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The Novel “Fracture” Gun at the DEVCOM Army Research Laboratory for Precise, Highly Instrumented Impact Experiments*

by Christopher S Meredith

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14. ABSTRACT This report describes the novel “fracture” gun recently built at the US Army Combat Capabilities Development Command Army Research Laboratory to study dynamic deformation and fracture mechanisms under impact loading using high-speed cameras with digital image correlation. This gun combines the precise projectile/target alignment capabilities typical of a plate-impact experiment with the ability to observe phenomena over a wide spatial and temporal scale. The velocity capabilities and the target tank are outlined. The target tank is small with large windows so that cameras can be placed very close to the impact location, which allows for small fields of view not typically achievable in these experiments. Velocity measurement, triggering, and lighting solutions are presented. There are very few experimental methods to probe fundamental deformation and fracture mechanisms within the ballistic regime, but this gun and the associated instrumentation are a big step toward better understanding these mechanisms.					
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1. Introduction

Ballistics testing has historically been a “shoot-and-look” exercise that often focuses on outcomes (i.e., full penetration vs. partial vs. no penetration). Flash X-rays have been used for decades that provide in-situ images; however, due to their cost and complexity, ballistic ranges typically are restricted to a few frames at most. Furthermore, the information that can be quantified from X-ray imaging is limited. In the last decade, high-speed cameras have become fast enough with a high-enough resolution to capture dynamic events in detail, and digital image correlation (DIC) allows an unprecedented amount of quantitative information to be extracted from an experiment.

The US Army Combat Capabilities Development Command recognized the need for a high-velocity gun to study fundamental deformation and fracture mechanisms under ballistic impact that would use the latest in-situ probes for quantitative measurements. These include high-speed cameras with DIC,^{1,2} laser interferometry,³ flash X-rays,³ strain/pressure/force gages, and so on, that can simultaneously measure and, ultimately, allow researchers to better understand ballistic phenomena. This report describes the major gun components and solutions to issues with projectile velocity measurement and triggering, especially regarding the triggering of strobe lighting for illuminating the object of interest for high-speed camera imaging. Next, the velocity performance of the gun is presented. Finally, potential future experiments and additional upgrades and paths forward are outlined and previewed.

2. Fracture Gun Components

The gun is a high-velocity gas gun driven by helium. The major components consist of the breech, gun barrel, target-mounting plate, target and catch tanks, and the gas handling and control systems. This section describes issues that occurred with measuring projectile velocity and triggering, and how to trigger strobe lights that take a relatively long time to reach usable brightness.

The breech is a “regenerative” type breech that uses a piston (Fig. 1). One end of the piston seals the outlet port to the barrel when the reservoir is pressurized. When gas at a relatively moderate pressure swiftly fills the “fire” chamber, the piston is rapidly driven back by differential area at the other end of the piston. This releases the gas very rapidly from the reservoir into the barrel. A deceleration chamber, with gas at a low pressure, “softly” stops the piston without damage, ensuring the cycle can be repeated for the next shot. There are two major advantages of this design over other gas gun breeches: 1) there are no expendable parts, unlike a double

diaphragm breech, and 2) the projectile does not need a seal to prevent gas leaking out of the reservoir like with a wrap-around breech; that is, the projectile can be freely sliding in the barrel. Being able to shoot projectiles with or without a sabot maximizes the types of projectiles and experiments that can be performed—everything between a Taylor anvil test and a plate-impact experiment.

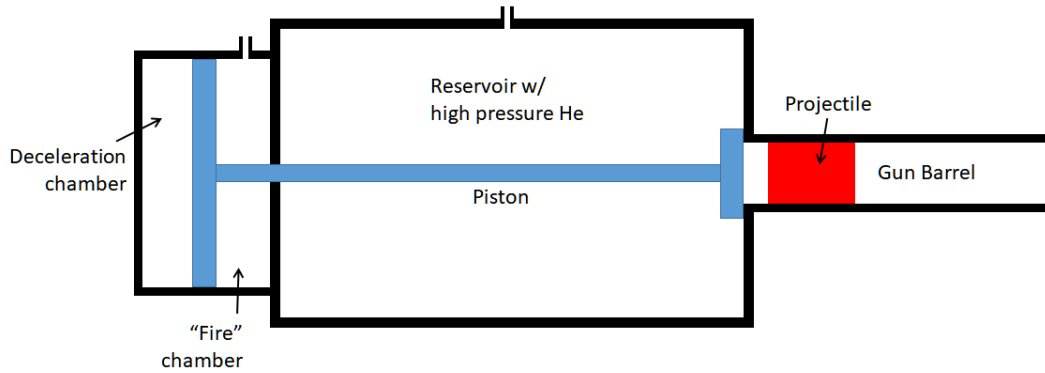


Fig. 1 “Regenerative” type gas gun breech (not to scale)

