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Asymmetric Material Impact: Achieving Free Surfaces Velocities Nearly Double That of the Projectile

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Abstract

Hypervelocity impact speeds are often limited by practical considerations in guns and explosive driven systems. In particular, for gas guns (both powder driven and light gas guns), there is the general trend that higher projectile speeds often come at the expense of smaller diameters, and thus less time for examining shock phenomena prior to two dimensional release waves affecting the observed quantities of interest. Similarly, explosive driven systems have their own set of limiting conditions due to limitations in explosive energy and size of devices required as engineering dimensions increase. The focus in this study is to present a methodology of obtaining free surface velocities well in excess of the projectile velocity. The key to this approach is in using a high impedance projectile that impacts a series of progressively lower impedance materials. The free surface velocity (if they were separated) of each of the progressively lower impedance materials would increase for each material. The theory behind this approach, as well as experimental results, are presented.

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Keywords: Gas gun, free surface velocity, asymmetric material impact

Nomenclature

u	velocity (km/s)
c	sound speed of material (km/s)
s	coefficient in linear relationship between u_p and u_s.
p	pressure (GPa)
Greek symbols	
Γ	Gruneisen parameter
γ	ratio of specific heats
ρ	density (g/cm^3)
Subscripts	
p	particle
s	shock

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o	initial conditions
f	flyer (projectile) properties
1,2…	various material designations

1. Introduction

All projectile launchers have practical limitations in the maximum velocities obtained due to physical material limitations. Generally to obtain hypervelocity projectile speeds limitations in projectile size must be sacrificed. For a wide variety of physical applications, hypervelocity impact physics of low to moderate impedance materials are of interest. Some applications are meteor impacts of regolith (dust, sand, soil), shock compression of foams, aerogels and porous materials, and shock physics of polymeric materials, gases and high explosives. These materials typically have densities in the 0.001-2 g/cc range. While it is desired to shock compress these materials at impact speeds up to 16 km/s or more, it is challenging to reliably launch substantial sized projectiles at these kinds of speeds. The focus of this paper is to demonstrate how to effectively launch materials at speeds nearly double the projectile speed, and thus open up the possibility of ~16 km/s impacts on 2-stage powder driven gas guns. Similar increases can be achieved with lower velocity guns as well as demonstrated in section 3. This is accomplished through the use of a high impedance material at the face of a projectile impacting either a single or series of progressively lower impedance materials; see figure 1. These lower impedance materials will have free surface velocities well in excess of the projectile velocity. A rather simple analysis of shock jump conditions can be utilized to select appropriate materials, as is presented in section 2.1. Hydrodynamic calculations can further be used to optimize dimensions and obtain the longest sustained shock/free surface drive. These are presented in section 2.2. Experimental results are presented in section 3. Finally, some conclusions and future work are discussed in section 4.

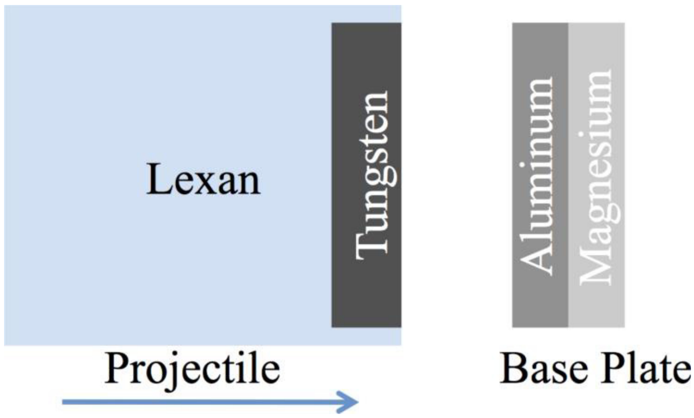

Fig. 1. Schematic of asymmetric impact experiment, with Tungsten flyer impacting a composite base plate made of Aluminum and Magnesium.

2. Theory

2.1. Shock Matching

The theory of shock matching between various materials is quite mature and can be used to give very good estimates of interactions (i.e. Riemann solutions) among the materials of interest. For the purpose of this work, we will assume the projectile and base plate materials will have a Hugoniot of the linear u_s-u_p form [1]:

$$u_s = c_o + s u_p \tag{1}$$

where u_s is the shock velocity, c_o is the ambient sound of the material, s is the slope of the Hugoniot curve and u_p is the post-shock particle velocity. For a particular material c_o and s are constants. This functional form assumes the initial particle velocity and initial pressure are zero. It further assumes that particle and shock velocities are positive (i.e. right going). A suitable change of coordinates can be utilized to take into account materials with initially moving material as well as shocks traveling to the left (as would be the case in the projectile).

