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HYPERVELOCITY PLATE ACCELERATION*

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Shock tubes have been used to accelerate 1.5-mm-thick stainless steel plates to high velocity while retaining their integrity. The fast shock tubes are 5.1-cm-diameter, 15.2-cm-long cylinders of PBX-9501 explosive containing a 1.1-cm-diameter cylindrical core of low-density polystyrene foam. The plates have been placed directly in contact with one face of the explosive system. Plane-wave detonation was initiated on the opposite face. A Mach disk was formed in the imploding styrofoam core, which provided the impulse required to accelerate the metal plate to high velocity. Parametric studies were made on this system to find the effect of varying plate metal, plate thickness, foam properties, and addition of a barrel. A maximum plate velocity of 9.0 km/s has been observed.

1. INTRODUCTION

Attempts to accelerate plates to higher velocities continue to hold interest for those doing equation-of-state research. Much data has been obtained in the last thirty years but most of this has been limited to 4 Mbar or less in common metals. Data above this pressure come slowly and are much less abundant than lower pressure data.

Recently, efforts have been directed to development of a relatively small explosive system that can drive stainless-steel impactor disks to velocities of 9 km/s. In the process, three systems were studied. These were the plane-wave shock tube (PWST), fast shock tube (FST), and fast shock tube with barrel (FSTB). These are discussed below.

2. HYDRODYNAMIC CALCULATIONS

A two-dimensional, Eulerian hydrodynamic code was used to model the three systems. The code has multi-material and programmed high-explosive (HE), burn capabilities. The equations of state used were Mie-Grüneisen with linear shock velocity-particle velocity Hugoniot for metals, JWL equation of state for explosive products, and ideal gas for foam plastics.

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3. EXPERIMENTAL TECHNIQUES

Diagnostics used on these experiments were two 300-keV flash x-ray sources triggered approximately 4 μ s apart to obtain both the velocity and breakup of the plate if any occurred. The explosive experiments were placed on styrofoam to prevent confinement effects. Detection of the x-ray images was obtained with x-ray film/intensifier screen combinations.

4. PLANE-WAVE SHOCK TUBE (PWST)

The first system studied was the PWST (Fig. 1a) in which a 1.9-cm ID stainless-steel (SS) barrel is placed against a cylinder of PBX-9501 explosive initiated by a 2.2-in.-diameter plane-wave lens.¹ The detonated gases expand behind an SS plate in the barrel, accelerating it down the barrel. The calculated initial plate acceleration is shown in Fig. 2. Because of a reflected shock from the inner corner of the barrel, HE gases reach the plate periphery first (Fig. 2a). As plate acceleration progresses, the shocked barrel wall expands, the plate periphery forms a forward bulge and is driven forward toward the original (larger) barrel ID, causing separation from the wall (Fig. 2b). A radiograph of this plate moving at a velocity of 6.4 km/s is shown in Fig. 3a.

Two other plate materials with the same areal density as the SS are shown in Fig. 3. In Fig. 3b, a tantalum plate can be seen to collapse on axis during its

formation, and in Fig. 3c, a titanium-6wt%Cu-4wt%V (Ti-6-4) plate is seen to form well and flies intact at a velocity of 6.0 km/s.

FIGURE 1

Shock tube configuration for PWST (a), FST (b), and FSTB (c). Indicated are A HE lens, B PBX-9501, C foam, D SS barrel, and E plate.

FIGURE 2

Plate acceleration. HE gases accelerate periphery of plate first (a) causing a forward bow and separation from barrel (b).

Calculations of the effect of barrel-wall thickness and length on plate velocity is shown in Fig. 4. A significant effect is seen as the barrel wall varies in thickness from 0.24 cm to 1.59 cm. However, the velocity is insensitive to barrel length in the interval between 1.38 cm and 4.28 cm, indicating little acceleration is occurring in that range. Consequently, a barrel-wall thickness and length of 2.2 cm and 2.1 cm, respectively, became the standard used in our experiments.

FIGURE 3

Radiographs of plates from a PWST moving to the right. The plate materials are SS (a), tantalum (b), and Ti-6-4 (c).

FIGURE 4

Variation of plate velocity with barrel wall thickness and length.

Thin SS plate acceleration in a PWST is shown for both calculation and experiment in Fig. 5. At a plate thickness of 0.080 cm, a reflected shock from the inner corner of the barrel reaches the back center of the plate

and causes it to bulge forward. HE gases bypass the plate periphery at this thickness and consequently a velocity of only 5.8 km/s was achieved instead of the calculated 7.6 km/s.

