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DESIGN AND ANALYSIS OF ISENTROPIC COMPRESSION EXPERIMENTS

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Design and Analysis of Isentropic Compression Experiments

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ABSTRACT

This paper briefly summarizes the use of magnetic flux compression to isentropically compress matter. Details of the process used to extract boundary data from the flash radiographs and the design criteria for the containment of very compressible material are discussed. Finally, suggestions for improvement of the next generation of experiments are made.

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1. INTRODUCTION

In 1969 a program was started at Lawrence Livermore Laboratory (LLL) with the intention of using magnetic-flux compression technology [1] to isentropically compress matter, as suggested by Bitter [2]. Flux compression is ideally suited for compressing matter without forming shockwaves while effectively utilizing the energy of explosives [3,4]. Most of the results of more than thirty experiments have been published [3-7] together with most of the details of the field generation [4], diagnostics [4,6], and some of the design criteria [4]. This paper summarizes the technique and discusses details on the compression dynamics, data reduction of the flash radiographs, and sample-containment design.

2. MAGNETIC COMPRESSION TECHNIQUE

The magnetic compression device is shown in Fig. 1. A capacitor bank (1 MJ at 35 kV) is discharged through a coil pair, generating a magnetic field that diffuses into the interior of the stainless-steel liner. The magnetic-flux density enclosed by the liner reaches a peak value of 5 to 6 T in about 300 μ s. At this time, a cylindrical explosive charge is detonated that implodes the copper-plated stainless-steel liner. The copper plating on the inside of the liner serves to increase the magnetic cumulation efficiency. Because of the rapid convergence of the liner, the magnetic flux is compressed in the region between the liner and the sample tube. In this manner, the magnetic-flux density is increased from its initial value to more than 1000 T (10 MG) during the ~ 10 - μ s implosion. The interaction of the magnetic field with eddy currents in the metal

sample tube produces pressure on the sample tube and thus on the contained sample.

Flash radiographs are taken before and during the experiment. Changes in the dimensions of the sample, the sample tube, and the liner are determined from the radiographs and used to compute the volumetric compressions. To determine sample conditions at times of importance with respect to other diagnostics, the boundary data are used in conjunction with calculations of experimental performance made with a magnetohydrodynamic (MHD) computer code [8] which was described by Kidder at the first convening of this conference. In many of the experiments, electrical conductivity of the sample was measured continuously as the pressure increased to about 500 GPa (5 Mbar).

Inset (a) of Fig. 1 shows the construction of a typical sample-tube assembly designed for an electrical conductivity measurement of a dielectric sample. (The sample assembly is longer than the 2 to 3-cm high-pressure region.) The sample material is used as the dielectric region of an open-circuit coaxial line that terminates a 50Ω transmission line. Termination impedance is in part determined by the resistivity of the sample. The sensitivity of the diagnostics and the configuration of the experiment are such that measurement of the magnitude and polarity of a reflected pulse train allowed determination of sample resistivities over a limited range and to distinguish between an insulator and a conductor [6]. Other less successful or less useful sample diagnostic techniques were used in some experiments. These included microwave and optical transmission and reflection measurements [5] and manganin pressure measurement.

3. IMPLOSION DYNAMICS

Compression of the sample results from a sequence of events that for illustrative purposes can be represented by the mechanical analog shown in Fig. 2. The nonlinear springs S_1 , S_2 , and S_3 represent the pressure of the high-explosive products, the magnetic field between the liner and sample tube, and pressure in the sample, respectively. In this analog, the spring coefficients k_1 , k_2 , and k_3 are time dependent, as is the magnetic flux diffusion. M_1 , M_2 , and M_3 represent the masses of the high explosive, liner, and sample-tube, respectively. Opening the latch L represents the arrival of the high-explosive pressure wave at the liner surface. From the analog, it is clear that the pressure in the sample cannot necessarily be determined directly from knowledge of the magnetic field intensity, B , alone.

