EXPERIMENTAL TECHNIQUES & MEASUREMENTS FOR CODE VALIDATION BEYOND THE CURRENT TESTABLE REGIME *i.e.*, AT IMPACT VELOCITIES OVER THE RANGE OF 7 TO 16 KM/S

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Abstract

Sandia National Laboratories has developed a hypervelocity launcher¹⁻⁴ which is capable of launching 0.5 mm to 1.0 mm thick by 6 mm to 19 mm diameter plates to velocities of 16 km/s. The hypervelocity launcher has been used to extend the shocked material properties data base at pressures and temperature states higher than those ever obtained in the laboratory. In this paper, recent results of one-dimensional and two-dimensional impact experiments at impact velocities over 10 km/s are presented. An example of an one-dimensional experiment consists of measurements of shock loading and release in titanium at ~ 2.3 Mbar resulting from symmetric impact at impact velocities of 10 km/s. Another example include the technique developed to probe the kinetics of shock-induced vaporization of a thin zinc plate shocked to 5.5 Mbar resulting from an initial tantalum impact at over 10 km/s. The velocity interferometer, VISAR, is being used to estimate the time-resolved particle velocity history at a sample/lithium-fluoride window interface in the above experiments. The hypervelocity launcher has also been used to perform two-dimensional experiments. In particular, the propagation characteristics of debris clouds resulting from impact of a flier plate on a thin bumper shield. Aluminum flier plates were used to impact aluminum bumper shields at impact velocities of 5 to 11 km/s. In this instance, radiographic and framing photography have been used to record the debris cloud motion. These experiments demonstrate the feasibility of using the hypervelocity launcher to determine material properties in pressure and temperature regimes that have never been accessible in the laboratory before. It is anticipated that experimental measurement of these material properties will lead to the development and validation of constitutive models for material behavior that are needed for hydrodynamic code calculations for many programmatic needs including space sciences and lethality assessments.

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Introduction

Currently, two-stage light-gas guns⁵ are used to introduce the highest pressures and temperatures states in material that can be achieved in the laboratory. This generally involves performing impact studies at impact velocities of 7 km/s using high impedance impactor materials such as tantalum or platinum. To complement these studies, a suite of diagnostic and experimental techniques^{6,7} also exists, and are used to measure material properties in the high-pressure, high-temperature shocked state induced in materials at these impact velocities. These techniques have been used to measure the shock-Hugoniot⁸, shock-loading and release behavior⁹, material strength^{9,10} shock-induced melting^{9,11,12} shock-induced vaporization¹² processes in materials. Experimental measurement of these material properties forms a data base needed to develop constitutive models for material behavior¹³.

There is continued interest and a need in determining the equations of state of materials at extremely high pressures, temperatures and strain rates than those attainable on current two-stage light-gas guns. The understanding of material behavior is crucial to address the physical processes associated with a variety of hypervelocity impact events related to space sciences, orbital-debris impact^{14,15}, debris-shield designs¹⁶⁻²¹, high-speed plasma propagation, and lethality applications²². Development of well-controlled and repeatable hypervelocity launch capabilities is the first step that is necessary to improve our understanding of material behavior at extreme pressures and temperatures not currently available using conventional two-stage light-gas gun techniques.

In this paper, techniques that have been used to extend the shocked material properties data base at pressures and temperature states higher than those ever obtained in the laboratory is described. These experiments have been performed on the newly developed hypervelocity launcher¹⁻⁴. The launcher has the capability to launch plates having macroscopic dimensions to 16 km/s⁴. The techniques have been used to determine shock-loading and release characteristics of materials, shock-induced vaporization

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Figure 1. A graded-density impactor/flier-plate experiment phenomena in fully vaporized states²², and also to evaluate the debris propagation characteristics²⁴ resulting from impact of thin sheets at hypervelocities.

Sandia HyperVelocity Launcher, HVL

The principle of operation of the Sandia HyperVelocity Launcher, HVL is briefly described inhere. However, a detailed experimental description of the technique and the launcher is given elsewhere^{1,4}. Very high driving pressures (tens or hundreds of GPa), are required to accelerate flier plates to hypervelocities. This loading pressure pulse on the flier plates must be nearly shockless to prevent the plate from melting or vaporizing. This is accomplished by using graded-density impactors^{4,10,25}. When this graded-density material is used to impact a flier-plate in a modified two-stage light gas gun, (See Figure 1) nearly shockless megabar pressures are introduced into the flier plate^{10,26}. The pressure pulse is also tailored to prevent spallation of the flier-plate. This technique has been used to launch nominally 1-mm-thick aluminum, magnesium and titanium (gram-size) intact plates to 10.4 km/s^{1,2} and 0.5-mm-thick aluminum and titanium (half-gram size) intact plates to 12.2 km/s³. More recently the technique has been enhanced to allow the launching of titanium plates and aluminum plates to velocities approaching 16 km/s⁴. This is the