FIGURE 5

Thin plate acceleration in PWST. The setup and calculated plate contour appear in (a) and a radiograph of the plate moving to the right in (b).

5. FAST SHOCK TUBE (FST)

The FST system is shown in Fig. 1b.^{2,3} A plane-wave explosive lens detonates a PBX-9501 disk and cylinder. As the detonation propagates along the HE that contains a styrofoam core, a Mach disk is formed in the foam.^{4,5} For properly chosen foam density, the disk diameter grows until its diameter matches the ID of the explosive and its position is at the detonation front of the explosive.⁶ It is the gases expanding from this highly shocked foam that provides impulse to the plate on the face of this system. A radiograph showing the detonation front in the explosive and the Mach disk in the styrofoam can be seen in Fig. 6 along with a hydrodynamic calculation showing the agreement of the isobars and the radiograph.

A hydrocalculation and radiograph of a 0.15-cm SS plate accelerated by an FST system is shown in Fig. 7. The comparison of the plate profile shows close agreement. The radiograph indicates a plate velocity of only 6.2 km/s compared to 7.4 km/s in the hydrocalculation. This is attributed to gases bypassing the plate before acceleration is complete when the central, faster part of the plate (over the styrofoam) yields in tension

away from the peripheral, slower part of the plate over the explosive.

FIGURE 6

Overlay of calculated and radiographic wave fronts in foam and HE for an FST system.

FIGURE 7

Overlay of setup and dynamic calculation (a) and radiograph (b) of plate contours of SS plate in an FST system.

The characteristics of the foam used in an FST in order to obtain an integral plate in flight are not well understood because the hydrocode does not treat that detail. That the foam should have reasonably fine porosity and uniformity seems apparent, but beyond that, the required characteristics are uncertain. Figure 8 shows identical 0.15-cm-thick SS plates being driven by foams of the similar density. The foams are polystyrene, 1- μ porosity (Fig. 8a); polyurethane, 300- μ porosity (Fig. 8b); and silica gel, 0.01- μ porosity (Fig. 8c). Of these, only the styrofoam has accelerated the plate intact.

FIGURE 8

SS plate from an FST system driven by styrofoam (a), polyurethane foam (b), and foamed silica gel (c).

The effect of the site of initiation of detonation of the PBX-9501 explosive was examined. In Fig. 9 the standard plane-wave initiation is compared to peripheral initiation (with the explosive lens removed). The two radiographs show similar profiles for the 0.15-cm SS plates with both plates intact, however, there is a 5% increase in plate velocity for the peripherally detonated $\frac{1}{2}$ ST.

Comparison of three different plate materials accelerated in the FST system are shown in Fig. 10. These are tantalum (Fig. 10a), Ti-6-4 (Fig. 10b), and a high strength Ti alloy, Ti(beta C) (Fig. 10c). These can be compared with the standard SS plate shown in Fig. 7b. The plate thickness used for the plates shown

in Fig. 10 was that thickness required to give the same areal density as the 0.15-cm-thick SS plate shown in Fig. 7b. The tantalum plate (Fig. 10a) remains intact and reaches the calculated velocity of 7.4 km/s. This is attributed to its high-strain-rate ductility being greater than that of SS and delaying its tensile fracture until plate acceleration is complete. The Ti-6-4 alloy undergoes large ductile deformation, becoming very thin. The higher strength Titanium(beta C) alloy remains much flatter, however, and reaches a plate velocity of 6.8 km/s, performing intermediate to SS and tantalum plates.

FIGURE 9

SS Plates from FSTs with plane detonation (a) and peripheral detonation (b).

FIGURE 10

FST system with plates of tantalum (a), Ti-6-4 (b), and titanium, beta C (c).

If the cylinders of explosive and styrofoam are doubled in length for the FST, the flatness of the SS plate improves and carries more of the plate shoulder along with it as seen in Fig. 11. The plate velocity in both the long and short systems (Fig. 11 and 7b, respectively) are the same at 6.2 km/s.

Decreasing the thickness of an SS plate was expected to increase its velocity because of the decreased areal density. However, at a thickness of 0.088 cm, the plate is penetrated by the accelerating gases at its center and breaks up into a ring of fragments having a velocity of 7.2 km/s (Fig. 12). This was verified by a witness plate downrange.

FIGURE 11
SS plate from a long FST.

FIGURE 12
FST-driven SS plate with a thickness of 0.088 cm.

