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MHD Modeling of ATLAS experiments to Study Transverse Shear Interface Interactions

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Abstract

The transverse shear established at the interface of two solids moving at differential velocities on the order of the sound speed is being studied in experiments on the ATLAS capacitor bank at Los Alamos. The ATLAS bank has finished certification tests and has demonstrated peak currents of 27.5 MA into an inductive load with a risetime of 5 microseconds. One-and two-dimensional MHD calculations have been performed in support of these "friction-like" ATLAS experiments. Current flowing along the outer surface of a thick aluminum liner, 10 mm thick at impact with the interaction target, accelerates the liner to velocities of ~1.0-1.5 km/s. This cylindrically imploding liner impacts a target assembly composed of alternating disks of high- and low-density materials. Different shock speeds in the two two materials leas to a differential velocity along the interface. Sock heatng, elastic-plastic flow, and stress transport are included in the calculations. Material strength properties are modeled with a Steinburg-Guinan treatment in these first studies. Various design configurations for the ATLAS experiments are now being considered and will be presented.

I. Transverse Shear at Solid Interfaces and Experimental Configuration.

When two solid surfaces slide against each transverse shear stresses are generated at the interface. These stresses are then transmitted into the material interiors. Microscopically, this process is due to production of dislocations within the material lattice. Macroscopically, it leads to the phenomenon commonly known as friction. Molecular dynamic calculations have been performed on sliding interface configurations[1]. These calculations have shown detailed evolution of the dislocation distribution. Hammerberg[2] has used these and other information to formulate a new "friction" model(ref. 2). This new model predicts a power law increase in the retarding "friction" force as the relative velocity of the interface motion increases from zero up to a critical speed. At speeds in excess of this critical value, the model assumes an *exponential?* decrease in the retarding force.

On the basis of this new model, a series of experiments has been conceived to test *quantitative* aspects of the model. All experiments involve an initial configuration, consisting of pairs of materials, with a common interface surface. These targets are shocked, so the differing shock speeds in the two materials results in a relative material motion. Typically, the higher density material will have a lower shock speed than that of the lower density material. We have chosen to use a high density c material with a known low shock speed, Tantalum(Ta), on one side, and a lower density material with higher shock speed, Aluminum(Al), on the other.

Planar target experiments can be conducted, that are shocked by flyer plates, accelerated by a gas gun. The experiments that we discuss in this paper are cylindrical targets. The "flyer plate" is a cylindrical aluminum liner, accelerated by magnetic pressure from a pulsed power source. Previous experiments[3] in such converging geometry assemblies were conducted using the, now-decommissioned PEGASUS II, capacitor bank. While these experiments were quite promising, the PEGASUS machine proved to be energy-limited. This limitation resulted in a less-than optimum experimental configuration: the liner was only 4.0 mm thick and the outer diameter of the target only about 30 mm. More powerful machines were needed to relax these constraints so that more satisfactory tests of the "friction" model could be designed.

The target geometry for ATLAS experiments will have a diameter of 40-54 mm, with a hollow opening in the center to ameliorate jet formation on the axis. The liner is designed so that it will be ~10 mm thick at the time of target impact. This will sustain the target shock waves for a longer period. The initial outer diameter of the aluminum liner will be 100 mm in the initial experiments, but may be reduced to 80-90 mm on subsequent shots, as dictated by radiographic needs. At 100 mm OD, the initial thickness will be between 5.73-6.87 mm thick, depending on the target diameter. In all cases, the impact liner thickness will be ~10 mm.

The primary diagnostic for transverse shear during the plastic flow will be thin, soft, high-density wires embedded in the more radiographically transparent material. With present LANL x-ray sources, the Tantalum is too opaque to yield any radiography data. The Aluminum can be accurately imaged, however. With high-Z material such as lead (Pb) for the wires, the wire/Aluminum contrast will allow imaging of the wire motion. If, as expected, the soft wire deforms and flows with the Aluminum material, then the motion of the wires will provide direct evidence of the plastic flow of Aluminum under the forces induced by the interface friction. Comparison of the measured wire motion with 2-D hydrodynamic calculations will help confirm the validity of the friction model.

II. Numerical Modeling of the Experiments

The ATLAS pulsed power system has recently been commissioned. Certification shots drove 27 MA of electrical current through an inductive load. Current rise time was 5-5.5 μs.

The basic experimental parameters were defined with one-dimensional MHD simulations of the liner motion, subject to the design constraints discussed above. The calculations were "driven" by a circuit model of the ATLAS pulsed-power system. ATLAS is modeled with a capacitance of 816 μF, a total inductance of xx nH, and series resistance of Ω. A typical current waveform from this circuit model is Figure 1.

