Techniques to Obtain Orbital Debris Encounter Speeds in the Laboratory

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Abstract

Understanding high-pressure material behavior is crucial to address the physical processes associated with a variety of hypervelocity impact events related to space sciences such as orbital-debris impact on a debris shield. At very high impact velocities material properties will be dominated by phase-changes, such as melting or vaporization, which cannot be achieved at lower impact velocities. Development of well-controlled and repeatable hypervelocity launch capabilities is the first step 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 used to extend the launch capabilities of a two-stage light gas gun to 16 km/s are described. It is anticipated that this technology will be useful in testing, evaluating, and design of various debris shields proposed for use with many different spacecrafts before deployment.

Introduction

Until approximately four years ago, two-stage light-gas guns (Charters, 1987) produced the highest pressure and temperature states in material that can be achieved in the laboratory. This generally involves performing impact studies at impact velocities of 8 km/s using high impedance impactor materials such as tantalum or platinum. For many space sciences applications, there is a requirement to extend the equations of state of materials to extremely high pressures, temperatures and strain rates to regimes not accessible by current two-stage light-gas guns. Many of these applications include orbital-debris impact (Kessler, 1989), debris-shield designs (Chhabildas, et al, 1992), high-speed plasma propagation, and impact lethality effects. At such high impact velocities material properties will be dominated by phase-changes, such as melting or vaporization, not routinely achieved at low impact velocities. Development of well-controlled and repeatable hypervelocity launch capabilities is the first step necessary to improve our understanding of material

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behavior in these regimes.

In this paper, techniques that have been used to extend the launch capability to those previously obtained in the laboratory are described. In particular, the Sandia HyperVelocity Launcher (Chhabildas *et al*, 1995) (HVL) which is capable of launching 0.5 mm to 1.0 mm thick by 6 mm to 19 mm diameter plates to velocities approaching 16 km/s, will be briefly described.

<u>Hypervelocity Launcher (HVL)</u>

The principle of operation of the Sandia HyperVelocity Launcher (HVL) is briefly described here. 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 time-dependent to prevent the plate from melting or vaporizing. This is accomplished by using graded-density impactors. When this graded-density material is used to impact a flier-plate in a modified two-stage light gas gun, as indicated in Figure 1(a), nearly shockless, megabar pressures are introduced into the flier plate. The pressure pulse must also be 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 and 0.5-mm-thick aluminum and titanium (half-gram size) intact plates to 12.2 km/s More recently the technique has been enhanced by using the experimental configuration described in Figure 1(b) to allow the launching of titanium and aluminum plates to velocities approaching 16 km/s. The experimental design shown in Figure 1(b) acts as a dynamic acceleration reservoir which further enhances the flier plate velocity . This is the highest mass-velocity capability attained with laboratory launchers to date, and is well suited to address technical issues relevant to orbital debris impact.
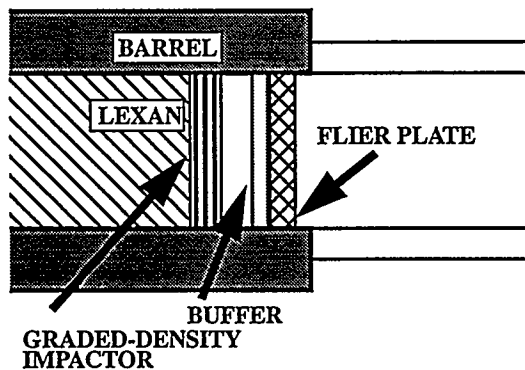

Figure 1(a). The Hypervelocity Launcher (HVL). Configuration used to launch flier plates to hypervelocities.
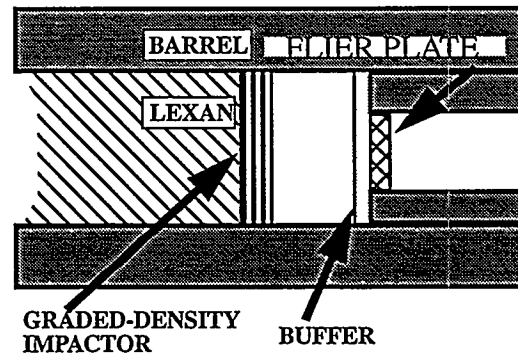
Figure 1(b). Enhanced HyperVelocity Launcher, (EHVL). Configuration used to launch confined flier plates in a tungsten barrel to hypervelocities.