Figure 2a. Radiographs of a titanium flier-plate traversing from left to right at 14.4 km/s over a flight distance of 1.4 meters

Figure 2b. Radiographs of a titanium flier-plate traversing from left to right at 15.8 km/s over a flight distance of 1.0 meter.

highest mass-velocity capability attained with laboratory launchers to date, and therefore should open up investigations of new regimes of impact physics using a variety of diagnostic tools..

Table 1: Summary of HVL Experiments

Expt. No.	Flier-Plate Diameter (mm)	FlierPlate Thickness (mm)	Impact Velocity (km/s)	Flier Plate Material/ Velocity (km/s)
WS6	19	0.98	6.4	Ti6/9.5
Al-46	19	0.98	6.4	Al/10.4
HVL2	19	0.43	7.4	Ti6/11.9
HVL3	19	0.42	7.4	Al/12.2
CP2	9.99	1.001	6.75	Ti6/13.4
CP3	5.922	0.994	6.75	Ti6/14.4
CP5	5.960	0.560	6.75	Ti6/15.8
CP6	9.99	1.003	6.00	Al/13.8

A schematic of the experimental description is provided in Figure 1, and a summary of the HVL capabilities is highlighted in Table 1. Flier plates have been launched intact and radiographed to distances of 1.4 meters from launch⁴. Radiographs of a titanium flier plate traversing at 14.4 km/s and 15.8 km/s are shown in Figures 2a and 2b, respectively.

Due to the severe loading conditions which entails using megabar loading pressures, the flier plate achieves peak velocities over tens of millimeter acceleration distances. The plate appears to be "flat" ~ over the first thirty millimeter flight distances (see Figs. 3b & 4b), and will generally bow with increasing flight path (see Fig. 5b). Even though, shockless loading conditions are used to accelerate the flier plate, the final temperature of the flier upon acceleration is approximately 600 K upon achieving velocities of 10 km/s.

One-Dimensional Experiments

We have used the hypervelocity launcher, HVL to perform one-dimensional experiments. To achieve one-dimensional conditions, the target plate is stationed ~ 20 mm from the flier-plate. This ensures that the flier plate achieves peak particle velocity prior to impact, and remains relatively flat (see Figs. 3b & 4b) prior to impact. No attempt has been made to date to characterize the *planarity* of the impacting flier plate. The experimental configuration used to perform shock-loading and release measurements and shock-induced vaporization experiments are shown in Figure 3 and 4, respectively.

Figure 3a. Experimental schematic indicating the set up used for shock loading and release experiments using HVL.

Shock-loading and Release Experiments

Symmetric plate impact experiments have been performed using aluminum, titanium, and tantalum at impact velocities of 10 km/s. As indicated in Figure 3a, a velocity interferometer VISAR²⁷, is used to estimate the particle-velocity history at the sample/ lithium-fluoride window interface. The technique is schematically depicted in Figure 3a. Figure 3b shows the radiograph of an experiment in which a 0.56 mm titanium flier-plate is launched at 9.6 km/s prior to impacting a 2.0 mm thick titanium target. The lithium-fluoride window²⁸ is clearly seen in the radiograph. The flat portion of the flier-plate

Figure 3b. Radiographs of a titanium flier-plate prior to impacting a titanium target. The flier-plate is traversing at 9.60 km/s

Figure 3c. Measured shock-loading and release particle velocity history in Ti-6Al-4V titanium alloy shocked to over 2.3 Mbar. The velocity measurements are made at the titanium sample/lithium-fluoride window interface as indicated in Figure 3a.

prior to impact as depicted in the radiograph is 19mm. The time-resolved particle velocity history measurements at the titanium/lithium fluoride window interface is indicated in Figure 3c. In this experiment, the titanium alloy is shocked to 2.3Mbar, and a full release profile is measured. These release profile can be used to determine the off-Hugoniot states of titanium shocked to ~ 2.3 Mbar. More significantly, the technique demonstrates the successful use of time-resolved velocity interferometric techniques developed earlier for use at lower stresses for similar investigations using the HVL. Although not shown in this paper, the technique has been used to determine the shock loading and release profile in aluminum shocked to over 1.6 Mbar at an impact velocity of 9.95 km/s.

