauges and replaced them with particle velocity gauges. Reactive hydrocode models have largely replaced Lagrange analysis.

Several changes have been made to the gauges for various purposes, including the use of one or more "shock trackers", as shown in Fig. 2. Vorthman conceived the shock tracker gauge in the early 1980's but the recording instrumentation was not fast enough to make the measurement useful. In the last several years this innovation has been shown to be of great value in both inert and reacting systems. A discussion of how this gauge works and the data obtained from it will be presented later. A new gauge configuration with two shock trackers is shown in Fig. 3.

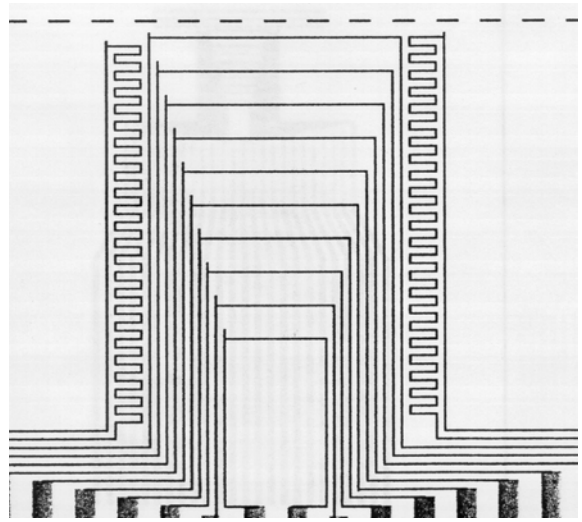

FIGURE 3. New gauge design presently being studied to determine its usefulness.

Experimental Setup – The fact that the gauge package was a thin membrane that could be embedded in the sample at an angle led to several advantages. These are: 1) the gauges were not shadowing each other, 2) the leads were not susceptible to spreading, 3) a thin aluminum layer could be etched to an intricate pattern, and 4) the membrane could be glued in reasonably easily rather than requiring assembly of a mosaic of target pieces as had been used by others. A typical sample buildup is shown in Fig. 4.

The sample is machined so the inclined surface makes a 30^{o} angle with the front surface. After assembly in the sample, the active elements on the membrane are at depths from about 1 to 5 mm on ½ mm increments. The membrane is glued to the sample with the gauges carefully aligned to a sample reference line. Then the top piece is glued on and finally the assembly is lightly machined to make the top flat.

A "stirrup" magnetic gauge is usually glued to the front of the sample to measure the input particle velocity. This gauge is shown rather clearly on the finished target assembly shown in Fig. 5.

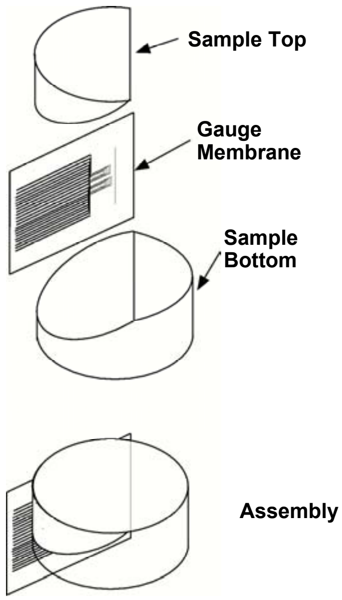

Figure 4. Details of the sample and the magnetic gauge package installation.

The leads from the gauges (up to 24 of them) are hooked to cables by using a computer card connector. The connection is shown on the right side of Fig. 5. There are two leads for each gauge to allow for differential measurement of the voltage. This reduces the noise from extraneous sources.

The overall configuration of an experiment on the gun is shown in Fig. 6. A non-metallic projectile impacts the target located in the magnetic field created by an electromagnet. The field is constant to better than 1% in the gauge region. Active gauge element lengths are typically between 6 and 10 mm long so, with a magnetic field of 750 gauss, a voltage on the order of one volt is produced. This technique has also been implemented on our two-stage gun.[14]

Two-Dimensional Effects – An impedance mismatch between the gauge membrane and the sample may cause a 2-D effect in the measurement. Bdzil has shown this from a theoretical standpoint.[15] In all the experiments we have done on solids this has not been a problem. However, when the gauge is suspended in liquids, we have shown experimentally[16] that there are errors in the measured particle velocity.