Due to the severe loading conditions which result from time-dependent megabar loading pressures, the flier plate achieves peak velocities over tens of millimeter acceleration distances. The plate appears to be "flat" for approximately the first

thirty millimeter flight distances and will then generally "bow" with increasing flight path. Flier plates have been launched intact and radiographed to flight distances of 1.4 meters from launch with this technique and is indicated in Figures 2(a) and 2(b). Even though shockless loading conditions are used to accelerate the flier plate, the final temperature of the flier plate upon acceleration is approximately 600 K for the geometry used in Figure 1(a) after achieving velocities of 10 km/s. This is "cold" compared to its melt temperature, despite using enormous energy (compared to its melt and vaporization energy) to achieve hypervelocities. Designs using lower-impedance buffers such as foam will further reduce the temperature of the accelerating flier-plate.
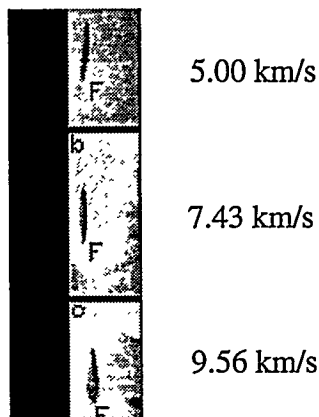

5.00 km/s

7.43 km/s

9.56 km/s

Figure 2(a). Radiographs of 6061-T6 Aluminum flier-plates. The plate has traversed over 800 mm from left to right at speeds indicated above.

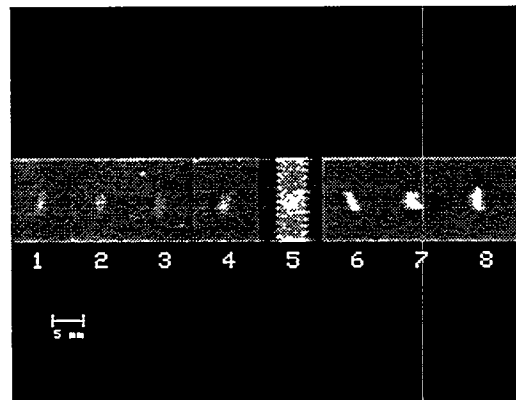
Figure 2(b). Radiographs of a titanium flier-plate traversing from left to right at 14.4 km/s over a flight distance of 1400 mm.

Discussion

As mentioned earlier, high pressures are needed to launch flier plates to hypervelocities. In addition, this loading must be nearly shockless, structured, and uniform over the entire surface. To satisfy these criteria, graded-density materials are

TABLE 1. Results of Graded-Density Impactor/Confined Flier-Plate Experiments

Expt. No.	Graded-Density Impactor Diameter D_{gdi} (mm)	Flier-Plate Diameter/ Material d_{fp} (mm)	Flier-Plate Thickness/ Mass (mm)/(g)	Impact Velocity V_i (km/s)	Flier-Plate Velocity V_{fp} (km/s)	d_{fp}/D_{gdi}	V_{fp}/V_i
CP2	18.75	9.994/Ti	1.001/0.337	6.75	13.4	0.533	1.99
CP3	19.08	5.922/Ti	0.994/0.115	6.75	14.4	0.310	2.13
CP4	12.70	9.995/Ti	0.982/0.339	7.00	11.5	0.787	1.64
CP5	19.07	5.960/Ti	0.560/0.068	6.75	15.8	0.313	2.34
CP6	27	9.99/Al	1.003/0.208	6.00	13.8	0.370	2.30

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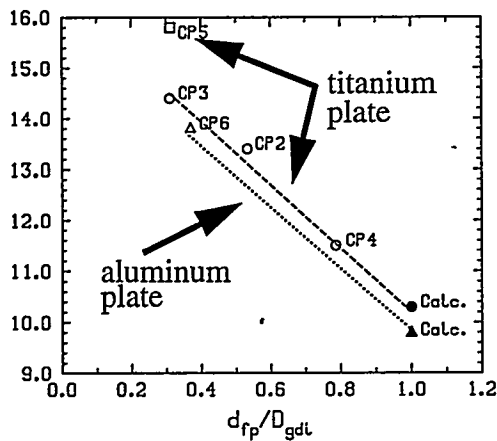
Figure 3: Variation of flier-plate velocity (km/s) with the ratio of the barrel diameter to the graded-density impactor diameter. The solid points are calculated estimates.
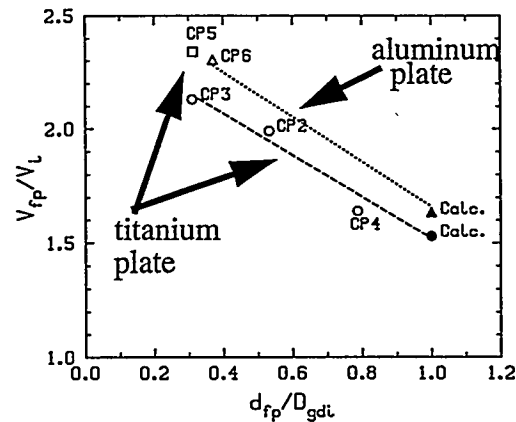

