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Compressed Gas Gun for Controlled Planar Impacts Over a Wide Velocity Range*

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A description is given of the mechanical characteristics and performance of a compressed gas gun capable of accelerating precisely aligned flat-faced projectiles over a wide velocity range. Predetermined reproducible velocities may be achieved between 150 and 5700 ft/sec with an angular misalignment between the impacting surfaces as small as 1.3×10^{-4} rad. The impact occurs in a vacuum with pressures as low as 10^{-4} mm Hg. The gun has an inside diameter of 2½ in., a length of 100 ft, and uses either air or helium at pressures as high as 5000 psi. The gun is particularly suited for experiments in which a well-defined impact is desired.

INTRODUCTION

THE controlled planar impact of flat-faced cylinders is a desirable way of obtaining a well-defined state of transient stress. For the idealized case of elastic materials for both projectile and target and a perfectly aligned impact, a compressive stress over an appreciable area can be attained that is a step function of long duration. In order to achieve a stress from within the elastic range of ordinary materials to the stress commonly achieved with high explosives, a wide range in impact velocity is required. The ability to achieve any predetermined velocity with good reproducibility minimizes the number of experiments required for an investigation.

If the angular alignment between the two impacting surfaces is precisely controlled and there are no air-cushioning effects, the projectile velocity immediately prior to impact may be used with confidence in a calculation of the particle velocity of the impacted surface. Typical experiments[1,2] involve times of less than 1 μsec, and require the angular misalignment between the impacting surfaces to be less than 10^{-3} rad for low velocity experi-

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* This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] R. A. Graham, Rev. Sci. Instr. **32**, 1308 (1961).

[2] W. J. Halpin, O. E. Jones, and R. A. Graham, "ASTM Symposium on Dynamic Behavior of Materials," 27 September 1962, Albuquerque, New Mexico.

ments. To eliminate air-cushioning effects between impacting surfaces, it is necessary that the impact occur in a vacuum of approximately 10^{-3} mm Hg.

It is the object of this paper to describe a gun which can be used to accelerate a precisely aligned projectile to predetermined reproducible velocities of from 150 to 5700 ft/sec. The impact of a target and projectile of the same material at the maximum impact velocity of 5700 ft/sec results in a stress of about 160 kilobars for aluminum, about 350 kilobars for brass, and about 850 kilobars for tungsten. The stress produced in aluminum is about the stress that would be produced by the detonation of Baratol high explosive in intimate contact with aluminum. An impact at the minimum velocity of 150 ft/sec produces a stress of approximately 3 kilobars for aluminum.

DESIGN PARAMETERS

The mechanical parameters which determine the projectile velocity V at the muzzle of an idealized compressed gas gun are storage chamber pressure P, barrel bore diameter D, projectile mass M, and barrel length L. For a given driver gas at a given temperature at equilibrium in the storage chamber, Hawk[3] shows that V is a function of the dimensional ratio PD^2L/M. For example, if a projectile velocity of 4950 ft/sec is desired with helium at 100°F as the driver gas, Hawk predicts that a PD^2L/M of 1.61×10^8 ft^2 sec^{-2} is required.

The nature of the experiments to be performed with this gun requires a minimum bore diameter of $2\frac{1}{2}$ in.; this, in turn, necessitates a projectile weight of approximately 0.5 lb if precise control is to be maintained on the alignment. Regarding D and M as fixed values, then it is evident from the above that the use of a long barrel allows the use of a gas supply system with a low maximum operating pressure. To minimize the hazards and design complications arising from the use of extremely high pressures, a maximum operating pressure of 5000 psi is used. Consequently, a barrel length of 80 ft is required to achieve the desired velocities.

The general arrangement of the gun is as shown in Fig. 1. Essentially, the apparatus consists of a helium or air supply system connected to a gas storage chamber 20 ft in length, two quick opening firing mechanisms, a barrel 80 ft in length, a barrel extension section, a vacuum manifold, a specimen mounting device, a catcher assembly, and two vacuum systems.