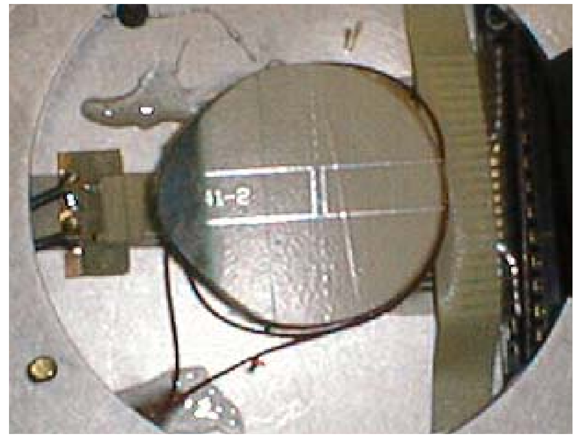

Figure 5. Finished target assembly showing the double stirrup gauge membrane glued to the front of the target. As can be seen on the left side of the sample, the sample edge is rounded, the leads of the stirrup gauge are glued to the rounded edge, and the extra volume is filled with glue to minimize lead spreading.

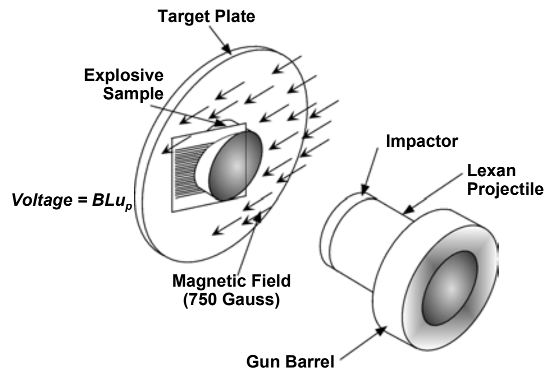

Figure 6. Overall experimental configuration showing the gun barrel, projectile, and explosive target in the magnetic field.

Shock Tracker Gauge – The center element of the gauge pattern shown in Fig. 2 is the "shock tracker" gauge. When mounted as shown in Fig. 4, the gauge has a periodically varying effective length with depth. As the shock sweeps through the sample, the effective length, and thus the output voltage, changes with the position of the shock front. The voltage output is high/low when the shock front is traversing a region where the gauge length is long/short, respectively. From this a distance-time plot can be obtained.[17] From shock tracker data in an explosive experiment, the following information can be obtained: initial shock velocity, the transition to detonation (Pop-plot data), and an estimate of the detonation velocity.[12]

MAGNETIC GAUGE MEASUREMENTS

The LANL magnetic gauge technique has been used extensively over the years to study a large number of different materials. Most of the work has had something to do with explosive or chemically reacting materials. Early measurements on explosives involved making both particle velocity and impulse measurement on explosive samples.[1,2]

We have also made measurements on Kel-F to look at the viscoelastic nature of the wave profiles. Fig. 7 is an example of one of these measurements.

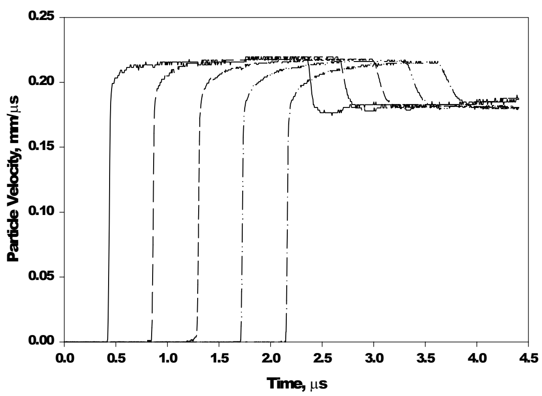

Figure 7. Particle velocity profiles in Kel-F showing the evolution of the wave front caused by the viscoelasticity. Shot 769 at an input of 1.1 GPa.

A number of organic liquids have been studied using this technique. Homogeneous initiation processes have been identified in chemically sensitized nitromethane. Phenylacetylene ($C_6H_5C{\equiv}CH$) has been studied because of the acetylene bond is thought to be vulnerable to breakage in a shock. The waveforms obtained from an experiment on this material are shown in Fig. 8. The evolution of a two-wave structure is apparent.

The magnetic gauge technique is particularly useful for studying HE because of the large amount of information obtained from a single experiment. In addition to the evolving particle velocity profiles of the reactive wave, the shock tracker provides data on the input shock velocity, the point at which detonation is attained, and the detonation velocity. Experiments have been done in both solid and liquid explosives.