The gun barrels are made from off-the-shelf drawn-over-mandrel (DOM) steel tubing that was subsequently honed to obtain a smooth finish. The DOM process produces tubes with tighter tolerances (straightness, circularity, concentricity, constant diameter along the length, and smoother surface finish) than other tubing methods, and the honing further improves some of the tolerances. The tubing is available in a wide range of sizes, including long lengths, and combined with their cheap cost make these a good choice as compared to fully custom barrels. This gun has barrels with bore sizes between 6.35 and 25.4 mm, all with a length of 2440 mm. In this report, all the generated data used the nominal 6.35-mm barrel.

Downrange of the gun barrel is the mounting plate, which holds the target, and the target tank, which surrounds the target and has windows for viewing the impact with high-speed cameras, and the catch tank, which stops and contains the projectile, target, fragments, other debris, and expended gas following impact. These components also bolt together, along with the gun barrel and breech, such that a vacuum can be pulled (<100 mTorr is easily achievable) prior to shooting the gun. Figure 2 shows a schematic of these components. The mounting plate is bolted into the floor and has bolting options so a wide variety of target holders and fixtures can be used. When they are properly designed, these fixtures allow precise alignment between the target and projectile to under a few milliradians (typical for plate-impact experiments). The target tank and its windows allow the impact to be viewed with a high-speed camera, so it is the most important from a design standpoint. The four windows of the target tank were purposefully made large, allowing a field of view (FOV) up to about 152 mm square. At the same time, the

outer diameter of the target tank was minimized to reduce the distance between the shot axis and the window, which allows a short working distance for the camera. The distances allow a 200-mm macro lens (magnification = 1) on a Shimadzu HPV-X2 high-speed camera to have a FOV of 12.8×8.0 mm. But beyond a single camera viewing an experiment, the target tank was designed so a pair of cameras in a stereo DIC configuration could image an impact event to calculate 3-D information. Figure 3 shows two extreme stereo DIC configurations with a pair of Shimadzu HPV-X2 cameras. In Fig. 3a, a 12.8-mm FOV can be imaged in 3-D using 200-mm macro lenses with the cameras at a 25° angle. At the large end of achievable FOV, the cameras can have 35-mm lenses and be at a 23° angle to image a 152-mm FOV in 3-D. Inspiration for the target tank partially came from small, portable gas guns recently used at X-ray synchrotrons for in-situ measurements during shock loading.⁴⁻⁶