DESCRIPTION

The storage chamber and the barrel are made from five 20-ft-long pieces of 4340 annealed steel tube, 4.00 in. o.d., 2.470 in. i.d., with a 32 μin. rms inside finish. One piece is used as the gas storage chamber and the other four pieces are joined by bolted flanges with split shear rings to form the main barrel. This arrangement is desirable for two reasons: first, the 20-ft length of the gas storage chamber allows the projectile to attain a high velocity before its acceleration is reduced by the rarefaction wave reflected from the rear of the driver gas chamber; and second, since the chamber is the same diameter as the barrel and aligned with the barrel, the gas is allowed to expand with a minimum interference to flow.

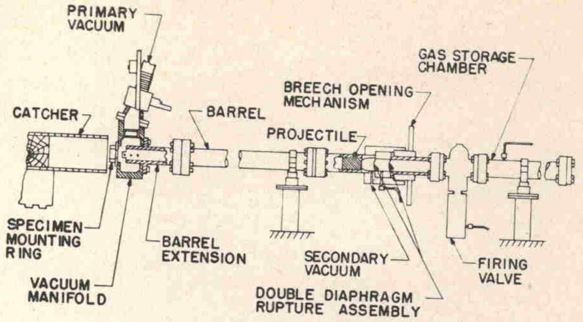

FIG. 1. Compressed gas gun general arrangement. Projectile moves from right to left.

Air is used as the driver gas when projectile velocities below 1000 ft/sec are desired, and helium is used when projectile velocities greater than 1000 ft/sec are desired. The necessary pressure is obtained with a five-stage compressor capable of pumping air from atmospheric pressure to 5000 psi, or helium from 40 to 5000 psi. Gas may be supplied to the storage chamber directly from 2500-psi gas bottles or may be routed through the compressor, where it is recompressed to 5000 psi, and then routed to the storage chamber.

Two alternate firing methods are provided, a quick opening gate valve and a double diaphragm rupture assembly. Both systems have the advantages of being able to release the projectile when the pressure in the storage chamber is at a definite predetermined value and to release it with no appreciable time delay between the fire command signal and actual projectile release.

For velocities up to 3000 ft/sec a commercially available, pneumatically controlled 5000-psi gate valve is used. A firing mechanism of this type is easy to use and requires no expendable parts. With its pneumatic controller operating at 1800 psi air, the opening time of this valve is approximately 65 msec.

For high projectile velocities, the firing valve is held in the open position and a double diaphragm assembly, as shown in Fig. 1, is used. The diaphragms are selected to operate before firing with a pressure differential of no more than 70% of their rated rupture pressure and are ruptured with a pressure of at least 120% of their rated pressure. It is possible to achieve projectile velocities from 3000 to 5700

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[3] N. E. Hawk, Sandia Corporation, Albuquerque, New Mexico (unpublished report).

ft/sec with four standard commercially available diaphragms. By means of an adjustable pressure regulator in a line between the storage chamber and the interdiaphragm chamber, i.e., the chamber between the two diaphragms, the pressure in the interdiaphragm chamber is maintained at one-half that in the storage chamber. Firing is initiated by closing the interconnecting line and dumping the pressure in the interdiaphragm chamber. The diaphragms are scored in a cross pattern to prevent fragmentation and have shown excellent opening characteristics.

The projectile diameter is 2.4635±0.0005 in. with the impact face perpendicular to the side to within 1×10^{-4} rad. The minimum practical length for adequate alignment guidance is approximately $2\frac{1}{2}$ in., resulting in a minimum practical weight of approximately 0.5 lb. The projectile is grooved for a hard rubber O-ring with Teflon back-up rings. This arrangement serves to seal the barrel for vacuum before firing and to prevent the driver gas from blowing by the projectile as the projectile moves down the barrel. For the low velocity range, where perpendicularity of impact is more important, projectiles 12 in. long are used to minimize the angular misalignment due to the looseness of fit.