A number of experiments have been conducted on PBX9501 to determine the effects of density and

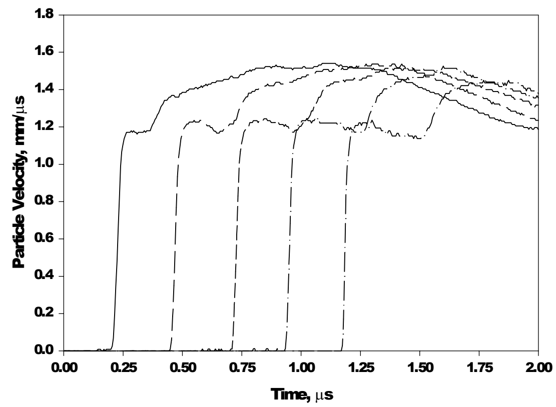

Figure 8. Particle velocity profiles in phenylacetylene showing the evolution of the two-wave structure resulting from the shock-induced chemical reaction. Shot 786 at an input of 6.8 GPa.

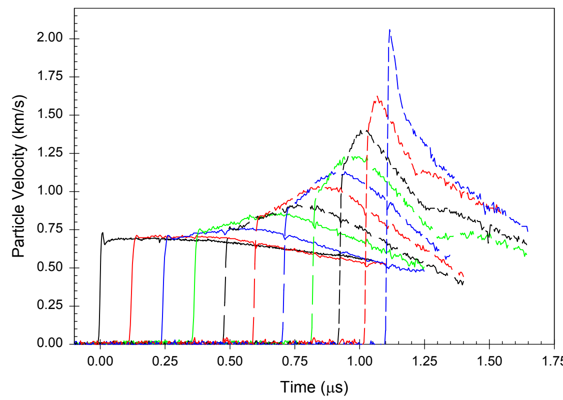

Figure 9. Particle velocity wave profiles from PBX9501 Shot 1133. The input was 5.15 GPa.

aging on shock initiation.[12] We have picked out a particular experiment (Shot 1133) to demonstrate the type of data obtained. The particle velocity profiles are shown in Fig. 9. Growth in the wave is clear in Fig. 9 as it moves through the sample. At the last gauge, the wave has nearly reached detonation.

Shock tracker data reduces to position-time data like that obtained in optically recorded wedge experiments. Fig. 10 shows this data along with the gauge arrival time data. The run distance-to-detonation was determined to be 5.1 mm and the detonation velocity from the shock tracker data was 8.74 mm/ms, very near what was expected.

This method has been used to study single-shock initiation, double-shock initiation, differences in materials, differences in density, differences in age, etc. An example is that differences in initiation properties have been measured for samples with density differences of only 0.005 g/cm^3.[12]

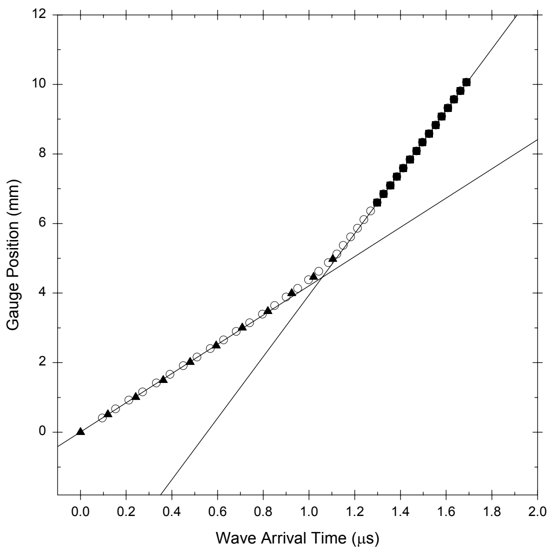

Figure 10. Distance-time (*x-t*) plot obtained from shock arrival at shock tracker points (before detonation--circles), shock tracker points (after detonation--squares) and particle velocity gauge points (triangles). Data are from Shot 1133.

ACKNOWLEDGMENTS

In addition to John Vorthman and Jerry Wackerle, others including the authors, Jerry Dick, Chuck Forest, Tom Elder, and Robi Mulford have been involved with this technique. Frank Hines and Scott Sahlin of RdF Corporation in Hudson, New Hampshire developed the gauge making process.

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