Upon impact of the projectile with the base plate, there will be a shock traveling backwards into the projectile and another traveling into the base plate. After each of these shocks, the material velocity and pressure must be equal in each of the materials. Conservation of mass, momentum and energy are used to determine this state. If there were only one material in the base plate (followed by vacuum), then a second computation would be needed to determine the free surface velocity when the shock in the base plate encounters the free surface. A reasonable assumption for solid materials is that this free surface velocity is roughly double that of the post-shock particle velocity. If subsequent base plate materials exist, we repeat the original impact matching procedure with a rough approximation of assuming the previous base plate material returns to its initial ambient state, but with the free surface speed previously computed as double the match velocity upon initial impact. This procedure is then repeated until the final material being tested.

Let's examine the algebraic steps to match between material 1 impacting material 2. Here, both materials are assumed to be at initially zero pressure. Material 1 is assumed to traveling at a velocity of u_f, while material 2 is stationary initially. Keep in mind that after impact both materials need to be in pressure and velocity equilibrium. The pressure for a right going shock into an initially quiescent material will be $p_2 = \rho_{o2}\, u_{s2}\, u_p$, or equivalently through using equation (1): $p = \rho_{o2}\,(c_{o2} + s_2\, u_p)\, u_p$. For a left going shock into the flyer material 1, the pressure will be $p = \rho_{o1}\,(c_{o1} + s_1\,(u_f\text{-}u_p))\;(u_f\text{-}u_p)$. From these two equations, we can solve for the match pressure, p, and the match velocity, u_p, with the material parameters ρ_{o1}, c_{o1}, s_1, ρ_{o2}, c_{o2}, s_2 and flyer velocity, u_f, known. Although the equation is quadratic and thus there are two roots, only one solution exists for $0<u_p<u_f$.

Without going through the detailed algebraic steps, which is best left suited to symbolic computations such as Mathematica or Maple, one can optimize the material parameters of each of the constituents to achieve the maximum drive in the final test material. Or alternatively, one can discretely search through as set of common materials for the best combination.

There are several items of note after performing the above optimization. To achieve the maximum final particle velocity (or equivalently free surface velocity of last material), it is beneficial to use the highest impedance material possible in the projectile. Furthermore, it is determined that using progressively lower impedance materials will increase the shock state in the final material. Also, adding more intermediate materials can increase the final shock state. There are of course practical limitations with adding more intermediate materials, and there exists diminishing returns on adding more materials. The other practical limitation is how disparate the impedances are between the projectile material and the final material to be tested. If the materials are similar, then there will be negligible gains. If the materials are disparate (such as the example shown in Fig 1), then a reasonable increase in final shock state (or free surface velocity) can be achieved.

2.2. Hydrodynamic Calculations

Hydrodynamic computations give further insight into the material interaction as well as shed light onto the timing of rarefactions, reflected waves, etc. These various timings can help in the geometrical design of both the impactor and base plate(s) used in the experimental setup to optimize the sustained drive while keeping the experiment one-dimensional as long as possible. A sample computation of a Tungsten impactor, backed by Lexan, impacting a base plate composed of Aluminum and Magnesium is shown in figure 2. Note that the computed free surface velocity of the Magnesium is 6.91 km/s, which is nearly double the Tungsten flyer of 3.5 km/s. Similar computations, with other material combinations and projectile speeds of 7 km/s, indicate free surface velocities in excess of 16 km/s.

The computational results given here are based on the numerical procedure of [2]. In short, the computational results use an approximate Riemann solver for arbitrary equations of state in conjunction with 2nd order total variation diminishing spatial interpolation on a Lagrangian grid.