The projectile is guided for the last 18 in. of barrel travel by a barrel extension section where the bore size is gradually decreased from the barrel diameter of 2.470 in. to a diameter of 2.4650 in. For a distance of $1\frac{3}{4}$ in., just prior to impact, the leading portion of the projectile leaves the barrel extension and enters the vacuum manifold chamber where it is no longer guided by the bore. Consequently, at impact, the leading $1\frac{3}{4}$ in. of the projectile is free of the barrel but still in a vacuum, while the major portion of the projectile (which contains the O-ring) is still in the barrel extension where the projectile is closely guided. The impact end of the projectile must be free since the projectile expands from the plastic deformation wave propagating in the projectile as a consequence of the impact.

To insure that no air-cushioning occurs at impact, the section of the barrel from projectile to specimen, $82\frac{1}{2}$ ft, is evacuated through the vacuum manifold and 20 ft of 3-in.-diam pipe by a mechanical vacuum pump with a pumping speed of 35 ft^3/min and a 2×10^{-5} mm Hg ultimate blank off pressure. In practice, it is found that pressures of less than 10^{-2} mm Hg can be achieved in 10 min and, by continued pumping, pressures of 2×10^{-4} mm Hg have been attained. The projectile is held in position at the breech end of the gun by a vacuum maintained between the firing mechanism and the projectile by a separate small vacuum pump. The pressure maintained in this secondary vacuum system is about 200 mm Hg. Sealing of the primary vacuum system from the rough secondary vacuum system is accomplished by the O-ring on the projectile.

OPERATION AND CONTROL

For the conditions at the time of impact to be well-defined, it is necessary that the angular misalignment between the impacting surfaces be minimized. Precise alignment control of the projectile face and specimen at impact is achieved by maintaining precise dimensional tolerances on all factors which contribute to misalignment. These factors are (1) perpendicularity of the specimen holder mounting surface to the barrel bore, (2) flatness and parallelism of the specimen in the holder, (3) perpendicularity of the projectile face to its cylindrical side, and (4) ratio of projectile clearance with the barrel bore to the projectile length.

One side of the vacuum manifold serves as the mounting surface of the specimen holder and was hand-lapped perpendicular to the barrel extension bore to 5×10^{-5} rad. The assembled specimen is kept flat and parallel to its holder mounting surface to at least 2×10^{-4} rad. All alignment tolerances are inspected just prior to an experiment, utilizing jigs designed to duplicate the alignment conditions in the barrel. The angle of misalignment at impact is measured in a majority of the experiments[4] performed with the gun. The alignment procedures have given misalignment angles as small as 1.3×10^{-4} rad and a mean value of misalignment of 5×10^{-4} rad.

A precise determination of projectile velocity is made just prior to impact. During its travel through the barrel extension, the projectile intercepts three coaxial switch pins positioned 1.200 in. apart, with the last pin located 1.200 in. from the plane of impact. With three pins, two time intervals are obtained, and from the two calculated velocites the acceleration of the projectile is determined. The short pin spacing minimizes differences between the measured average velocity and the true instantaneous velocity. The velocity at impact is determined to within 0.3%. A detailed description of the velocity measuring system is given by Ingram.[5]

The gun facility is operated from a control station located remote to the gun installation for reasons of safety and convenience. From the control station, it is possible to fill the gas storage chamber to a desired pressure (within ±0.4 psi from 0 to 1000 psi and within ±2 psi from 1000 to 5000 psi) either directly from the gas bottle or through the compressors, start or stop the primary and secondary vacuum systems, control all firing operations, and record all test data. For reasons of safety and reliability, all prefiring operations are electrically programmed so that the operations must be performed in a definite sequence. The pressure in the storage chamber and the vacuum in front of and behind the projectile are continuously monitored at the control station.

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[4] For a description of the method for determining the angular misalignment, see Ref. 2.

[5] G. E. Ingram (to be published).

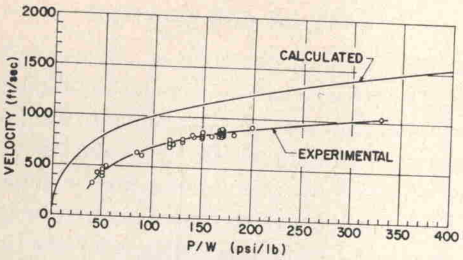

FIG. 2. Calculated and experimental projectile velocities vs chamber pressure per pound of projectile: 100°F air driver gas, 82.5-ft barrel length, and 2.470-in. barrel bore. Experimental velocities were obtained with pneumatically operated firing valve.

