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RATE

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Imploding Liner Material Strength Measurements at High-Strain and High Strain Rate

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Abstract

Imploding, cylindrical liners provide a unique, shockless means of simultaneously accessing high strain and high-strain-rate for measurement of strength of materials in plastic flow. The radial convergence in the liner geometry results in the liner thickening as the circumference becomes smaller. Strains of up to ~ 1.25 and strain rates of up to $\sim 10^6 \text{ sec}^{-1}$ can be readily achieved in a material sample placed inside of an aluminum driver liner, using the Pegasus II capacitor bank. This provides yield strength data at conditions where none presently exists. The heating from work done against the yield strength is measured with multichannel pyrometry from infrared radiation emitted by the material sample. The temperature data as a function of liner position are unfolded to give the yield strength along the strain, strain-rate trajectory. Proper design of the liner and sample configuration ensures that the current diffused into the sample adds negligible heating. An important issue, in this type of temperature measurement, is shielding of the pickup optics from other sources of radiation. At strains greater than those achievable on Pegasus, e.g. the LANL Atlas facility, some materials may be heated all the way to melt by this process. Recent data on 6061-T6 Aluminum will be compared with an existing model for strain and strain-rate heating. The liner configuration and pyrometry diagnostic will also be discussed.

Introduction

Liner implosion hydrodynamic experiments using pulsed power typically have high purity aluminum as the current carrying element—frequently in combination with another metal as an impactor, or sample, on the inner surface.^[1] In addition to ohmic heating from the drive current, cylindrical convergence results in heating of the liner and sample layer due to plastic deformation from strain and strain-rate effects.

This additional heating can change the state of the material, i.e. melt, and alter the stability of the liner system.^[2,3] Moreover, viscous forces that oppose strain and lead to heating can alter the dynamics of the liner's radial motion. A typical, moderate energy experiment on Pegasus has a liner velocity, at maximum convergence (impact with a target) of $\sim 4 \text{ mm}/\mu\text{sec}$. Therefore, the energy density from radial motion is $\sim 20 \text{ kJ}/\text{cm}^3$ for the aluminum layer(s). For a $\sim 3:1$ radial convergence the strain and strain rate heating of the high purity aluminum portion of the liner system can reach $\sim 500 \text{ J}/\text{cm}^3$ with a temperature rise of 200° K . The present series of Pegasus experiments to evaluate strain and

strain rate heating operate at strains up to 200% and strain-rates of nearly $2 \times 10^6/\text{sec}$.

The Atlas facility, presently under construction at Los Alamos, will be able to drive liners at up to 15 to 20 mm/ μsec . and radial convergences of more than 10:1. Under these conditions strain-rates of well over $10^6/\text{sec}$ and strains of 200 to 300% can be reached. If full work hardening is assumed at these levels of strain and strain rate, and the maximum yield strength of 480 MPA applies for high purity aluminum,^[4] the driver liner will nearly reach melt based on material strength effects alone. This added source of heating has strong and linked implications for the material-strength-dependent stability of the Atlas liner and the diffusion of the drive current into the driver liner. The resistivity of the high purity aluminum can increase $\sim 4\times$ as it is heated (from room temperature) to melt.

Pegasus Experiments and Analysis

Liner implosion experiments have been conducted on Pegasus, to (a) measure the strain and strain-rate heating of high strength, 6061-T6 aluminum and infer a yield strength, and (b) develop the i.r. pyrometry diagnostic which is key to the application of liner implosions to strain and strain-rate material strength measurements.^[2] The liner for these experiments consists of 700 micron thick 1100 series aluminum driver liner, which is 2 cm high and 1.75 cm inner radius, and an attached inner layer of 400 microns of 6061-T6 aluminum. For these experiments, the Pegasus capacitor bank drive system is operated at 42 kV, a peak current of $\sim 6\text{MA}$, and a time-to-peak-current of $\sim 7\mu\text{sec}$. Inner and outer liner radii as a function of time are shown in Fig. 1 for the second experiment in this series. The measured data are from side-on flash X-ray radiography and agree with the calculated trajectories. Impact with the 0.5 cm radius pyrometry structure, located on axis, occurs at 10 μsec . In a cylindrically convergent system, the strain ϵ is related to the radius by $\epsilon = K \ln(r(0)/r(t))$, where an approximate analytic derivation yields $K = 2/\sqrt{3}$, and a code calculation $K \sim 1.33$.

A simple, approximate connection can be made between the strength of the 6061-T6 aluminum sample and the observed strain and temperature due to the liner implosion. This is possible because (a) work hardening from strain, for strains greater than a few percent, results in a nearly flat saturation of the plastic strength for this material, and (b) recent data using a Hopkinson bar suggests that strain rate effects may also saturate well below the nominal range for these Pegasus shots.^[2,6] In this case the material strength is constant at its maximum value, Y_{max} (tabulated by Steinberg), and the temperature rise is given by

$$\Delta T = \frac{1}{B} \left(1 - e^{-B \frac{Y_{\text{max}} \epsilon}{C_v}} \right)$$

where C_v is the specific heat at constant volume and B is the temperature softening factor. For 6061-T6 aluminum $B = 1/1623^\circ\text{C}$, $Y_{\max} = 680\text{J}/\text{cm}^3$ and C_v is $2.55\text{ J}/\text{cm}^3\text{C}$. A temperature trajectory based on this model and the experimental $r(t)$ is compared in Fig. 2 with the temperature measured by a four channel i.r. pyrometer.⁵ In this case, some background subtraction has been performed to reduce the effect of contaminating radiation. This arises from the interaction of the moving liner and the stationary conductors—glide planes—at top and bottom. The liner configuration is shown schematically in Fig. 3. As the liner collapses against the pyrometer structure at 0.5 cm radius, the configuration is self-shielding. The final experimental data point for the temperature is observed to agree with the simple model presented.

The temperature data in Fig. 2 illustrate key factors in i.r. pyrometry measurements; (1) avoiding spurious radiation, and (2) knowledge of the emissivity in dynamic systems. A third experiment was fielded in this series, with low density foam baffles to block radiation from the liner-electrode interface. This proved unsatisfactory, since the foam was heated to high temperature from the snowplow action by the imploding liner. The foam did, however, block the background radiation generated by shear-strain heating at the liner-electrode interface. A fourth experiment is in preparation with a 2x higher liner and improved radiation absorption on the non-viewed surfaces of the liner system's interior.

Conclusion

Future experiments will apply this liner based high-strain, high-strain-rate yield strength measurement technique to high density metals such as platinum, tungsten, and tantalum, which have application as impactor layers on Atlas. These experiments will provide strength data in a range of combined strain and strain rate not currently accessible by other means. Data from these experiments will also facilitate a comparison between two phenomenological strength models which have different parametric dependences on strain rates.^[7,8]

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Fig. 1: Calculated and measured liner position vs. time—inner and outer radii. Measured from side-on radiography.

Fig. 2: Measured inner surface temperature compared with analytic estimate based on fully work hardened model. Strain for the analytic estimate from the measured and calculated $r(t)$. Error bars on measured temperature are due to uncertain emissivity on the sample surface (0.2 to 0.5).

Fig. 3: Cross-section of liner assembly with pyrometer head located on-axis. i.e. fiber-optic assembly not shown. 400 micron 6061-T6 Aluminum sample layer on the liner i.d.