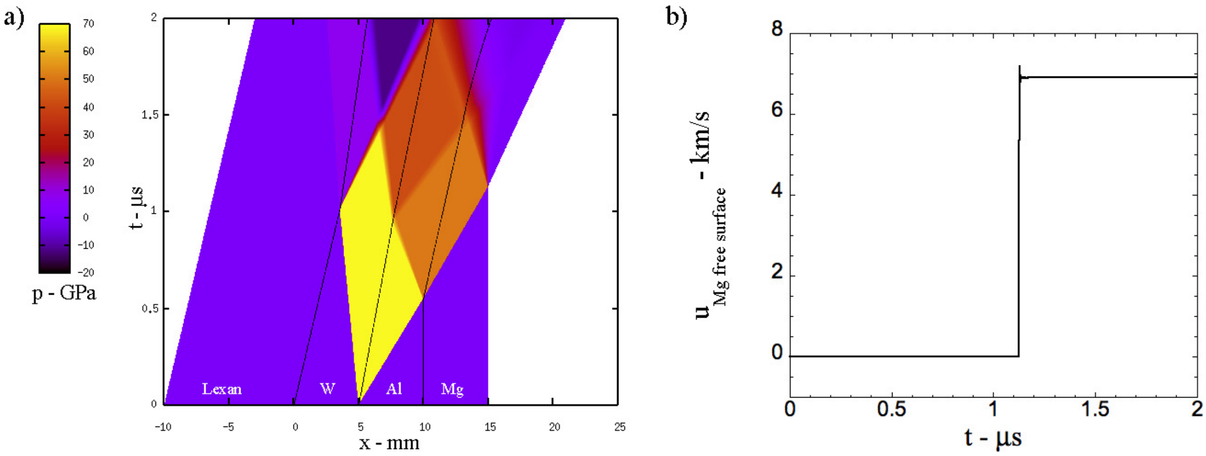

Fig. 2. Sample computation of 3.5 km/s Lexan/Tungsten projectile impacting a two-material composite base plate of Aluminum and Magnesium. a) computed x-t pressure and material interface locations. b) computed Magnesium free surface velocity as a function of time.

3. Experimental Results

Here, we present results from two experiments, demonstrating the ability of asymmetric impact on final drive of the material under investigation. In particular, we examine shock compression of aerogels and gases. This is ideally suited for asymmetric impact, in terms of having the requisite disparity between projectile and final drive material.

3.1. 2s-815

The purpose of this shot is to study the shock compression of a variety of polyuria aerogels [2]. As a proof of principle, free surface measurements of an Aluminum 6061 driver plate was also directly measured. See Fig. 3 for schematic. Here, we focus on the free surface velocity of the Aluminum.

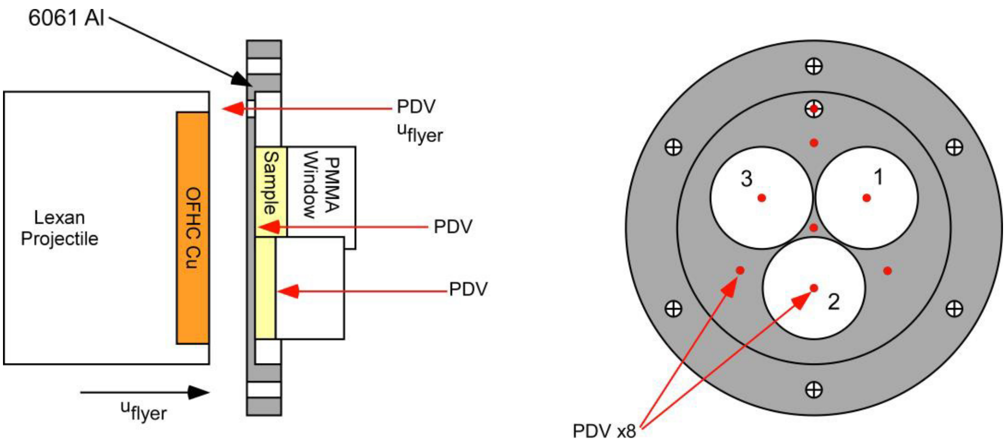

Fig. 3. Schematic of shot 2s-815. 3.502 km/s Copper projectile impacting a base plate of Aluminum 6061. PDV diagnostics are shown which directly measured flyer velocity, free surface velocity of the Aluminum 6061 base plate and polyuria samples.

