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Influence of shockwave profile on ejection of micron-scale material from shocked Sn surfaces: An experimental study

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Abstract. This effort experimentally investigates the relationship between shock-breakout pressure^a and the amount of micron-scale fragments ejected (ejecta) upon shock release at the metal/vacuum interface of Sn targets shocked with a supported shockwave. The results are compared with an analogous set derived from HE shocked Sn targets, Taylor shockwave loading. The supported shock-pulse was created by impacting a Sn target with a Ti64^b impactor that was accelerated using a powder gun. Ejecta production at the free-surface or back-side of the Sn targets were characterized through use of piezoelectric pins and Asay foils, and heterodyne velocimetry verified the time of shock release and the breakout pressure.

1. INTRODUCTION

Los Alamos National Laboratory (LANL) is actively engaged in the development of a model to predict the formation of micron-scale fragments ejected (ejecta) from shocked metal surfaces. This work consists of experimental, computational, and theoretical efforts [1-7]. Across all efforts, it has been assumed that the shock pulse shape, i.e., the shock pressure vs. time profile, does not affect the quantity or distribution of ejecta. Recent work in the shock compression field, however, links the shock-pulse's shape to the amount, and type, of material damage within bulk shocked material [8-9]. These results imply creation of ejecta, which is also a damage process, may be related to the shock loading profile.

Previous ejecta characterization, where the ejecta was created from machine roughened Sn targets using Taylor shockwave loading, examined production as a function of varying shock-breakout pressure, $185 \leq P_{SB} \leq 285$ kbar [3,6]. This P_{SB} region is of particular interest because it crosses a Sn material phase boundary near 195 kbar [10-12]. The experiments in [3,6] showed that the ejecta quantity and distributions are primarily dependant on material phase at shock-release and the surface defect geometry. To evaluate whether the shock loading profile affects ejecta production, we repeated the HE-shockwave loading experiments using supported shockwave loading.

To quantify the ejecta production and distribution, we measured ejecta properties such as the ejecta dynamic areal density, dm/dA , the dynamic volume density, $\rho^*(t, \zeta)$, and the static volume density distribution, $\rho(z, \tau)$, using piezoelectric pins [2] and Asay foils [13]. Additionally, optical-heterodyne velocimetry (OHV) [14-15] was fielded to measure the asymptotic free-surface velocity and shock-breakout time.

^a Shock-breakout pressure is defined as the peak internal longitudinal material pressure just prior to shock release at the material free-surface.

^b Ti64 (Ti-6Al-4V) is a titanium alloy with 6 weight percent aluminum and 4 weight percent vanadium.

2. EXPERIMENT METHOD

A total of seven supported shockwave experiments monitoring ejecta production from Sn targets were conducted at LANL. The supported shockwave profiles were tailored by launching *sabots* tipped with 2mm thick Ti64 plate impactors at the targets using a powder-driven gun. Ti64 was selected as the impactor material because of its close shock-impedance match to Sn at these pressures, which minimizes the amplitude of shock reflections from the impactor/target interface.

The powder-driven gun, schematically depicted in Fig. 1, has a 40mm bore within a barrel that is 3 meters in length, and is able to launch *sabots* to velocities up to ~ 1.9 km/s. Varying the quantity of IMR-4350 powder deflagrated for each shot varied the impact velocity, and consequently P_{SB} . Measurements of tilt between the impactor and target typically ranged from 1 to 5 mrad, validating our approximation of one-dimensional loading in the shocked samples.

The Sn targets (ESPI, >99.99% purity) were cylinders of 50 mm diameter and 2 mm thick. The target impact side (front-side) and free-surface (back-side) were prepared with a “fly-cut” machine finishes^c. The front-sides were characterized by a surface roughness average of $R_a = 16$ μm and wavelength $\lambda = 83^\circ$, and the back-side by $R_a = 32$ μm and $\lambda = 83^\circ$.