The successful measurements demonstrate the transparency of the lithium-fluoride window at much higher pressure (2 Mbar) and temperature states than the window material has ever been subjected to before²⁸. Previous study has demonstrated transparency of LiF windows to stresses of 1.2 Mbar²⁸. A symmetric impact experiment at 10 km/s using both tantalum as a target and as a flier plate, however, did not yield a release profile as indicated above in Figure 3c. This corresponds to a stress of ~ 8 Mbar in tantalum and 3 Mbar in the LiF window. This is believed to be directly related to a transparency loss in the LiF window. More experiments are needed, however, to further resolve this issue. This also points to a need in developing new techniques to allow successful measurements of off-Hugoniot states at extremely high pressures.

Figure 4a. Experimental schematic indicating the set up used for shock-induced vaporization experiments using HVL.

Shock-Induced Vaporization Experiments

This section briefly describes the use of the hypervelocity launcher to probe the kinetics of shock-induced vaporization process in materials²³. In particular, the HVL was used to impact a thin zinc plate with tantalum at velocities over the range of 8.0 km/s to 10.1 km/s. At these impact velocities stress states over the range of 3 to 5.5 Mbar are induced in the zinc target²³. Following the arrival of this compressive wave at the free surface, a decompression wave propagates back into the zinc sample which is now in a mixed phase of liquid and vapor. The rarefied liquid-vapor products left in the wake of

Figure 4b. Radiograph of a tantalum flier-plate launched to velocities of 10 km/s prior to impacting a zinc target in the final frame using HVL.

Figure 4c. Measured stagnation particle velocity histories of experiments conducted at an impact velocity of 10.1 km/s

this wave traverse a gap of known dimensions and stagnate against an aluminum witness plate backed by a lithium-fluoride laser-interferometer window²⁸. The stagnation velocity history is determined through the use of a velocity interferometer²⁷ commonly referred to as VISAR. The experimental schematic is indicated in Figure 4a, while the radiographs of the experiment is depicted in Figure 4b. Measured time-resolved stagnation particle velocity histories of experiments conducted at 10.1 km/s are shown in Figure 4c. In these experiments the vaporized products are allowed to traverse gap distances of up to 20 mm.

It should be noted that these results represent the first time-resolved measurements of full vaporization in zinc²³ at tantalum impact velocities of over 10 km/s. Although not discussed in this paper, the experiments indicate a lack of agreement with hydrodynamic CTH code calculations using existing ANEOS material models indicating a need to develop and/or refine EOS models describing the shock-induced vaporization process. Results of these experiments are further discussed in detail elsewhere²³.

Two-Dimensional Experiments

In this section, an experimental technique used to perform two-dimensional experiments on the HyperVelocity Launcher, HVL, is described. The experimental configuration used to generate debris clouds upon impact is indicated in Figure 5a. Aluminum flier plate 17-mm diameter by 0.92-mm thick were accelerated to velocities over the range of 5 to 11 km/s²⁴. The flier plates impacted 1.27 mm thick aluminum bumper plates. Aluminum witness plates 3.18 mm thick were positioned

Figure 5a. Experimental schematic indicating the set up used for shock loading and release experiments using HVL.

203 mm behind the bumper plate. The debris cloud is viewed between the bumper shield and the witness plate using flash X-ray radiographic techniques. The back surface of the witness plate was also radiographed at an angle to determine the effect of subsequent loading (on the witness plate) by the impact-generated debris cloud. The X-ray measurements of the debris cloud are indicated in Figure 5b. Only those X-rays that are not absorbed by the debris cloud *i.e.*, the relatively higher density material within the cloud, are being imaged

Generally, the data indicate a central core of higher density debris surrounded by a diffused layer. These experiments allow measurements of debris cloud expansion velocities as the material undergoes a phase change from solid fragments at impact velocities of 5 km/s to a mixture of liquid and vapor phase at higher impact velocities. The expansion velocity of the debris cloud increases with increasing impact velocity, with the high-density leading edge travelling faster than the impact velocity. Details of these experiments are presented and discussed in Reference 24.

Figure 5b. Radiographs of the debris cloud formed upon impact of an aluminum flier plate *F* with an aluminum bumper plate at (a) 5km/s, (b) 7.43km/s, (c) 9.56km/s, and (d) 11.1 km/s. These experiments were performed on the Sandia hypervelocity launcher

Summary

Examples of one and two dimensional experiments described in this report demonstrate the feasibility of using the hypervelocity launcher to determine material properties in pressure and temperature regimes that have never been accessible in the laboratory before. It is anticipated that experimental measurement of the material properties and the physical processes related to hypervelocity impact will lead to

the development and validation of constitutive models for material behavior that are needed for hydrodynamic code calculations for many programmatic needs including lethality assessments.

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