Title: Transport of Particulate Matter from a Shocked Interface

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Transport of particulate matter from a shocked interface

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We have performed a series of shock experiments to measure the evolution and transport of micron and sub-micron Tungsten particles from a 40 micron thick layer deposited on an Aluminum substrate. Densities and velocity distributions were measured using proton radiography at the Los Alamos Neutron Science Center for vacuum conditions and with contained Argon and Xenon gas atmospheres at initial pressures of 9.5 bar and room temperature. A common shock drive resulted in free surface velocities of 1.25 km/s. An analysis of the time dependence of Lithium Niobate piezo-electric pin pressure profiles is given in terms of solutions to the particulate drag equations and the evolution equation for the particulate distribution function. The spatial and temporal fore-shortening in the shocked gas can be accounted for using reasonable values for the compressed gas shear viscosities and the vacuum distributions. The detailed form of the pin pressure data for Xenon indicates particulate breakup in the hot compressed gas.
Transport of Particulate Matter from a Shocked Interface

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Material Ejection at a Shocked Interface

There are three processes which characterize particulate ejection at a metal – gas interface.

1. Shock release at the interface into a solid, fluid or mixed phase
2. Interface instability and production of a size and velocity distribution of particles
3. Transport through the shocked gas and possible particle breakup

We describe an experiment for particle transport for which the initial distribution of W particles is well characterized and the subsequent time-dependent velocity distribution function is measured in Ar and Xe gases.
Experimental Assembly

Analysis of the Piezo-Pin Data

Distribution function:

\[ f(r, v, m; t) \, dr \, dv \, dm \]

\[
\frac{\partial f}{\partial t} + v \cdot \nabla f + \frac{F}{m} \cdot \frac{\partial f}{\partial v} \frac{dt}{dt_{local}} = \frac{1}{\tau} \frac{df}{dt}
\]

Solution in absence of scattering

\[
f(r, v, m; t) = \int \delta(r-r(t))\delta(v-v(t)) f_0(r_0, v_0, m) \, dr_0 \, dv_0
\]

\[
\frac{dr(t)}{dt} = v(t) \quad \frac{dv(t)}{dt} = \frac{F}{m}
\]

\[ r(0) = r_p \text{ and } v(0) = v_0 \]
Analysis of the Piezo-Pin Data

Piezo probe pressure assuming fully inelastic collisions

\[ P(t) = \int f(z, v, m, t) m v^2 \mathrm{d}m \mathrm{d}v \]

Solutions for non-zero external field: particle drag

\[
F = -\frac{1}{2} \rho \mathcal{C}_D \mathcal{A} (v - v_a) (v - v) \\
\mathcal{C}_D = 0.42 \\
\mathcal{D} = \frac{D}{v} \\
\mathcal{R}_e = \frac{v}{\nu} \\
\mathcal{R}_e = 1.67(Re) \mathcal{D} \\
\mathcal{R}_e \leq 10^3
\]

General spherical drag coefficient

\[
\mathcal{C}_D = \frac{24}{Re} (1 + 0.167 Re^{0.7}) \\
\mathcal{C}_D = 0.42 \\
\mathcal{D} = \frac{D}{v} \\
\mathcal{R}_e = \frac{v}{\nu} \\
\mathcal{R}_e = 1.67(Re) \mathcal{D} \\
\mathcal{R}_e \leq 10^3
\]
Analysis of the Piezo-Pin Data

