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Plane Shock Generator Explosive Lens: Shock Characterization of 4340 and PH13-8Mo Steels, C360 Brass and PZT 65/35 Ferro-Electric Ceramic

Lawrence J. Weirick

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Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
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PLANE SHOCK GENERATOR EXPLOSIVE LENS: SHOCK CHARACTERIZATION OF 4340 and PH13-8Mo STEELS, C360 BRASS and PZT 65/35 FERRO-ELECTRIC CERAMIC*

Lawrence J. Weirick
Explosive Projects & Diagnostics Department
Sandia National Laboratories
Albuquerque, NM 87185-0327

ABSTRACT

Sandia National Laboratories is currently involved in the optimization of a Plane Shock Generator Explosive Lens (PSGEL). The PSGEL component consists of a detonator, explosive, brass cone and tamper housing. The purpose of the PSGEL component is to transmit a plane shock wave through the 4340 steel bulkhead (wave separator) which has a ferro-electric (PZT) ceramic disk attached to the opposite surface of the steel bulkhead. The planar shock wave depolarizes the PZT 65/35 ferro-electric ceramic to produce an electrical output. One aspect of the optimization program involves the possible replacement of 4340 steel with PH13-8Mo steel for the bulkhead. These materials, as well as the PZT 65/35 ferro-electric ceramic and the brass for the cone, required the shock characterization with respect to Hugoniot parameters. The work presented here gives the shock Hugoniot values for these four materials and documents their measurements.

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Mike Navarro, K-Tech Corp., operated the gas gun system in Area II, Bldg. 922; Doug Dugan, retired, operated the laser interferometer associated with the gas gun; Heidi Anderson, K-Tech Corp., built the projectiles and the targets; George Clark, 2671, provided the PZT 65/35 ceramic material; Don Marchi, provided the 4340 and PH13-8Mo steels and brass; and Manny Vigil, 2653, determined the program requirements.

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Introduction

Sandia National Laboratories is currently involved in the optimization of a Plane Shock Generator Explosive Lens (PSGEL) component[1]. The PSGEL component consists of a detonator, explosive, brass cone and tamper housing as shown in Figure 1. One purpose of the optimization program is to reduce the amount of explosive and reduce or eliminate the housing fragments and shock overpressure so that collateral damage to adjacent components is minimized.

The purpose of the PSGEL component is to transmit a plane shock wave input across the 4340 steel bulkhead and into a PZT ferro-electric ceramic disk attached to the opposite side of the bulkhead, see Figure 1[1]. The planar shock wave depolarizes the PZT 65/35 ceramic to produce an electrical output. The explosively generated shock separates into three waves as it transverses the steel bulkhead. Elastic, plastic I and plastic II waves with different velocities are generated as shown in Figure 2[1-3]. The depolarization of the PZT ceramic is produced by the elastic wave of specific amplitude (10-20 kilobars) and this process must be completed before the first plastic wave arrives at the PZT ceramic. (Approximately 0.15 microseconds are required for the elastic wave to transmit the 0.030 inch thickness of the PZT ceramic.)

One part of the optimization program was to determine the shock velocity-particle velocity Hugoniot data for the following materials: 4340 steel, PH13-8Mo steel, brass, and PZT 65/35 ferro-electric ceramic. This report presents the investigation details and results.

Experimental Procedure

MATERIALS:

4340 and PH13-8Mo Steels - Steels have the unique property of supporting more than one stable compressive wave at driving pressures above 100 kilobars. As shown in Figure 2, the leading wave in this three-wave system is called the Hugoniot elastic wave and is propagated at a velocity of about 6.0 mm/ μ s with pressures between 5 and 40 kilobars depending on the hardness of the steel. The second wave is a polymorphic transition wave (plastic I) and is propagated at approximately 5.0 mm/ μ s with pressures up to 130 kilobars. The third wave, plastic II, is generated by a phase change in the steel and is propagated with pressures above 130 kilobars with velocity determined by the actual pressure.