Figure 4: Variation of ratio of flier-plate velocity to impact velocity with the ratio of the barrel diameter to the graded-density impactor diameter. The solid points are calculated estimates.

used to launch flier-plates to high velocities. When this graded-density material is used as an impactor on a two-stage light-gas gun, nearly shockless 100 GPa pressure pulses are introduced into the flier-plate. This time-dependent pressure pulse subsequently accelerates the flier-plates to high velocities. The resultant plate velocity is ~1.53 times the impact velocity for a titanium plate, and 1.63 times the impact velocity for an aluminum plate for the HVL configuration depicted in Figure 1(a)..

The configuration shown in Figure 1(b) yield flier-plate velocities that are now 1.64 times to 2.3 times the impact velocity (Table 1). This improvement is due to the experimental geometry used in this investigation. Specifically, the flier-plate diameter, d_{fp} is small, while the diameter of the graded-density impactor D_{gdi} is significantly larger. In the earlier HVL studies, the flier-plate diameter is the same as the graded-density impactor diameter, i.e., the ratio d_{fp}/D_{gdi} is 1. In Figure 3, the variation of flier-plate velocity is shown as a function of the ratio of the flier-plate diameter to the graded-density impactor diameter. The same results are shown in Figure 4, with the flier-plate velocity normalized with respect to the impact velocity. In each of these figures, notice that the flier-plate velocity increases with decreasing d_{fp}/D_{gdi}. The values shown at $d_{fp}/D_{gdi} = 1$ are calculated values based on previous HVL studies. Thus, to enhance flier-plate velocities, a necessary requirement is to impact a step-down barrel as indicated in Figure 1(b).

Upon impact, the step down barrel itself is loaded to high pressures. The stress states at the barrel/flier boundary are now higher than those found in the original HVL configuration shown in Figure 1(a). This prevents the release of the driving pressure behind the flier-plates and sustains higher loading stresses over a longer duration. As the graded-density impactor material enters the step-down barrel, it speeds up, further maintaining an efficient push behind the flier-plate. Both these factors contribute significantly toward accelerating the flier-plate to yet higher velocities. The experimental geometry indicated in Figure 1(a), therefore, operates as an (impact-generated) acceleration reservoir to launch flier plates to yet higher velocities.

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Summary

This paper presents a novel technique which allows the launching of ~ 0.1 g to 1 g metallic plates to record velocities approaching 16 km/s. What is new in this study is that relatively heavy metallic plates are propelled to hypervelocities. To obtain higher velocities, the impact velocity may be increased or the plastic buffer may be replaced with hydrogen. Increasing the impact velocity to 8 km/s will, *in principle,* yield flier-plate velocities approaching 19 km/s. (In practice, however, it is not simple to obtain such high velocities for a "heavy" two-stage light-gas gun projectile required for these studies.) This would, however, require a proper design of the graded-density impactor and the barrel to ensure that the plate would not melt or fracture. Additional calculational studies were made to determine if hydrogen, with its high sound speed, could be used to further enhance flier velocities. By replacing the plastic buffer in Figure 1 with a 5.0-mm thick frozen hydrogen plate, the velocity of a 0.2-mm titanium flier was predicted to be 13 km/s for a graded-density impact at 6.5 km/s. The expansion velocity of hydrogen compressed to very high pressures is extremely high resulting in an efficient push on the flier plate and can further enhance the flier-plate velocity. Alternately, frozen hydrogen buffers in combination with higher impact velocities could offer a way to achieve flier-plate velocities to 20km/s.

References

Charters, A. C. Int., J. Impact Engng., V5 (1987) 181.

Chhabildas, L. C., E. S. Hertel, S. A. Hill, in *Shock Waves in Condensed Matter-1991,* ed. by S. C. Schmidt, R. D. Dick J. W. Forbes and D. G. Tasker, Elsevier Science Publishers, (1992) 991.

Chhabildas, L. C., E. S. Hertel, S. A. Hill, in *Proceedings of the Hypervelocity Impact Symposium-1991,* University of Kent at Canterbury, Kent, U.K., ed. by J. A. M. McDonnel (1992) 247.

Chhabildas, L. C., L. N. Kmetyk, W. D. Reinhart and C. A. Hall, Int. J. Impact Engng., V17, (1995).

Kessler, D. J., R. C. Reynolds and P. D. Anz-Meador, NASA TM 100-471, (1989).

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