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A PEGASUS DYNAMIC LINER FRICTION EXPERIMENT[†]

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Abstract. We report on a pulsed power experiment performed at the Los Alamos National Laboratory Pegasus facility which was designed to measure material flow at metal interfaces driven to high relative velocities. Material motion at and near four flat Ta/Al(6061) interfaces was measured using flash radiographic techniques. A series of fine Pb wires (407 micron diameter) was implanted in the Al normal to the interfaces. The motion of these markers under shock loading provided a picture of material motion in the Al interfacial region. The surface roughness of the interfaces was varied between 32 and 125 micro-inches. We discuss the implications of these measurements for constitutive models of high speed friction and interfacial morphological change.

INTRODUCTION

Material motion at a shock loaded metal-metal interface is extremely difficult to observe in a quantitative fashion. The theory of the tangential force law appropriate to hydrodynamic computer codes is very approximate for material slip velocities approaching significant fractions of the sound speeds of the interfacial materials and for the large pressures achieved in shock loading. There is evidence from atomistic simulations (1) that for relative velocities greater than 0.1 times the sound speed, the coefficient of friction scales as $(v_{rel} / c_t)^\alpha$ with α of order 0.7 where c_t is the transverse sound speed. However, the experimental data is meager at best for such high speeds and at very large compressions (pressures of order 100kbar and above) is non-existent. The present experiment is an attempt to rectify this situation by interrogating a shock loaded ductile metal - ductile metal interface. The technique is to radiograph thin (407 μ m diameter) lead wires placed perpendicular to a Ta/Al interface. The wave speeds in these two materials are such that high relative

velocities are achieved in tangential shock loading. This method allows us to map Lagrangian mesh motion at and near the interface. The following sections discuss the Pegasus friction experiment target, diagnostics, results, and a preliminary analysis of the data.

THE PEGASUS FRICTION TARGET

The Pegasus pulsed power facility is designed to accelerate a cylindrical liner (usually an Al(1100) alloy) onto a target object which is typically cylindrical in shape. The drive is provided by $\mathbf{j} \times \mathbf{B}$ forces generated by the discharge of a high energy capacitor bank (2). In the present experiment, we have taken advantage of this geometry to drive a set of cylindrical shock waves along a set of interfaces. The target geometry is shown in fig.1. It consists of an Al(1100) outer cylinder of thickness 2mm and outer diameter 30mm. This cylinder consists of four wedges, two Al(6061) pieces and two Ta pieces. The Ta wedges have opening angles of 60° and 120°. The interfaces between the Ta and Al were machined to different surface roughnesses. Along

the 120° Ta piece, the roughness was 32 μ inches rms. The surface roughnesses for the 60° Ta wedge faces were 63 and 125 μ inches. The inner cylindrical hole (diameter 6mm) was filled with Xe gas at 2 atmospheres pressure. The target was closed at the top and bottom with a lexan endcap.

FIGURE 1. Top view of target geometry. Stars indicate axial sources. Radial source directions are indicated by P1, P7, and P13.

The cylindrically symmetric liner impact drives shock waves inward into the two materials. Since the shock wave speeds in Al are greater by roughly a factor of 1.6 than the shock speeds in the Ta, the Ta/Al interface experiences differential slip. The amount of slip depends on the tangential force at the interface, i.e. on the interfacial frictional force. It was the purpose of the present experiment to attempt to measure, radiographically, the true extent of deformation in the aluminum near the interface under loading conditions such that the radial velocity of the liner at impact with the target was 1.2 km/sec. The method we used to do this was to implant a series of thin wires into the aluminum normal to the interface. These wires are representations of Lagrangian mesh lines and the object of this experiment was to measure the deformation of the wires and hence the deformation of the mesh near the interface as a function of time. In order for the wires to truly represent the mesh, they must be fine enough to present a minor perturbation to the material flow in the aluminum. They must, however, be thick enough to give sufficient radiographic contrast relative to the Al background in which they are embedded. We have found that Pb and Sb have

shock impedances sufficiently near Al and high enough atomic number to give good hydrodynamic matching and x-ray contrast. They also have relatively high melting temperatures ($T_m(\text{Al})=934^\circ\text{K}$, $T_m(\text{Pb})=601^\circ\text{K}$, and $T_m(\text{Sb})=904^\circ\text{K}$). The Pb wires were radiographed in a static sample and wires of 407 μm were deemed to give sufficient contrast. These wires were placed in the aluminum about the midplane of the Al/Ta interfaces. They were placed in a skewed arrangement rather than along the midline so as to avoid possible wake effects from the other wires in the presence of the radially converging shock. The wires were typically 3mm in length although some were shorter. Two wires of diameter 370 and 308 μm were placed along one of the 120° faces near the central void so that we could compare their images with the symmetrically placed 407 μm wires on the other 120° face. The arrangement of the wires is shown in fig. 2 in a top view.

