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MEASUREMENTS AT HIGH STRAIN RATES.

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Magnetic Implosion for Novel Strength Measurements At High Strain Rates

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Abstract

Recently Lee and Preston have proposed to use magnetic implosions as a new method for measuring material strength in a regime of large strains and high strain rates inaccessible to previously established techniques. By its shockless nature, this method avoids the intrinsic difficulties associated with an earlier approach using high explosives. We illustrate how the stress-strain relation for an imploding liner can be obtained by measuring the velocity and temperature history of its inner surface. We discuss the physical requirements that lead us to a composite liner design applicable to different test materials, and also compare the code-simulated prediction with the measured data for the high strain-rate experiments conducted recently at LANL. Finally, we present a novel diagnostic scheme that will enable us to remove the background in the pyrometric measurement through data reduction.

Introduction

The material strength models used for hydrodynamic code simulations of dynamic metal deformation must be fit to accurate flow stress data spanning the strains, strain rates, and temperatures characteristic of the deformation process. Hydraulic testing machines can access large strains, but the strain rates are limited to about 10^3 s^{-1} . The split Hopkinson pressure bar (SHPB) has been used for accurate strength measurements up to plastic strain rates of roughly 10^4 s^{-1} . However, there is at present no developed technique for measuring material strength to large plastic strains of order 100%, at rates above 10^4 s^{-1} . Data in this regime is essential for benchmarking and validating the existing material strength models and for the development of advanced models.

Over ten years ago Preston [1] proposed a novel technique for measuring the material strength of metals to strains of a few hundred percent at a rate beyond 10^6 . The proposed experimental vehicle was a spherical shell of test metal imploded by high explosives. Initial attempts to make time-resolved pyrometric temperature measurements met with serious difficulty because the appearance of hot spots at shock breakout and the additional shock loading to the convergence-induced stresses in the shell. Both effects complicated the data analysis significantly and compromised its value for model development.

Recently, two of us (HL and DLP) proposed a promising modification [2] of the original approach, by using z-pinch to implode a cylindrical liner. The use of magnetic implosion is a significant improvement because it induces no shocks in

the test material. Their analysis indicated that a maximum plastic strain of about 200% and strain rates exceeding 10^6 s^{-1} could be attained using the pulsed power facility Pegasus at Los Alamos. An experimental effort was initiated after its technical feasibility was affirmed by a detailed theoretical investigation.

Physics Issues and Constraints in Liner Design

Let $r(t)$ be the inner liner radius as a function of time. Neglecting material compression, the strain and strain rate are given by (dot stands for time derivative)

$$\varepsilon(t) = (2/\sqrt{3}) \ln[r(0)/r(t)] \quad (1)$$

and

$$\dot{\varepsilon}(t) = -(2/\sqrt{3}) \dot{r}(t)/r(t) . \quad (2)$$

It has been shown [1] that the rr -component of the stress deviator tensor, $S_{rr}(t)$, of the liner can be solved numerically from the following differential equation,

$$\dot{S}_{rr} - \frac{2\dot{r}}{\sqrt{3}r} \left(\frac{B}{\rho C_v T} - \gamma S_{rr} \right) = \frac{B\dot{T}}{\gamma T}, \quad (3)$$

provided that $r(t)$ and the absolute temperature $T(t)$ are measured. In Eq.(3) B , γ , C_v and ρ are, respectively, the bulk modulus, Grüneisen parameter, constant-volume heat capacity and density of the liner material. With the strain history $\varepsilon(t)$ given by Eq.(1), we obtain the stress-strain ($S_{rr} - \varepsilon$) curve which can be compared with the calculated results obtained from different strength models. We can also compare the measured and computed $T(t)$ directly to discriminate various models.

From Eq.(1) we see that high strain can be achieved only if we have a large convergence ratio, $r(0)/r_f \gg 1$, where r_f is the final radius at $t = t_f$. To achieve high strain rate, Eq.(2) implies that we must also make the final velocity v_f large and r_f small. Diagnostic requirement sets the lower limit $r_f = 0.5 \text{ cm}$. Thus we need $v_f \geq 4 \text{ mm}/\mu\text{s}$ for $\dot{\varepsilon}$ to exceed 10^6 s^{-1} . Now the task is how to maximize v_f using the equation of motion, subjecting to the requirement that the ohmic heating in the inner liner layer be kept negligibly small compared to the plastic strain heating. This requirement is equivalent to minimize the liner mass per unit length, m , satisfying the condition $T_p \gg t_f$, where T_p is the current penetration time across the liner. In an earlier theoretical investigation on the liner design that maximizes the shock pressure via impact velocity, Lee [3] has established a general conclusion that a composite liner using aluminum as the outer layer, when optimized, will give the best performance. The underlying chain of physical reasoning [3,4] is rather lengthy to be given here; but it is also applicable to the liner optimization for the high strain rate experiments.

Liner Design and Modeling for the Experiment

The composite liner optimally designed for our experiments on Pegasus consisted of two layers, with the outer one (0.7 mm thick) always made of 1100 series aluminum and the inner one made of test material. As a start, we chose the

6061-T6 aluminum (0.4 mm thick) as the test material to boost the pyrometer signal level, since its high strength would give a much higher strain heating than the soft aluminum. The liner was 2 cm long, with an inner radius of 1.75 cm. The drive current used in liner design has an approximate sinusoidal waveform, with a peak value of 5.8 MA at 7.6 μs . In Fig.1 we show the calculated time-dependent strain and strain rate in the innermost layer, using the Steinberg-Guinan (SG) model. The two curves reach about 200% and $2 \times 10^6 \text{ s}^{-1}$, respectively, when the implosion ends at 9.9 μs . For a detailed description of the experimental setup, we refer the readers to a companion paper [5].

Figure 1. Predicted time-dependent plastic strain (dotted curve) and strain rate (in μs^{-1}) in the innermost liner layer.

Experimental Results and Future Challenge

The first two experiments were successfully carried out in June and October of 1997, using identical liner specifications and drive conditions to ascertain the reproducibility of the pyrometer data. The temperature history inferred from pyrometer data for the second shot is compared with the code-simulated result in Fig.2. We notice that the final temperature is about $200 \pm 60 \text{ K}$ higher than the result calculated from the SG model. Furthermore, the temperature history exhibits a large and sudden jump at 4.5 μs , suggesting the onset of a large background. A careful examination of the 2-D simulation has convinced us that this background radiation came from the end areas of the liner where extra heat is generated by shear strain as the electrodes cut through the moving liner. The peak temperature in these areas indeed increases rapidly by more than 350 K, at a time coincident with the sudden jump observed in the data. We are still searching for a good solution to block out this undesirable background.

In the future we plan to develop a new measuring technique proposed recently by Lee [6] that will enable us to separate the background (reflected rad-

Figure 2. Calculated temperature history of the inner liner surface compared with the one deduced from pyrometer data.

iation) from the signal (emitted radiation) through data reduction, taking advantage of fact that they have different dependence on emissivity. The experimental setup requires a dual-detector system looking at two diametrically opposite portions of the liner surface, which are roughened to have different static emissivities. This new scheme, if validated in the near future, will provide us accurate temperature data that are essential for model development or benchmarking of the material strength models.

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