The properties of the PH13-8Mo stainless and 4340 steels are compared in Table 1[1]. For this particular study, the Rc hardness values were 35 and 32 for 4340 and PH13-8Mo, respectively. The PH13-8Mo is a corrosion resistant steel, whereas the 4340 steel is not. In previous designs using 4340, the steel was plated with cadmium to minimize the potential for corrosion. From an Environment, Safety and Health (ES&H) viewpoint, the cadmium plating process and material are undesirable. This is the strong motivation for using PH13-8Mo steel as the wave separator material.

Brass - Brass was chosen to obtain a planar shock output because of its relatively low sound speed and good machinability. The low sound speed results in the lower shock velocities in the brass necessary to obtain shock planarity in a reasonable geometry at the 0.904 inch diameter free surface. The properties of the brass chosen for this application are listed in Table 1; the designation for this brass is "C360 half-hard".

PZT 65/35 Ferro-electric Ceramic - The PZT 65/35 ferro-electric ceramic material was chosen for properties including [4]: its high remnant polarization, ease of manufacture, and low coercive field. The density of the PZT 65/35 is approximately the same as steel (7.8 g/cc). The sound speed is approximately 3.4 mm/ μ s - significantly lower than that for steel (4.5 mm/ μ s). Therefore, the shock impedance of PZT 65/35 ceramic is lower than that for steel.

GAS GUN SYSTEM:

Gas Gun - The light-gas gun system used is described in detail in Reference 5. Briefly, the barrel is 9 meters long, with an inside diameter of 63.4 mm. The breech is of a quick-acting, quick-change design with two inserts; one termed a "wrap-around" for low-velocity shots utilizing nitrogen (below 0.5 km/s) and a second called a "dual-diaphragm" for higher-velocity shots using helium (up to 1.5 km/s for projectiles with mass below 0.2 kg).

VISAR - One modern technique used for measurement of shock phenomena is the Velocity Interferometer System for Any Reflector, referred to as VISAR[6]. A "Push-Pull" VISAR method developed by Hemsing[7] and used in these experiments results in effective cancellation of light intensity changes during the measurement. In addition, the return laser light is divided between two interferometer legs (dual-leg) with different calibration factors to insure the proper measurement of peak particle velocities.

Projectile/Targets for Hugoniot Measurements - Schematics of the projectile/target configurations for Hugoniot experiments are shown in Figures 3-6 for 4340, PH13-8Mo, brass and PZT, respectively. The material specimens were mounted on the front of either nylon/foam or aluminum sabots. The material specimens acted as flyer plates in impacts with the target materials. The target materials were either polymethyl methacrylate (Polycast), fused silica, Lithium Fluoride (LiF) or sapphire with known Hugoniot relationships[8]. The Hugoniot parameters used for these target materials are listed in Table 2. Polycast is the presently available version of PMMA whose Hugoniot relationship was recently determined by Matthews and Weirick[9] and was found to be experimentally identical to PMMA. The targets consisted of both a thin, 1 mm, buffer plate and thicker, 12.7 mm, window of the same material. Between the buffer and window a 0.5 mil thick foil of aluminum was inserted to act as a reflector for the laser beam. The particle velocity measurements were made at the buffer/window interface.

Results

4340 and PH13-8Mo STEELS

Table 3 lists the shot conditions and results for Hugoniot tests on 4340 steel. The shot conditions include the shot number, the buffer material (known Hugoniot material) with a thickness of 1 mm, target material with a thickness of 12.7 mm, and projectile velocity. Plots of measured particle velocity in the buffer/target versus time are given in Figure 7 for these Hugoniot shots on 4340. The equilibrium, maximum particle velocity taken from these plots is tabulated in Table 3. Table 3 also lists the calculated results from these Hugoniot tests. These results include the particle velocity in the sample material (4340) which is calculated by subtracting the value of the particle velocity measured in the buffer/target from the measured projectile velocity, Equation (1).

$$U_p (\text{sample}) = \text{Projectile Velocity} - U_p (\text{buffer/target}) \quad (1)$$

The impact pressure is determined by correlating the particle velocity measured in the buffer/target with the pressure known[8] to produce that particle velocity in the given buffer/window material. The shock velocity in the sample material is calculated from the following conservation equation:

$$U_s = P/\rho_o U_p \quad (2)$$

where U_s is the shock velocity, P is the impact pressure, ρ_o is the initial density, and U_p is the particle velocity.