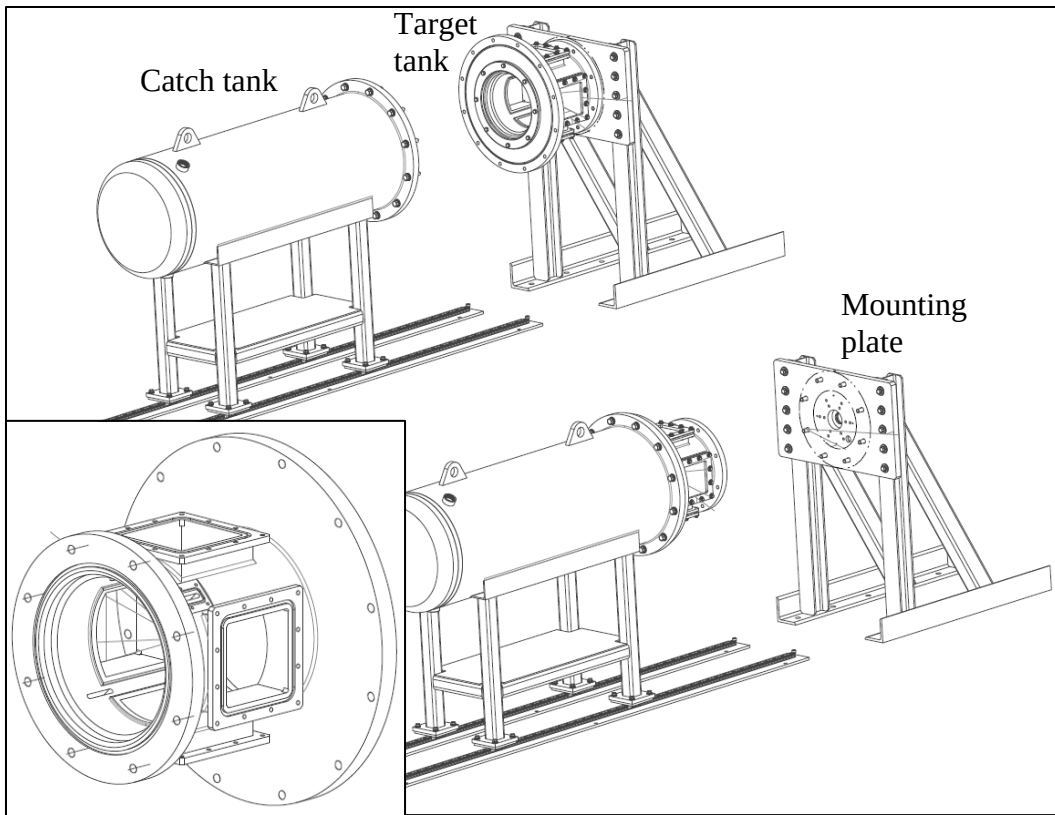


Fig. 2 The mounting plate, target tank, and catch tank; inset shows the target tank in greater detail

Finally, there is the catch tank, which can do more than abruptly stop the projectile and target. There is a recovery system for “softly” catching the projectile and/or target using rags, foam, or other appropriate medium. Recovering the sample without additional damage after impact allows it to be interrogated further using microscopy techniques, for example, so microstructural changes can be correlated directly with the impact event. This is almost never done with ballistic experiments and is another aspect of the gun that was purposely designed from the beginning.

The source gas is from 41.4-MPa (6000-psi) gas cylinders with a pressure booster with an output up to 41.4 MPa. The booster can fill either a couple storage tanks or fill the gun directly. This ensures all shots can be at the maximum 41.4-MPa pressure, even as the pressure drops in the source cylinders. A vacuum can be pulled from either the target tank (and gun barrel), or catch tank, or both. The target and catch tanks can also be pulled to different vacuum levels, which can save significant time because the vacuum level in the target tank is less critical in most situations. Vacuum levels of less than 100 mTorr can be readily achieved only in the target tank in less than a few minutes. All the gun operations are controlled remotely from a control room next to the gun.

The velocity system uses laser beams and photodetectors to measure the drop in signal when the projectile blocks the beam. For freely sliding projectiles there is blow-by, and this turbulent gas in front of the projectile (Fig. 4a) can disrupt the laser beams making it difficult to determine when the projectile has blocked the beam. At a few MPa (hundreds of psi) this can be alleviated somewhat by increasing the power of the laser, but above a few MPa this has no effect. After more testing it turns out blow-by only has a small role in disrupting the laser beams as the pressure (and, thus, projectile velocity) is increased further. The biggest effect by far is due to the compression of the air in front of the projectile when no vacuum is pulled. This was confirmed by shooting projectiles in atmosphere that were freely sliding and had some blow-by, and ones that were press-fit into the barrel with little to no blow-by. Under both these conditions the laser velocity signals were poor. Repeating the shots under a vacuum produced very clean signals for both types of projectile. Figure 4b shows the air in front of the barrel prior to a press-fit projectile exiting. This projectile is traveling fast enough to compress the air in front of it, creating a shock wave in the air. The leading shock wave is identified with the red arrow, and there are a few waves following the leading one. This shock wave is likely produced when the projectile velocity rises above the speed of sound in the air, which is about 330 m/s. Under every situation, pulling a vacuum improves the signals and is essentially a requirement above a few MPa firing pressure.