Figure 3 shows the results of calculations made with the MHD code [8]. In Fig. 3(a), the sample is relatively incompressible and the pressure in the sample very close to the magnetic pressure on the sample tube. This is representative of sample materials such as CsI , SiO_2 , and Al_2O_3 . Figure 3(b) shows the results for a very compressible, i.e., soft, sample material such as hydrogen. In this case, the inertia of the sample tube first delays the movement of the tube as the applied magnetic pressure increases. Later, the sample-tube momentum continues sample compression even though the sample pressure exceeds the applied magnetic pressure. Hence, the sample pressure is not necessarily in phase with the magnetic pressure. Thin, low-density sample tubes would reduce the discrepancy in pressures but are not compatible with the requirements imposed by the flash radiograph or with the avoidance of excessive magnetic diffusion.

Furthermore, in soft samples there is no possible initial radius external to the sample tube at which a field sensing device could be located prior to the implosion and not be destroyed by the liner before a high pressure is generated in the sample. Hence, for soft samples a flash radiograph was essential to obtain sample-compression data.

4. DATA REDUCTION OF FLASH RADIOGRAPH

The diagnostic importance of the flash radiograph taken during each experiment at the time of near-maximum compression warranted development of an extensive data-reduction technique.

Flash radiographs typically are both very "grainy" (as a result of the intensifier screen needed for image formation) and blurred by a finite beam-size (~ 2 mm). Furthermore, when the gap between liner and sample tube is small, it is not resolvable from the radiograph by the unaided eye.

As indicated in Fig. 4, the first step was to scan the radiograph perpendicular to the experimental axis, with a microdensitometer set at a 0.1-mm square aperture. The optical transmission of the radiograph was digitized at 0.1-mm intervals. Sequential parallel scans were made and digitized at 0.1-mm intervals along the experimental axis. A typical scan of density vs radius is shown in Fig. 5(a).

A median-window filtering technique [9] was then used to find the median value of the intensities in a small region surrounding each point. Median-window filtering is spatially variant, i.e., the smoothing characteristics depend on the nature of the region being smoothed. The technique is well suited for reducing the noise caused by granularity without any additional loss of boundary definition. The region used in this case extends five points radially and nine points axially from each

point, for a total of 209 points (1.1×1.9 -mm region). The result of this process is shown in Fig. 5(b).

A second filtering process 10 was then used on scan groups composed of five radial scans averaged together. The Fourier transforms of the scan groups were passed through a low-pass filter and then inverted back to spatial data.

A computer simulation code [11] was used to calculate the shadowgraph density profile of known input parameters, including the radii and x-ray absorption coefficients of cylinders of different materials, x-ray beam size and beam source to experiment, and film distances. These parameters were adjusted until the calculated profile slopes matched the slopes of the processed experimental data. Figure 6 shows a portion of a typical processed data scan and computed match.

This whole process was repeated with changes in Fourier filter parameters, and the number of scan lines per scan group. The results were compared until convergence was established for each parameter. It was determined that boundaries could be located to an accuracy better than 0.1 mm. These parameters were then used for the data reduction of the experiments on Al_2O_3 [6], hydrogen, and neon [7].

5. SAMPLE CONTAINER DESIGN

Other factors important to consider in experiment design are sample-tube diameter and, in the case of low density samples, anvils to prevent axial escape of the sample.

A. Sample-tube diameter

The useful magnetic field contained between liner and sample tube increases in intensity at the expense of the area between the two metal

cylinders. A larger sample-tube diameter results in a thinner gap and an earlier collision at a lower field-intensity. Hence, a compromise between high field-intensity and large samples must be made for each experiment. Initial diameters of stiff-samples were smaller than those for soft-samples.

Another restriction on the sample-tube diameter results from the need to avoid formation of a shockwave. For cylindrical compression, the maximum rate at which pressure can be applied, without formation of a shockwave, is a function of the equation of state of the sample and an inverse function of the sample radius [4]. Hence, in some cases there is a maximum sample radius that is compatible with a given compression rate. This requirement can be alleviated by using less energetic explosives that provide less liner implosion velocity. For example, the experiments on hydrogen used TNT instead of 9404, to permit a larger sample diameter [12].