Table 4 lists the shot conditions and results for Hugoniot shots on PH13-8Mo stainless steel analogous to those on 4340 in Table 3. The measured particle velocity in the buffer/target versus time for PH13-8Mo flyer plate impacts is given in Figure 8. The results in Table 4 include the measured particle velocity in the buffer/targets, and the particle velocity, impact pressure and shock velocity calculated in the PH13-8Mo.

The relationship of pressure as a function of particle velocity for the 4340 and PH13-8Mo steels is given in Figure 9 and compared to that for 304 stainless steel (SS). Figure 10 gives the shock Hugoniot for the 4340 and PH13-8Mo steels compared to 304 SS as the particle velocity versus shock velocity. In the shock Hugoniot equation:

$$U_s = C_o + S U_p \quad (3)$$

where C_o is the intercept which should be equivalent to the bulk sound velocity and S is the slope.

This equation is used in conjunction with the data plotted on Figures 9 and 10 to determine the C_0 and S values for 4340 and PH13-8Mo. The values determined for 4340 are C_0 equals 4.37 mm/ μ s and S is 1.65. The values determined for PH13-8Mo are C_0 equals 4.55 mm/ μ s and S is 1.41. The reported values for 304 SS are C_0 is 4.58 mm/ μ s and S is 1.49[8]. For the pressure range studied in these sets of shots (30 to 300 kilobars), the 304 SS data fits the following relationship: C_0 is 4.57 mm/ μ s and S is 1.48.

Comparing these values of C_0 and S as well as the visual observation of Figure 10 suggests the following relationship. All three steels have similar shock Hugoniot with the shock Hugoniot of the two stainless steels, 304 and Ph13-8Mo, being very similar. This, of course, is not surprising since they are in the same family of materials and have similar densities.

BRASS

Specifics of shot conditions and results for the Hugoniot tests on the C360 Half-Hard Brass are given in Table 5. These include the shot number, the buffer and target materials with thicknesses of 1 mm and 12.7 mm, respectively, and the projectile velocity. Plots of measured particle velocity in the buffer/targets versus time are given in Figures 11. A summary of the shot results for brass is also given in Table 5. These include the particle velocity measured in the buffer/target, the particle velocity in the brass calculated from that measured in the buffer/target, the pressure in the brass calculated from the impact conditions and the known Hugoniot values for the buffer/target materials, and the shock velocity in the brass calculated using Eqn. (1).

The relationship of pressure as a function of particle velocity for brass is given in Figure 12. Figure 13 gives the shock Hugoniot for brass as the particle velocity versus shock velocity and compares that measured in this study (data points) with that previously reported for "generic" brass (solid line)[8]. The results from the C360 Half-Hard brass of this study matched very well the values for the family of brass. The Hugoniot values in Eqn. (2) were determined to be as follows: C_0 equals 3.73 mm/ μ s and S is 1.43

PZT FERRO-ELECTRIC CERAMIC

Table 6 lists the specifics of shot conditions and results for the Hugoniot tests on the PZT 65/35 ferro-electric ceramic. Plots of measured particle velocity in the buffer/targets as impacted by the PZT flyer plates are given in Figures 14. A summary of the shot results for PZT ceramic is included in Table 6. Figure 15 shows the relationship of pressure as a function of particle velocity for PZT. The shock Hugoniot measured for the PZT 65/35 ferro-electric ceramic of this study (data points) is compared to the shock Hugoniot of "generic" PZT (solid line)[10] in Figure 16. The results from this study show an excellent match with the family of PZT materials. The Hugoniot values in Eqn. (2) were determined to be: C_0 is 3.40 mm/ μ s and S is 2.0.

Summary

The shock Hugoniot relationships for 4340 and PH13-8Mo steels, C360 half-hard brass and 65/35 ferro-electric PZT ceramic were determined and compared with their respective family of materials. It was found that the steels had Hugoniot relationships similar to that of 304 stainless steel, that the relationships for C360 brass and PZT ceramic were within experimental measurements for their respective family of material previously reported in the open literature.