The free surface velocity measurement via PDV of the Aluminum 6061 was 4.891 ± 0.011 km/s. Assuming a Cu density of 8.93 g/cc and a Hugoniot of u_s=3.94+1.49u_p and an Aluminum density of 2.703 g/cc and a Hugoniot of u_s=5.288+1.3756u_p leads to an interfacial match velocity of 2.392 km/s. Assuming the free surface of the Aluminum is double this match velocity leads to a free surface velocity of 4.784 km/s. A full simulation of the impact and release phenomena using a Mie-Gruneisen EOS for Aluminum with Γ = 2.14, leads to a free surface velocity of 4.874 km/s. The assumption of free surface velocity being double the match velocity is valid for no entropy being generated in the shock process. Shock heating leads to a lower final density of the Aluminum and thus a slightly higher free surface velocity. Note that the simple theoretical analysis, full simulation and experiments are within a couple percent. Note that the free surface velocity of Aluminum is ~40% higher than the Cu flyer velocity. Using a higher impedance flyer material, as well as multiple base plate materials can yield even higher gains in the free surface velocity. Such an example is given next.

3.2. 2s-809

This experiment fielded multiple PDV as well as VISAR diagnostics. See Fig 4. In particular, PDV is used to measure both the free surface of the Aluminum, the sapphire/Argon interface and shock velocity in the Argon. Here, the flyer, composed of Tantalum, had an initial speed of 3.428 km/s. The baseplate was a composite of 304 stainless steel and Aluminum 6061. The Argon gas was initially at a pressure of 222.2 psig and density of 0.0265 g/cc.

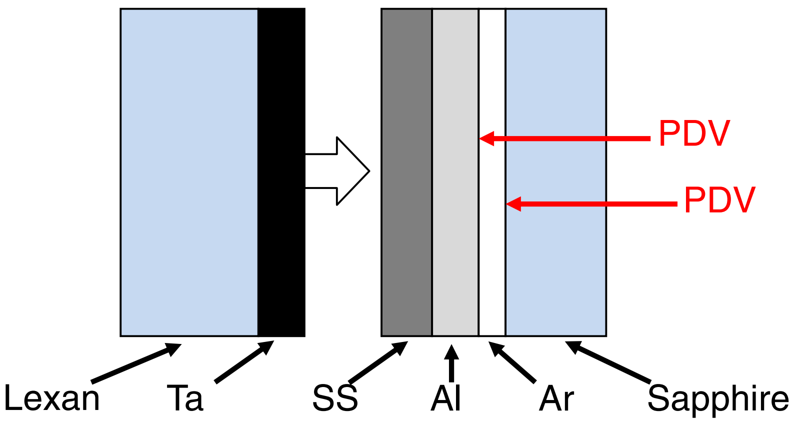

Fig. 4. Schematic of shot 2s-809. 3.428 km/s Tantalum projectile impacting a two-material composite base plate of 304 stainless steel and Aluminum 6061. The ~1mm Argon gas is sandwiched between the Aluminum and Z-cut sapphire. PDV diagnostics are shown.

Firstly, let's examine the match conditions through the Ta/SS interaction, followed by the SS/Al interaction. The densities of Ta, SS and Al are assumed to be 16.654 g/cc, 7.89 g/cc and 2.703 g/cc respectively. The Hugoniots of Ta, SS and Al are assumed to be u_s=3.402+1.2196u_p, u_s=4.58+1.49u_p and u_s=5.288+1.3756u_p respectively. The match condition between Ta ans SS lead to a velocity of 2.015 km/s. Assuming the steel would release back to zero pressure and a free surface velocity of double the match velocity leads to 4.030 km/s. Steel at this free surface velocity impacting the Aluminum would lead to a match velocity of 2.731 km/s. If the Aluminum was released into a vacuum, then the approximate free surface velocity would be double this velocity of 5.462 km/s. At these kinds of drives, Argon is highly nonideal and the gas will likely become ionized [3][4].

A full simulation of the interaction process was performed (assuming Ar gas was ideal with γ=5/3). The simulation determined a drive into the Argon of 5.531 km/s. Unfortunately, the free surface velocity of the Aluminum was obstructed by the shocked Argon gas. We believe the Argon shock velocity was measured instead. See Fig. 4 for the PDV spectrogram. Fig. 5 shows the experimental and simulated interfacial velocities. The experimental results indicate an Argon shock velocity of 6.45±0.1 km/s. This shock velocity is associated with a particle velocity of 5.67±0.1 km/s, albeit at a lower initial pressure [3]. This is very close to the simulated drive of

5.531 km/s. If the simulations utilized a better Argon EOS (i.e. softer principal Hugoniot due to more molecular internal degrees of freedom associated with ionization), the agreement would be even better in both the velocity at the Aluminum/Argon interface as well as timing of the shock at the Sapphire window. Nevertheless, the drive into the Argon was ~65% higher than the flyer velocity, which was the intent of these experiments.