6. FAST SHOCK TUBE WITH BARREL (FSTB)

In order to confine the accelerating gases in the FST so that higher and/or longer plate accelerations could be achieved, a barrel was added to the FST system (Fig. 1c). The configuration is the same as the FST (Fig. 1b) except that the plate has been replaced with a barrel containing the plate with a small stand-off from the face of the HE/foam charge. This is referred to as an FST with barrel (FSTB). The calculated and experimental performance of this system is shown in Fig. 13. The hydrocalculation shows the 0.15 cm SS plate deforming with a concave forward bow and moving at a velocity of 9.0 km/s. The radiograph of this

plate, however, shows it to be flat and having a velocity of 9.0 km/s. These differences are the result of not having a fracture model in the code that treats the erosion of the plate periphery during acceleration, allowing gases to bypass the plate before acceleration is complete.

FIGURE 13
Calculated (a) and radiographic (b) contours of SS plate from a fast shock tube with barrel (FSTB).

The reason for reducing the barrel diameter to one half of the HE/foam interface diameter is that at larger barrel diameter the reflected shock from the inner barrel corner does not develop like the reflected shock in the PWST (Fig. 2), and cause the plate to be separated from the inner barrel wall. Instead, the plate periphery is pinned against the wall by the gas pressure causing plate fragmentation. Figure 14 shows the convex-forward bowing in a large-diameter, thin-walled barrel.

For barrels with ODs matching that of the explosive, plates were accelerated in barrel IDs that varied from 2.54 cm to 0.95 cm. Radiographs are shown in Fig. 15. For a barrel ID of 2.54 cm (larger than the HE/foam interface diameter of 1.91 cm) the plate's convex-forward bow can be inferred from the fragment pattern (Fig. 15a). At a barrel ID of 1.51 cm, the plate

still has a forward bow but now fragmentation is slow as the plate expands (Fig. 15b). At a barrel ID of 0.95 cm, the plate remains flat and no fragmentation is evident (Fig. 13b). The plate, barrel now perform in this system in a similar way to their performance in the PWST system with the plate periphery accelerating first, causing the calculated plate contour to bow concave-forward (Fig. 13a).

FIGURE 14
Early plate bowing in a large-diameter barrel.

FIGURE 15
Plates from FSTB system with barrel IDs of 2.54 cm (a) and 1.51 cm (b).

FIGURE 16
Plates of tantalum (a), Ti-6-4 (b), and Ti(beta C) (c) from FSTB systems.

The comparison of the same three plate materials shown in Fig. 10 for the FST are shown in Fig. 16 for the FSTB. These can be compared with the standard SS plate in the FSTB shown in Fig. 13b. While the SS plate stays intact during its acceleration, the other materials do not maintain integrity. Tantalum is seen to pulverize into a toroidal pattern of particles (Fig. 16a). Ti-6-4 and Ti(beta C) are also pulverized by these system stresses (Figs. 16b and 16c, respectively).

Calculations of the effect of varying the foam density in an FSTB on an SS plate are shown in Fig. 17. The type of deformation experienced by the plate is similar for all of the three foam densities 0.27, 0.32, and 0.37 g/cm³ (Figs. 17a, 17b, and 17c, respectively). However, the calculated velocities do vary somewhat, being 9.4, 9.9, and 9.8 km/s for the three foam densities, respectively.

7. CONCLUSIONS

For identical areal plate densities, the maximum intact plate velocities achieved in the PWST, FST, and FSTB systems were 6.5, 7.4, and 9.0 km/s, respectively.

In the three shock tube systems, the FSTB system makes the greatest demand on the strength of the plate material. For the same areal density, both SS and Ti-6-4 plates remain intact during accelerating in a PWST while a tantalum plate collapses on axis. In an FST system, SS, Tantalum, and Ti(beta C) plates remain intact during acceleration but Ti-6-4 balloons ductally. In an FSTB system, only SS remains intact.

The results obtained in the PWST show that plate velocity increases with barrel-wall thickness, and that a barrel length of 2 cm is adequate to reach maximum velocity. It is assumed that this holds true for the FSTB, also.

According to hydrocalculations, the foam density in an FSTB can vary from 0.27 to 0.37 g/cm³ and still perform well if uniform in that system.

Plane-wave and peripheral explosive detonation produce only a slight difference in SS plate velocity for an FST.

In order for an SS plate in an FSTB to accelerate intact, the barrel ID must have approximately half the diameter of the HE foam interface.

FIGURE 17

Setup and calculated dynamic contours for a SS plate from FSTB systems with foam densities of 0.27 g cm^{-3} (a), 0.32 g cm^{-3} (b), and 0.37 g cm^{-3} (c). The in-flight contours are all at $22 \mu\text{s}$ after HE detonation.

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