Simplifications for separable distribution functions

\[ f_v(v,m) = f_v^{(1)}(v)f_v^{(2)}(m) \]

\[ \rho(z,t) = \frac{1}{A} \int f_v^{(1)}(v_0(z,t)) \left[ \int_{\text{d}u_0} \rho_0(z_0,m) \text{d}m \right] \text{d}v \]

\[ = \frac{1}{M} \int P_0 \left[ \int_{\text{d}u_0} \frac{v_0(z,t)}{v_0(z,t)} \right] \left[ \frac{v_0(z,t)}{v_0(z,t)} \right] \rho_0(m) \text{d}m \]

\[ P(t) = \frac{1}{M} \int P_0 \left[ \int_{\text{d}u_0} \frac{v_0(z,t)}{v_0(z,t)} \right] \left[ \frac{v_0(z,t)}{v_0(z,t)} \right] \rho_0(m) \text{d}m \]

where

\[ v_0(z,t) = v_n + u_n(z,t) \]

and \( u_n(z,t) \) is the solution of

\[ z - v_n t = u_n(z,t)r(t,u_n(z,t)) \]
Transport of W surface ejecta in Ar and Xe

Recent experiments with W nearly monodisperse particles were carried out with Ar and Xe gases at the Los Alamos Neutron Scattering Center.

For a monodisperse distribution of particles the 1-D integrals become functions:

\[ P(Z, t) = \frac{t}{\lambda(z,t)\tau(t)} \left\{ 1 - \frac{t}{t_0} \frac{1}{\lambda(z,t)} \left( 1 - \frac{V_{st}t}{z} \right) \right\}^2 \frac{t}{P_0} \frac{1}{\lambda(z,t)} \]

\[ \lambda(z,t) = 1 + \left( \frac{t}{\tau(t)} - 1 \right) \left( 1 - \frac{V_{st}t}{z} \right) \]

\[ \tau(t) = t_0 \left( 1 - \exp\left(-\frac{t}{t_0}\right) \right) \]

Stokes drag – Μικρον παρτικλέ σιζε Ω παρτικλέσιν Αρ

Vertical scale: Pressure (bar). Horizontal scale: Velocity (km/s). Thick curve: Argon gas experimental data. Thin curve: Calculation assuming Stokes drag using \( t_0 = 8.5 \mu s \), corresponding to a value of viscosity of 118 microPa·s.
Stokes drag: 0.1–1.0 μm particles σιζε Ω

Vertical scale: Pressure (bar). Horizontal scale: Velocity (km/s). Thick curve: Argon gas experimental data. Thin curve: Calculation assuming a viscosity of 100 μm² Pa·s and a distribution of particle diameters in the ratios 0.1(0.2) + 0.1(0.3) + 0.1(0.4) + 0.1(0.5) + 0.5(1) microns.

Stokes drag: 0.1–1.0 μm particles σιζε Ω

Vertical scale: Pressure (bar). Horizontal scale: Velocity (km/s). Thick curve: Xenon gas experimental data. Thin curve: Calculation assuming a viscosity of 186 μm² Pa·s and a distribution of particle diameters in the ratios 0.1(0.2) + 0.1(0.3) + 0.1(0.4) + 0.1(0.5) + 0.5(1) microns.
Conclusions

- The Ar data are reproduced assuming a broader distribution of particle sizes.
- If the initial distributions are the same this distribution should reproduce the Xe data but it does not and there is too much mass in larger particles.
- A possible explanation is the shocked gas temperature in Xe. The approximate shock temperatures in Ar and Xe are 3200 K and 9500 K respectively. The low pressure melting temperature of W is 3700 K. It is likely that there is substantial reduction in particle size due to melting for Xe. These issues are being pursued in new experiments.
- It should also be borne in mind, however, that a separability assumption has been made in the analysis.
Summary of transport measurements

Calculation Varies Particle Sizes and Viscosity to Fit to Measured Pin Pressures
\( \rho(\text{Ar}) = \rho(\text{Xe}) = 17 \text{ mg/cm}^3 \)

- Xe Piezo-Pin Pressure
  - \( \eta = 185 \text{ \mu Pa-s} \)
- Ar Pin Piezo-Pressure
  - \( \eta = 100 \text{ \mu Pa-s} \)
- Vacuum Piezo-Pin Pressure

Ejecta Velocity (mm/\(\mu\)s)