Lithium Niobate piezoelectric pins and Asay foils were fielded to measure ejecta created upon shock release at the target/vacuum interface. A detailed description of the piezoelectric pins [2,4,7] and Asay foils [13], as well as their operational physics, are given elsewhere. Generally, the pin diagnostics return a voltage signal that is proportional to the time derivative of the pressure (force) on the pins as the ejecta accrete onto the pin surface. Using the pin’s known offset from the target free-surface, and measured piezoelectric sensitivity coefficients, one can calculate the desired quantities used to characterize the ejecta (dm/dA , $\rho^*(t, \zeta)$, and $\rho(z, \tau)$ [4,7]). Asay foils relate similar information, but operate on the principle that momentum transfer from accreting ejecta accelerates a foil. The foil acceleration is monitored using velocimetry interferometer system for any reflector (VISAR) [16].

Figure 1. Schematic representation of the powder-driven gun used to collect the supported shockwave ejecta data.

The experimental configuration used to obtain ejecta measurements is shown schematically in Fig. 2. Design of the experimental configuration accounted for shockwave reflections at the target edges, as well as the possibility of ejecta jetting from piezoelectric pin and Asay foil diagnostics, to ensure uncorrupted ejecta measurements. Analysis in this work centers on piezoelectric pin results that were validated with coincident Asay foil measurements.

^c A “fly-cut” machine finish consists of a series of concentric triangular or saw-tooth grooves machined into the surface. A detailed description of fly-cut machined targets is given elsewhere [3].

Figure 2. Schematic representation of the experimental configuration used when acquiring ejecta data.

3. RESULTS AND DISCUSSION

3.1 CTH calculations

Figure 3 shows one-dimensional CTH [17] calculations of the supported shockwave profiles from the seven experiments. The calculations use the experimentally measured *sabot* velocities (u_{impact}) to infer the internal longitudinal stress (or pressure) of the shock profile throughout the materials just prior to shock-breakout at the Sn/vacuum interface. All calculations used a Mie-Gruneisen (MG) equation of state (EOS) for the Sn target, Ti64 impactor, and Lexan sabot. Further, the calculations used pristine finishes, without “fly-cut” perturbations, therefore focusing on shockwave propagation without development of surface instabilities.

Figure 3. One-dimensional CTH calculations of internal longitudinal stress (or pressure) through the bulk material just prior to shock release at the Sn/Vacuum interface.

The calculated forward traveling (left-to-right) shockwaves show steep rises in pressure to $P = P_{\max}^{Sn}$, which is sustained throughout the Sn target bulk (a.k.a. a supported profile). The calculated backward traveling (right-to-left) shockwaves show steep rises in pressure to $P = P_{\max}^{Ti64}$, with corresponding $P_{\max}^{Ti64} < P_{\max}^{Sn}$ due to material shock impedance mismatches. It is noted that $P_{\max}^{Sn}$ is directly proportional to the *sabot* impact velocity. As time progresses, the forward traveling shockwave releases at the Sn/vacuum interface, causing instabilities to quickly form ejecta from the surface perturbations, returning the material to a near-zero pressure state, $P^{Sn} \approx P_0 \approx 0$. Interaction of this release wave with a reflected release wave from the Ti64/Lexan interface occurs within the bulk of the Ti64 impactor, extinguishing reflections that might reach the Sn/vacuum interface. This enables an uncorrupted ejecta measurement from a single supported shock event.

3.2 Experimental results

Figure 4 shows the measured, supported shockwave cumulative areal masses normalized to the product of the Sn volume density ($\sim 7.3 \text{ mg/cm}^3$) with the surface defect volume, defined as the jetting factors, $R(\Theta)$. In the figure, $R(\Theta)$ is plotted versus the breakout pressure P_{SB} . In the region of $P_{SB} \leq 195 \text{ kbar}$, Region 1, the Sn shocks to a solid material state and releases to a solid material state [10-12]. It was previously shown that metals prepared with large, "classical" grooves (defects of order 10 to 100 μm), that the total ejected mass could be approximated by the missing mass associated with the defect volume, i.e., $R(\Theta) \sim 1$ [18-19]. Our measurements present quantities of ejecta slightly lower than those published results. The differences between the earlier results and those reported here could be linked to several factors. For example, we measured ejecta masses from surfaces prepared with periodic machining grooves whereas the earlier results measured ejecta masses from a single groove.