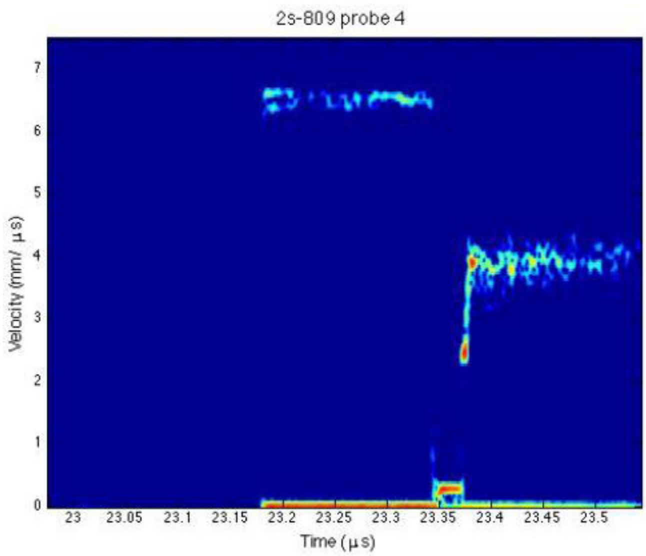

Fig. 5. PDV spectrogram from probe 4 of shot 2s-809.

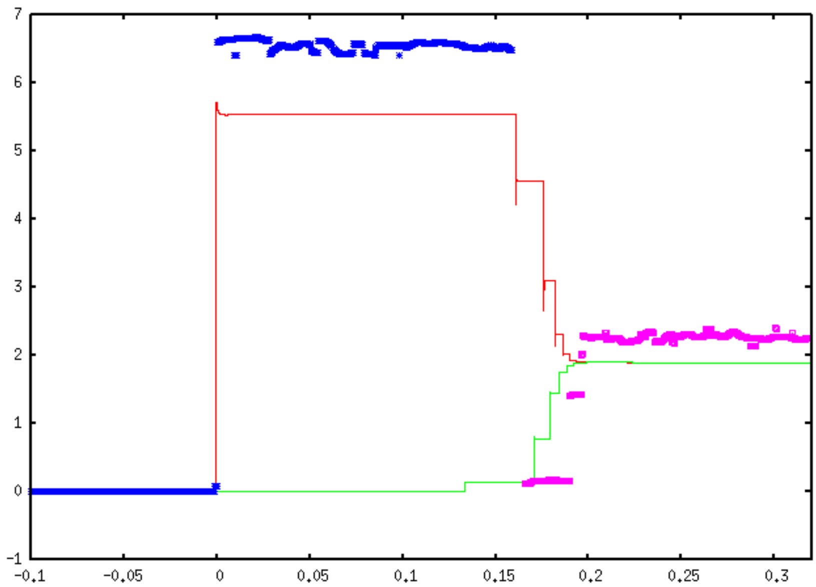

Fig. 6. Velocities in km/s from 2s-809 versus time in μs. The time axis was shifted, such that the breakout on the Aluminum/Argon interface occurred at t=0. The blue symbols are from the PDV looking through the Argon (shock velocity). The pink symbols are from the PDV examining the Argon/Sapphire interface. The red curve is the simulation of the Aluminum/Argon interface velocity (not shock velocity). The green curve is the simulated Argon/Sapphire interface.

4. Conclusions and Discussion

An experimental procedure for increasing the drive of low to moderate impedance materials has been presented. Theoretical and computational results utilizing asymmetric materials under impact conditions have been backed by experimental observation. The procedure is rather simple, and can be applied to gas gun and explosively driven (and others) systems used in impact studies. Depending on the disparity in materials, one to three intermediate materials can be used to help push the final material to a state greater than a single projectile material can achieve.

The process can be reversed to achieve very slow drive conditions as well. In such a way, a much wider range of impact conditions can effectively be achieved on a single experimental platform.

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