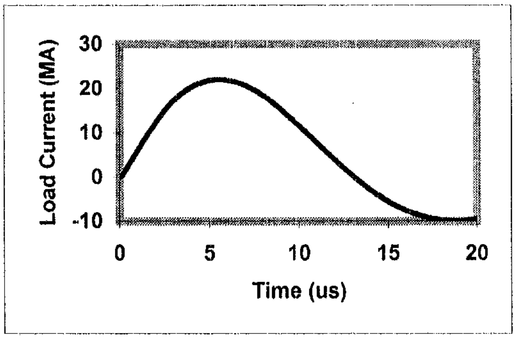

Figure 1. Typical load current waveform from ATLAS circuit model, 150 kV bank voltage.

The calculation closes approximately the current waveform measured during the ATLAS certification tests. Note that current reversal occurs at about 13 μs. This is significant because some of these very thick liner designs do not impact the target until 18-20 μs. Behavior of these liners during current reversal should prove interesting.

III. 1-D MHD Numerical Study

The basic experimental parameters, liner thickness, liner radius, target radius, and peak current were derived from the 1-D calculations, with the ATLAS bank voltage being the independent variable, used to vary load current. All design calculations were conducted subject to the constraint that the impact velocity on the target should be 1.4-1.5 km/s, and that the liner, approximately 10 mm thick at impact. The evolution of a the liner and target surfaces of a promising design, with initial outer liner radius of 50.0 mm and initial outer target radius of 26.0 mm is shown in Figure 2. The corresponding velocity history of the liner's inner surface is displayed in Figure 3.

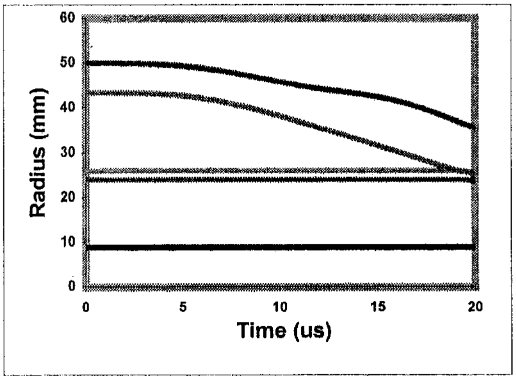

Figure 2. Motion of liner an target surfaces, driven by the Current in Figure 1.

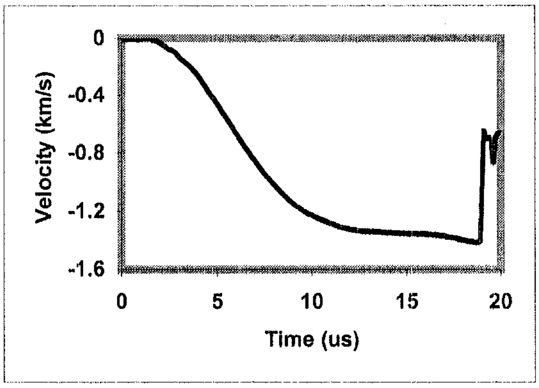

Figure 3. Time history of the velocity of the liner inner surface.

It should be noted that the liner reaches 95% of its peak velocity by time 13.0 μs (current reversal). It has traveled only 9.09 mm by this time. Since the initial distance between liner and target was 17.3 mm, additional time was required to reach the target, during which the liner essentially coasted ballistically. The choice of 50.0 mm for an initial liner radius is motivated by our intention to maximize the liner/glide plane interaction, to assess any effects related to current reversal, and to validate our numerical design tools. This last will be discussed more in Section IV.

The fact that these thick liners almost reach the limiting velocity much earlier in the waveform (c.F. Fig. 3), suggests that a liner could satisfy the target impact constraint with a reduced initial liner radius. Such an experiment could be designed to impact the target before current reversal. Detailed calculations confirm this. For instance, a liner that is initially 8.0 mm thick, with a 44.0 mm outer radius is predicted to reach a 27.0 mm radius target at 12.4 μs. At that time, the 1-D calculations yield an inner surface velocity of 1.48 km/s.

Parametric numerical studies have been conducted to better understand the range of acceptable liner designs, subject to the above-discussed constraints, driven by an ATLAS waveform. These studies are examined the variation of bank charging voltage, of initial liner radius, and of target radius. This last has practical significance, because extant LANL radiographic sources do not provide adequate contrast when then chordal thickness of the liner/target assembly is too thick. Smaller targets give better X-ray transmission with the photon spectrum of existing sources. The variation of impact velocity with target radius is shown in Figure 4, for three different bank voltages. Initial radius for all liners here was 50.0 mm.