Figure 4. Jetting factors from the seven supported shockwave experiments. Each point represents the average jetting factor from ~ 6 Lithium Niobate piezoelectric pins, fielded simultaneously, during the seven shockwave experiments.

In addition, the measured peak-to-valley amplitudes for our target groove defects were significantly less than the previous work, $\sim 3.2 \mu\text{m}$ compared with $\sim 100 \mu\text{m}$. Finally, we measured Sn ejecta masses and the previous work measured Al and Pb ejecta masses.

Returning to our Sn work, as the Sn shock pressure increases beyond $P_{\text{SB}} \sim 195 \text{ kbar}$, Region 2, Sn is thought to undergo a shock induced phase transition on release, e.g., above these pressures Sn is thought to shock to a solid state, but release to a mixed solid/liquid state [10-12] in Fig. 4. As P_{SB} increases, the liquid to solid mass fraction at shock-release increases until $P_{\text{SB}} \sim 330 \text{ kbar}$, at which time Sn is thought to shock to a solid state and then release to a 100% liquid state [20]. Our measurements of ejecta jetting factors throughout this region show the quantity of ejecta increases approximately linearly with P_{SB} , at a rate of $0.108/\text{kbar}$. This is contrasted with the Taylor wave results [3,6] where the quantity of ejecta mass appears to quickly rise from $R(\Theta) \ll 1$ to $R(\Theta) \sim 4$ between $195 \leq P_{\text{SB}} \leq 230 \text{ kbar}$, followed by nominally constant ejecta production, $R(\Theta) \sim 4$, from $230 < P_{\text{SB}} \leq 285 \text{ kbar}$ [3,6].

Possible reasons for differences in the ejecta quantity produced via Taylor and supported shockwave loading arise because ejecta production is a time dependant process, not an instantaneous event. Using Taylor loading, the material releases into a state of tension immediately upon shock release/reflection at the free-surface. Using supported loading, the internal material pressure cancels, ideally to zero pressure, upon release/reflection at the free-surface. These differences may influence instability formations differently for the different shockwave loading regimes. Further, it is possible that the different shockwave physics may influence physical mechanisms that contribute to the production and/or halting of instability growth, i.e., possible micro-spall separation of layers near the free-surface. Another possibility is that the two loading profiles contribute different particle size distributions of ejecta. This may effect the particle velocity distribution as well as the total quantity.

4. CONCLUSION

We characterized ejecta from seven machine roughened Sn targets shocked with supported shockwave profiles spanning the region $185 \leq P_{\text{SB}} \leq 266 \text{ kbar}$. This region served well for ejecta studies because it covers pressures that result in release to a solid state throughout pressures that release to a mixed solid/liquid material states.

For $P_{\text{SB}} \leq 195 \text{ kbar}$, ejecta jetting factors resulted in values less than unity. This indicates that the machine-roughened surfaces did not eject the amount of mass associated with one defect volume, as was previously reported from "classical" grove measurements on other materials.

For $195 < P_{\text{SB}} \leq 265 \text{ kbar}$, ejecta jetting factors increased with a linearly dependant relation to P_{SB} , at a rate of $0.108/\text{kbar}$. These results differ from Taylor shockwave loading ejecta measurements, which showed a relatively steep increase from $195 < P_{\text{SB}} \leq 230 \text{ kbar}$, followed by a region of relative constant quantities of ejecta production from $230 < P_{\text{SB}} \leq 285$.

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