FIGURE 2. Top view of target showing Pb wire configuration

The diagnostics included four axial x-ray sources, three radial sources, and an axial framing camera to view the progression of the Xe gas shock. These diagnostics are described in the next section.

DIAGNOSTICS

Flash radiography was the primary diagnostic for the experiment. Four radiographs were taken with a line-of-sight along the target axis (axial radiographs), and three radiographs were taken with lines-of-sight along target radii (radial radiographs). The purpose of the axial radiographs was to view

the motion and distortion of the lead markers as the experiment progressed.

The purpose of the radial radiographs was two-fold: One radial radiograph was used to view the liner prior to impact with the target; the other two radial radiographs were used to view gross distortions of the target during the experiment. The x-ray sources are marx driven diodes that employ a tapered tungsten rod, 1.5 mm in diameter, as the x-ray emitter. The duration of the x-ray pulses is 20 ns FWHM. The axial radiographs are imaged with a sodium iodide fluor that is viewed by four gated CCD cameras. This configuration permits capturing four images separated in time along the same line-of-sight. For this experiment, axial radiographs were imaged using a film-screen combination. Each radial radiograph has separate line-of-sight and each is rotated by 120 degrees from the other. The radial radiographs were taken at 13.69, 15.87, and 17.37 μsec after current start.

In addition to viewing the target with x-rays, the central cavity of the target was also viewed axially with two framing cameras. The purpose of the cameras was to sequentially image the luminous shock front in the xenon filled cavity that was expected when the shock exited the aluminum and tantalum pieces. Also employed during this experiment were a number of current diagnostics used to measure the current through the liner and the symmetry of the current drive.

EXPERIMENTAL RESULTS

The timings for the axial and radial sources and the framing camera were chosen based upon a calculation of liner impact which used a model shown to be valid for precision liner experiments. This calculation gave liner impact at 14.12 μsec after current onset. For adequate image separation it is necessary to separate the axial images by 0.75 μsec . The axial timings were taken to be 15.12, 15.87, 16.62, and 17.37 μsec so that the first image would occur when the Al shock had traversed roughly 1/3 the distance to the inner surface, the second image when the Al shock has almost reached the inner surface, the third image close to maximum compression and the last image occurring during disassembly. The 16 visible framing images were spaced 0.10 μsec apart and

timed to be able to see shock breakout. The first radial image at 13.69 μsec was calculated to show the state of the liner 0.42 μsec before target impact and the remaining two images at 15.87 and 17.37 μsec were timed to see subtle features in the Ta deformation.

All of the sources and cameras performed nominally. However, the framing camera images were all dark, i.e. prior to 17.12 μsec , the last framing image, no shock had entered the Xe gas region. Also, the radial image at 13.69 μsec showed the liner to be at a distance of 1.9 mm from the target surface. The radial image at 15.87 μsec is consistent with contact and we estimate that actual impact occurred probably close to 15.3 μsec . Assuming that this number is correct, the last image at 17.37 μsec corresponds to the Al(6061) shock being at the inner surface. This is consistent with the fact that there is no evidence for Al extrusion into the central region at this time. There is, however, significant observable motion of the Pb marker wires at this time.

The present experiment used a thicker than usual liner. An unanticipated consequence of this fact was that the sample was recovered quasi intact. The Al liner flowed plastically about the target and engulfed the Ta pieces and part of the Al wedges. Other parts of the Al wedges separated from the target. The final state of the recovered target is shown in fig. 3.

FIGURE 3. Recovered target. dark wedges are Ta pieces.

DISCUSSION

Figure 4 shows a comparison of the last dynamic axial (17.37 μsec) image with the static image. The static dynamic, and subtracted images

FIGURE 4. Comparison of deformation of target at 17.37 μ sec with initial state. Left image static; middle image: dynamic; right image: difference.

are shown. There has been significant motion along the interface of order 0.5 mm. This motion is consistent with the order of magnitude of motion indicated in two-dimensional Lagrangian materials dynamics computer code simulations of this impact using rate-dependent models of material flow for Al and Ta. There is significant motion for the first five wires. The last three wires, nearest the center, have not yet had time to move appreciably.