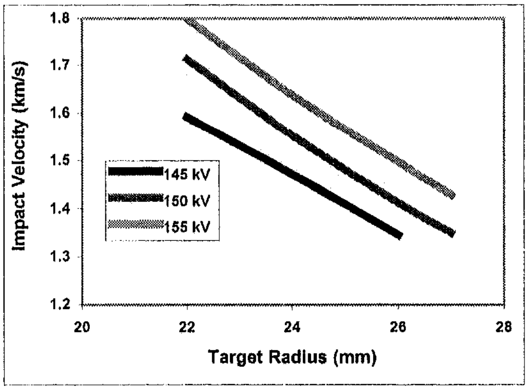

Figure 4. Variation of final liner velocity as a function of target radius; 10 mm thick liner at impact.

During early operations at ATLAS, it is expected that peak currents will be limited to about 22 MA, which corresponds to about 155 kV for these thick liner loads. It is not known certainly at this time what the lower voltage limit for reliable triggering will be, so 145 kV is a conservative lower bound.

IV. 2-D MHD Numerical Study

The impact times for all of the large radius designs were well beyond 13 μs. Since these were 1-D calculations, the significant interaction between the thick liners and the electrode walls was not treated. For all designs in which the liner is drifting during the current reversal phase, it is highly doubtful that this interaction is really negligible. To better estimate the long-time (~15-20 μs) interaction effect, two-dimensional MHD calculations are being performed to investigate liner/wall phenomenon.

A typical two-dimensional configuration for these 2-D calculations in shown in Figure 5.

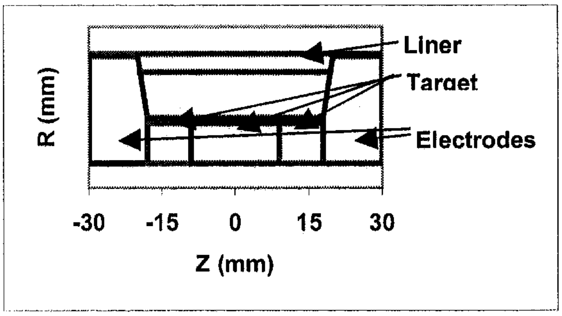

Figure 5. Schematic of initial configuration used in 2-D MHD calculations.

The liner is composed of virtually pure, soft Al-1100 aluminum alloy. To minimize the early-time shear effects, only about 1 mm of the liner thickness extends above the top edge of the electrodes. The target is composed of alternating "lifesaver" wedges, as discussed in Section I. For the first calculations, a Steinberg-Guinan (ref) strength model is employed for all materials. Other, more sophisticated strength models exist, but the liner should experience only modest strains and strain rates. From the 1-D calculations, we expect that the liner will be strained about 45% by the time it has imploded to the radius of the target. Similarly, the strain rate is predicted to be less than 10^5 s^{-1}. Steinberg-Guinan is probably adequate for these conditions.

Preliminary results show that the liner gives moderate galling on the electrode surfaces after only a few millimeters of motion. As the liner accelerates above 1 km/s, however, this deformation of the electrode appears to saturate. The inner surface of the liner near the electrode bends so that the middle of the liner (axial-sense) lags that part near the walls after about 10 mm of motion. The discrepancy is less than one millimeter at that point.

A suggestion has been made to employ harder, denser materials for the electrodes. The initial design used copper electrodes, which have excellent electrical properties, but are quite soft. Early results using tungsten (W) electrodes seem promising, but further analysis is needed before the value of tungsten electrodes is properly assessed.

V. Summary

A new model for the transverse, sliding forces between two solid interfaces has been proposed. The critical speed differential is accessible with liner/target experiments being designed for the ATLAS pulsed power system. Liners with unprecedented thickness are required to sustain shocks in multi-material targets. One-dimensional MHD calculations indicate that there will be a significant spectrum of design parameters that should yield successful liner performance. The design constrains are that the liner should be 10 mm thick at the time of liner impact with the target, that the inner surface velocity should be 1.4-15 km/s, and that the inner surface should be flat. Two-dimensional MHD calculations are being performed to evaluate the large interaction between the liner and the electrode walls, and to confirm the "flatness" of the liner at impact time. ATLAS experiments are scheduled for the first and second quarters of FY02 at LANL.

VI. References

[1] Hammerberg, Holian
[2] Hammerberg
[3]Kyrala
[4] D. Steinberg, Guinan, ...