Safety interlocks are provided to insure that the rooms containing the gun are cleared of personnel before the storage chamber can be filled or the firing command initiated. All electrical systems were made fail-safe to insure that the gun will not inadvertently fire from a power failure.

PERFORMANCE

Analytical predictions or the velocities for a given pressure and projectile weight were made by the method given by Hawk.[3] He assumes that the gun has an infinite reservoir and no restrictions to gas flow, the expansion occurs as a simple isentropic expansion wave, and there are no frictional forces restraining the projectile. Values of specific heats for the gases at standard conditions were used for all computations. Calculated projectile velocities for air and helium are shown in Figs. 2 and 3, respectively.

One would generally expect that the velocities actually attained would be lower than predicted by the idealized analysis, and, as shown in Fig. 2, this is the case for air. The experimental velocities were obtained with the pneumatically operated gate valve and a considerable portion of the reduction in velocity is felt to be due to the finite opening time of the valve. For P/W values from 60 to 300 in.$^{-2}$ the velocities attained show a typical standard deviation of 1.2%. For a P/W value lower than 60 in.$^{-2}$ the velocity is more dependent on the frictional drag on the projectile so that good reproducibility is achieved only for a given projectile size, weight, fit to the bore, and O-ring squeeze. Below a P/W value of 30 in.$^{-2}$, the velocities attained become erratic, limiting the lowest velocity that can be conveniently achieved to about 150 ft/sec.

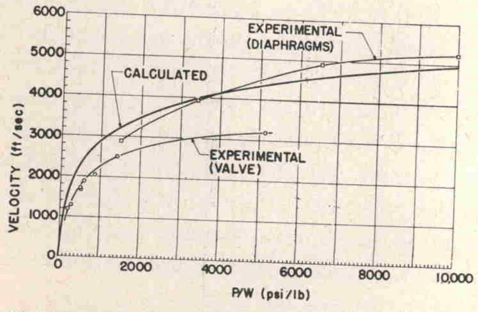

FIG. 3. Calculated and experimental projectile velocities vs chamber pressure per pound of projectile: 100°F helium driver gas, 82.5-ft barrel length, and 2.470-in. barrel bore. Experimental velocities were obtained with both firing valve and double diaphragm rupture system.

Velocities attained with helium as the driver gas are shown in Fig. 3 for both the valve firing and the double diaphragm rupture firing. The valve firing curve is substantially below the calculated and diaphragm firing curves but is quite reproducible and covers the velocity range from 1000 to 3000 ft/sec.

The rupture diaphragms provide a faster unrestricted flow and measured velocities approach the calculated valves more closely. Higher velocities than predicted by the analysis are obtained for velocities greater than about 4200 ft/sec. Brody[6] and Horn[7] have also observed higher velocities than predicted by the analysis for velocities greater than about 4000 ft/sec. Thus, for three widely different high pressure helium guns an excess velocity is observed at different pressures and different P/W ratios, but beginning at the same velocity or, equivalently, the same PD^2L/M. Rupture diaphragm shots with compressed air under identical conditions in our gun show that air gives a velocity of 94% of that predicted by the isentropic expansion. Velocities higher than calculated are then characteristic of compressed helium and not compressed air.

The maximum velocity of 5690 ft/sec obtained to date was accomplished at a P/W value of 14 220 in.$^{-2}$ and is not shown on Fig. 3.

The acceleration measured at the muzzle end of the gun is zero within experimental error between velocities of 200 and 1000 ft/sec. For velocities greater than 1000 ft/sec, the acceleration causes a 1 to 2% increase in velocity between the two velocity stations, the higher accelerations being generally obtained for higher velocities.

The gun has proven to be a valuable and versatile research tool for a wide variety of experimental programs involving the effects of high amplitude stress on the mechanical and electrical properties of materials.

ACKNOWLEDGMENTS

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[6] P. Brody, Report TR–869, October 1960, Harry Diamond Laboratories.

[7] L. Horn, Report TR–932, July 1961, Harry Diamond Laboratories.

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