FIGURE 5. Line traces parallel to the 63 μ in interface. Minima correspond to wire positions. Y axis in arbitrary units. X axis is in pixel units. Lower curve in Ta, upper curves in Al. $t = 17.37 \mu$ sec.

Figure 5 shows a preliminary analysis of the wire distortions for the interface having 63 μ inch roughness. A rectangular section of the total image, containing this interface, was analyzed using a singular value decomposition of the bit mapped image using 5 eigenvectors (see (3) for a description of this

method). A series of line traces leading away from the interface is shown in fig.5 with the initial (lower curve) trace located just within the Ta. The inner surface is at the right of the figure. The minima locate the wire positions. The wire shape is clearly discernible.

These preliminary analyses of the experimental data indicate that we are able to map the Lagrangian flow near the interface at the 0.1mm level. The radiography in this first Pegasus friction measurement performed very well and has allowed us to resolve interfacial flow under dynamic conditions. This information will allow us to assess the validity of models for interfacial frictional forces and computer code representations of interfacial hydrodynamics. We are presently completing a detailed analysis of all four interfaces and metallographic examination of the recovered object. Of particular interest to us is the change in surface and subsurface morphology.

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- † Work performed under auspices of U.S. DOE at LANL under contract W-7405-Eng-36

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INTRODUCTION

- Theory of tangential force at compressed metal-metal interfaces moving at large relative velocities is in a state of development.
- Atomistic simulations indicate the possibility of universal behavior for speeds above $0.1 C_{\text{transverse}}$ with a decrease of the coefficient of friction with increasing velocity due to the dynamic formation of microstructure.

- There is very little experimental data at high velocities and high pressures (~100kbar).
- The purpose of the PEGASUS experiment was to demonstrate a new technique to obtain information about interfacial deformation under these conditions.

PEGASUS FRICTION TARGET

- Cylindrical target composed of Ta and Al wedges
- Surface roughness machined on Ta/Al(6061) interfaces: 32 μm , 63 μm , 125 μm , and 125 μm .
- Initial Al(1100) liner impact velocity 1.2 km/sec
- Pb wires (3mm length, 407 μm diameter) implanted in Al perpendicular to the Al/Ta interface near mid-plane

TopView Layout:

8 Holes, each hole size is the same and is .425 diam
 Centers Separated vertically by 0.450 mm [17.72 mils]
 Centers Separated radially by 1.2857 mm [50.62 mils]
 Fill each hole by a 407 micron-diameter Lead Wire [16.5 mils]
 Except for 2 holes at 120 degrees.

Velocities at Impact

$$V_{\text{radial}} = 0.14 \text{ cm} / \mu\text{sec}$$
$$T = 0$$

FIG. 2

V_R VS. R

$T = 1.5 \mu\text{sec}$

P VS. R

$T=1.5\mu\text{sec}$

DIAGNOSTICS

- Flash radiography was primary diagnostic
- Four line-of-sight axial images to measure distortion and movement of Pb markers
- Three line-of-sight radial images separated by 120 degrees to view gross target distortions

- Central cavity viewed axially with two framing cameras to view shock in Xenon gas
- Axial detectors sodium iodide fluor viewed with four gated CCD cameras
- Axial timings: 15.52, 15.87, 16.62, and 17.37 μsec after current onset
- Radial timings: 13.69, 15.87, and 17.37 μsec after current onset
- Optical framing camera: sixteen images 0.1 μsec apart beginning at 15.62 μsec after current onset

EXPERIMENTAL RESULTS

- All sources and cameras performed nominally
- No images seen in framing cameras due to late impact of liner on target
- Actual impact occurred at approximately 15.4 μsec after current onset.
- All radial and axial images obtained with the last radial image at 17.37 μsec

corresponding to AI shock near the
inner surface of the target

Friction

Pegasus #1112, 1 October 1998

Static

Dynamic

Difference

Time: 15.12 μ s

Friction

Pegasus #112, 1 October 1998

Static

Dynamic

Difference

Time: 15.87 μ s

Friction

Pegasus #112, 1 October 1998

Static

Dynamic

Difference

Time: 16.61 μ s

Static

Dynamic

Difference

Time: 17.35 μ s

DISCUSSION

- Motion of Pb markers of order 0.5 mm observed
- We have begun analysis of the detailed wire shape using principal component analysis and anticipate shape accuracy to 0.1mm
- Target recovered almost intact and is being analyzed metallographically to quantify microstructural changes near the interface

- Experiment has provided detailed dynamic information of the interfacial deformation at relative velocities of order 0.5 km/sec and pressures of order 200 kbar for frictional force models