B. Inertial anvils

For low-density samples, the compression process is slow enough that unrestrained samples would escape along the axis of a hollow sample tube. Hence, anvils with a density of at least 1.0 g/cm^3 are needed for sample confinement. For the hydrogen and neon experiments, tapered conical anvils were used (Figs. 1b and 7). The angle of the taper was chosen on the basis of two considerations. First, to prevent premature collision, the axial shape of the sample tube when near full-compression has to match closely the shape of the liner.

Second, to avoid jet formation in the hydrogen, one of two criteria [13,14] had to be met: Either the velocity of the point of intersection of the sample tube and anvil, i.e., impinging velocity u_i must be faster than the speed of sound in the sample or, if this is not the case the

included angle ϕ must be less than a critical angle ϕ_c . Figure 8 shows the impinging velocity and sound velocity of hydrogen as a function of liner implosion time. Up to about 11.9 μ s, the impinging velocity exceeds the sound speed in hydrogen, hence no jet will form. After that, no jet will form if ϕ less than ϕ_c . In the case shown, ϕ_c was calculated to be about 62° for hydrogen whereas ϕ was only 11°. Hence, again no jetting of the hydrogen should occur.

In the case of the silver sample tube impinging on the silver anvil, the critical angle is about 11°, or greater if the impinging velocity is greater than 5.5 mm/ μ s, which is the case throughout all but the earliest portion of the implosion. The expected absence of silver jetting was confirmed by the flash radiographs.

6. MISCELLANEOUS OBSERVATIONS

During the course of the experiments many anticipated problems either did not occur or were solvable. A few are noted below.

A. Hydrodynamic instabilities

Instability and nonuniformity of implosion of the liner and sample tube were not observed in properly assembled experiments. The uniformity of the liner implosion doubtless was enhanced by the 168 detonation points and the 50.8-mm thick cylinder of explosive. In a test on an explosive and liner system twice as large as the ones usually used, it was observed that a 0.89-mm thick, 20-cm diameter stainless-steel liner imploded perfectly circularly to a diameter of less than one millimeter.

B. Electrical resistivity at high temperature

It was found that electrical resistivity did not suddenly increase to a high value in the vicinity of the critical temperature, as had been

predicted [8]. On the contrary, the flux containment efficiency indicated that the electrical resistivity of copper and silver never exceeded 100-200 $\mu\Omega\text{cm}$.

C. Surface temperatures

Framing camera records indicated light emission from the liner and sample-tube surfaces occurred prior to their collision. It was estimated that the emitted light intensity was equivalent to that of a blackbody at 30,000 K.

7. AREAS FOR IMPROVEMENT

A. Pressure measurement

The single most important improvement needed for equation-of-state studies with magnetic compression is a time-resolved sample-pressure measurement. For stiff samples and larger flux compression systems, faraday rotation measurements of the magnetic field intensity are useful [10] until the liner collides with the faraday element. In the more general case, a pressure gage is needed in the sample. Piezoresistive pressure measurement was used in a few experiments. This technique worked in a soft sample but was difficult to implement in the presence of the magnetic field in the sample tube. The ruby fluorescence wavelength shift is a promising technique for measuring the sample pressure, and should be tried [15]. Application of any internal diagnostics of the sample requires conveyance from the sample, through a region exposed to a 25-50 GPa/mm pressure-gradient, to ambient pressure.

B. Density measurement

Time-resolved measurement of the sample volume coupled with time-resolved pressure measurement would provide complete pressure-volume

isentropes for a material from a single experiment. The most promising technique for obtaining the sample density would be a streaking x-ray system 15 .

C. Larger systems

Larger diameter liners with larger initial magnetic flux would alleviate some of the constraints of smaller systems. Faraday or magnetic-probe field measurements would be possible to higher field intensities. Larger samples could be used to yield better volume-measurement resolution. However, generally cost increases rapidly with larger systems.