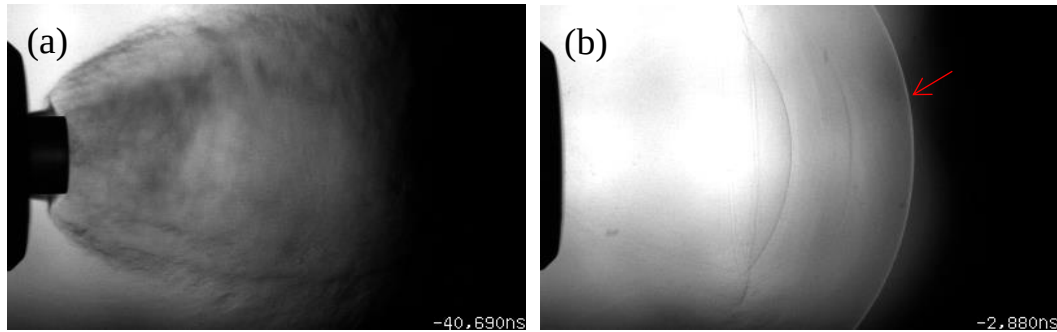


Fig. 4 (a) Turbulent air/gas in front of the projectile due to blow-by as the projectile exits the barrel when no vacuum is pulled and (b) a shock wave (red arrow) is produced in front of the projectile prior to it exiting the barrel after the projectile velocity is high enough when no vacuum is pulled

Often the biggest challenge with high-speed cameras is getting enough light at the desired frame rates of the camera. Typically, strobe lights are the only type of light bright enough for reflected light imaging at exposure times below about $1\ \mu\text{s}$, but these lights take time to reach useable or full brightness (up to a couple-hundred microseconds) and the light is only usable for a short period of time (hundreds of microseconds). Assuming a peak projectile velocity of $1.5\ \text{km/s}$ and a strobe turn-on time of $200\ \mu\text{s}$, then the projectile will be at least $300\ \text{mm}$ from the target. Thus, the projectile will not have even left the barrel when the light needs to be triggered. Solutions such as drilling cross holes through the barrel about $300\ \text{mm}$ from the muzzle for a laser beam was not an option because that would severely reduce gun performance. Sensors that detect the passage of an electrically conductive projectile (or component of the projectile) that exploits magnetic inductance do not work with a steel gun barrel. The solution was to mount semiconductor strain gages on the gun barrel in the hoop direction 300 and $450\ \text{mm}$ from the muzzle. The strain gage signals are measured, which serve as the source signal for triggering the lights to turn on.

Figure 5 shows the strain gage signals from shots with a variety of breech pressures, projectiles, and velocities. In all the plots, time equal to zero corresponds to the front of the projectile exiting the barrel—detected via it blocking a laser beam. The signal from a gage is a relatively slowly varying sinusoidal wave, where there are only a couple periods or less to the wave between when the gage starts reading nonzero strain to when the projectile exits the barrel. The signal does not have an obvious feature when the projectile passes by the gage. However, the oscillations are consistent in time from shot to shot, such that one can generally reliably trigger a light off them. But for each mass–pressure–velocity combination of a projectile, a practice shot (or two) needs to be done to establish the timing.

Figure 5a shows a few shots at the highest achievable velocity showing the shot-to-shot error, called jitter, is less than a couple dozen microseconds. However, the timing is quite sensitive to the projectile velocity, as shown by the one shot at a few percent lower velocity corresponding to over a couple-hundred microseconds' time shift in the signals. Triggering the scope, and thus the trigger signal to the lights, is accomplished with a two-step condition. The first step is the signal from the strain gage 450 mm away from the muzzle must rise above a setpoint voltage value for a certain amount of time, say above 50 mV for 500 μ s. The second condition is the same signal then needs to drop below 0 V (negative slope), at which point the scope will send a signal to a digital delay generator (DDG). The DDG then sends a signal to the lights after a user-set time delay, which in this case would be about 600 μ s. Figure 5b shows a couple shots at a slower velocity, almost 1200 m/s, but still at the maximum pressure (one shot did not measure the signal from the gage 300 mm from the muzzle). The same two-step trigger was used, and the jitter appears to be only a couple dozen microseconds, which was confirmed by performing several successful shots with good timing of the lights (the signals are not shown). Figure 5c show the strain gage signals from shots at even lower velocities and at breech pressures well below the maximum. The jitter is about 200 μ s with a projectile velocity of 628 m/s, but only two shots were conducted. Finally, Fig. 5d shows signals with projectile velocities of a few hundred meters per second, where a similar couple-hundred-microsecond jitter is observed. While the velocities are within a couple percent of each other, the projectiles did have different diameters (see Fig. 7a), which could be contributing to the small time shifts in the signals.