TABLE 1
Properties of PH13-8Mo Stainless, 4340 Steel, and C360 Brass

	PROPERTY	PH13-8Mo	4340	Brass
1.	Density (g/cc)	7.758	7.788	8.43
2.	Yield Strength (ksi)	85	150	42
3.	Tensile Strength (ksi)	138		55
4.	Rockwell Hardness	Rc-32	Rc-35	Rb-78
5.	Poisson's Ratio	0.30	0.30	0.31
6.	Elongation (%)	14		28

TABLE 2
Shock Hugoniot Parameters for Buffer/Target Materials [8]

	Material	ρ_0 density (g/cc)	C_0 bulk sound speed (mm/ μ s)	S slope
1.	PMMA	1.186	2.598	1.516
2.	Fused Silica	2.204	5.258	-0.118
3.	Lithium Fluoride	2.638	5.150	1.350
4.	Sapphire	4.022	11.190	1.000

TABLE 3
Shot Conditions and Results for Hugoniot Shots on 4340 Steel

Shot #	Buffer/ Target Material	Projectile Velocity (mm/ μ s)	Particle Velocity Buffer/Target (mm/ μ s)	Particle Velocity Sample Material (mm/ μ s)	Pressure (GPa)	Shock Velocity Sample (mm/ μ s)
466	Fused Silica	0.840	0.640	0.200	7.313	4.70
471	LiF	1.317	0.920	0.397	15.516	5.02
469	Sapphire	1.327	0.630	0.697	29.958	5.52

TABLE 4
Shot Conditions and Results for Hugoniot Shots on PH13-8Mo Stainless Steel

Shot #	Buffer/ Target Material	Projectile Velocity (mm/ μ s)	Particle Velocity Buffer/Target (mm/ μ s)	Particle Velocity Sample Material (mm/ μ s)	Pressure (GPa)	Shock Velocity Sample (mm/ μ s)
465	PMMA	0.789	0.705	0.084	3.065	4.70
467	Fused Silica	0.849	0.650	0.199	7.424	4.81
470	LiF	1.314	0.920	0.394	15.518	5.08
468	Sapphire	1.326	0.630	0.696	29.960	5.55

TABLE 5
Shot Conditions and Results for Hugoniot Shots on C360 Brass

Shot #	Buffer/ Target Material	Projectile Velocity (mm/ μ s)	Particle Velocity Buffer/Target (mm/ μ s)	Particle Velocity Sample Material (mm/ μ s)	Pressure (GPa)	Shock Velocity Sample (mm/ μ s)
478	PMMA	0.573	0.51	0.063	2.04	3.82
479	PMMA	1.000	0.87	0.130	4.08	3.90
480	PMMA	1.160	1.01	0.150	4.95	3.94
482	LiF	1.000	0.69	0.310	11.02	4.18
484	LiF	1.178	0.81	0.368	13.30	4.26

TABLE 6
Shot Conditions and Results for Hugoniot Shots on PZT 65/35 Ceramic

Shot #	Buffer/ Target Material	Projectile Velocity (mm/ μ s)	Particle Velocity Buffer/Target (mm/ μ s)	Particle Velocity Sample Material (mm/ μ s)	Pressure (GPa)	Shock Velocity Sample (mm/ μ s)
494	PMMA	0.592	0.52	0.072	2.08	3.55
495	PMMA	1.018	0.88	0.138	4.10	3.68
500	PMMA	1.236	1.06	0.176	5.29	3.75
497	Fused Silica	1.014	0.74	0.274	8.49	3.93
498	LiF	1.015	0.69	0.335	10.90	4.07
499	LiF	1.206	0.825	0.396	13.32	4.19

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Figure 1

PLANE SHOCK GENERATOR EXPLOSIVE LENS CONFIGURATION

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Figure 2

FIGURE 2. ELASTIC AND PLASTIC WAVE PROFILE FOR 4340 STEEL

Figure 3

4340 STEEL HUGONIOT

Figure 4

PH13-8Mo HUGONIOT

Figure 5

BRASS HUGONIOT

Figure 6

PZT HUGONIOT

Figure 7

4340 Steel onto Fused Silica, LiF and Sapphire Date: 11/23/93

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

23

Figure 14

PZT onto PMMA, Fused Silica and LiF Date: 11/30/93

Figure 15

Figure 16

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