D. Laboratory systems

It would be most advantageous to be able to generate high field intensities in large volumes for isentropic compression without the use of high explosives. Quite probably this will be reported at the third convening of this conference series.

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REFERENCES AND NOTES

- [1] FOWLER, C. M., GARN, W. B., CAIRD, R. S., J. Appl. Phys. 31 (1960) 588.
- [2] BITTER, F., Sci. Am. 213 (1965) 65.
- [3] HAWKE, R. S., DUERRE, D. E., HUEBEL, J. G., KEELER, R. N., KLAPPER, H., Nature 233 (1971) 79.
- [4] HAWKE, R. S., DUERRE, D. E., HUEBEL, J. G., KLAPPER, H., STEINBERG, D. J., KEELER, R. N., J. Appl. Phys. 43 (1972) 2734.
- [5] HAWKE, R. S., DUERRE, D. E., HUEBEL, J. G., KEELER, R. N., KLAPPER, H., Phys. Earth Planetary Interiors 6 (1972) 44.
- [6] HAWKE, R. S., DUERRE, D. E., HUEBEL, J. G., KEELER, R. N., WALLACE, W. C., J. Appl. Phys. 49 (1978) 3298.
- [7] HAWKE, R. S., BURGESS, T. J., DUERRE, D. E., HUEBEL, J. G., KEELER, R. N., KLAPPER, H., WALLACE, W. C., Phys. Rev. Lett. 41 (1978) 994.
- [8] The MHD code used is a refined version of the code described by KIDDER, R., in Proceedings of the Conference on Megagauss Field Generation by Explosive and Related Experiments, Frascati, Italy, 1965 (EURATOM, Brussels, 1966), p. 37.
- [9] This process was developed by G. Meyers, based on the work of FRIEDAN, B. R., J. Opt. Sci. Am. 66 (1976) 280.
- [10] SCUDDER, J. K., Diagnostics Development for Magnetic Flux Compression Experiments, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-51767 (1975). Available from Nat. Tech. Info. Service, U.S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, Virginia 22151.

- [11] This code was written by J. K. Scudder [10] and developed by D. Larger.
- [12] A continuous range of implosion velocities could be obtained by the use of explosives loaded with various fractions of metals.
- [13] WALSH, J. M., SHREFFLER, R. G., WILLIG, F. J., J. Appl. Phys. 24 (1953) 349.
- [14] COWAN, G. R., HOLTZMAN, A. H., J. Appl. Phys. 34 (1963) 928.
- [15] FOWLER, C. M., CAIRD, R. S., HAWKE, R. S., BURGESS, T. J., in High Pressure Science and Technology (Proc. 6th AIRAPT Conf., Boulder, Colorado, U.S.A., 1977) Vol. 2, 981.

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FIGURE CAPTIONS

- Fig. 1. Magnetic compression device with sample container design for high and low density samples.
- Fig. 2. Cross section of (a) magnetic compression device and (b) its mechanical analog. P_e is the pressure generated by explosion products. P_m is the magnetic pressure. P_s is the pressure resulting from compression of the sample.
- Fig. 3. Relationship between magnetic and sample pressures for (a) stiff (Al_2O_3) and (b) soft (Ne) samples.
- Fig. 4. Radiograph data-reduction process.
- Fig. 5. Optical density for a radial scan of a typical radiograph, (a) before and (b) after median value filtering.
- Fig. 6. Actual and computed optical density versus radius for best match of radii.
- Fig. 7. Sample tube and anvil arrangement used for low density samples u is sample-tube implosion velocity, u_i is the impinging velocity, and ϕ is the included angle of sample tube and anvil.
- Fig. 8. Sample-tube radius, radial velocity, impinging velocity, and the sound speed in hydrogen versus time, for a typical experiment.

Hawke - Fig. 2

Hawke - Fig. 3

Hawke - Fig. 4

Hawke - Fig. 6

Hawke - Fig. 7

Hawke - Fig. 8