Velocities between 500–700 m/s are in a transition regime, where depending on the distance between the muzzle and the target and the turn-on time of the light, triggering off the strain gage signal may not be required because one of the laser's beams used for velocity measurement, especially those passing through the barrel, could be back in enough time and space to use its signal as the source for triggering the lights. Under these conditions the jitter should be well below a couple-hundred microseconds because the projectile is much closer to the target, so the DDG delay times will be less. For all velocities below a few-hundred meters per second, triggering the lights with one of the velocity measurement laser beams is not an issue since there will be plenty of time for the lights to turn on at these low velocities. However, if a particular velocity and target position forces the strain gate signal to be used, the results from Figs. 5c and d indicate there may be some issues with optimum timing of the lights due to the jitter. Strobe lights often never have constant brightness and optimum lighting may fall within a relatively narrow hundred-microsecond window, for example.

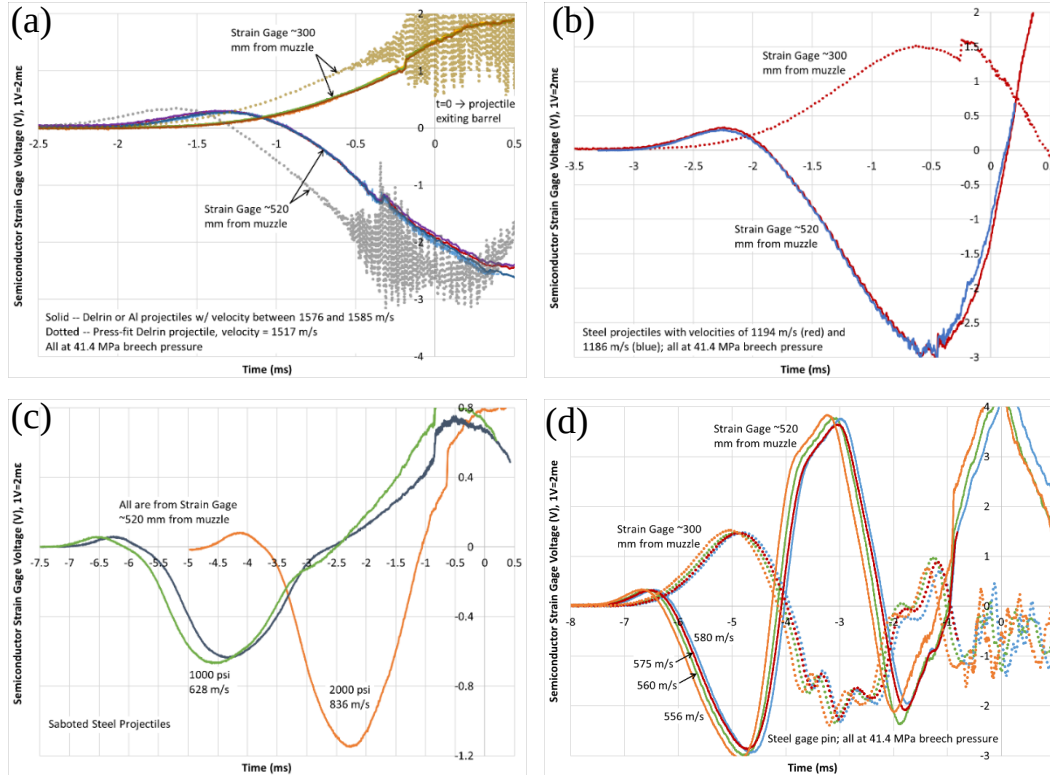


Fig. 5 Signals from semiconductor strain gages oriented in the hoop direction of the barrel located about 300 and 540 mm from the muzzle, where $t = 0$ corresponds to the front of the projectile exiting the barrel via it blocking a laser beam. (a) Freely sliding Delrin or aluminum (Al) projectiles with a velocity between 1576 and 1585 m/s, and a press-fit Delrin projectile at 1517 m/s, where the breech pressure for all is 41.4 MPa. (b) Freely sliding steel projectiles with velocities of 1194 and 1186 m/s, both at a breech pressure of 41.4 MPa. (c) Saboted steel projectiles with velocities of 836 and 628 m/s at a breech pressure of 41.4 MPa.

The observed strain gage signals in Fig. 5 reveal the strain gages are not measuring the pressure pulse in the barrel as the projectile flies past the strain gage location. If that were the case, the signal would be relatively low, then suddenly jump higher as the projectile passed by and would stay high due to the high-pressure helium gas behind the projectile. Additionally, since the gages are aligned in the hoop direction, positive values imply internal pressure in the barrel, but negative values imply external pressure. Since the latter is not physically occurring, then something other than the internal pressure dominates the signal. The author speculates it is the vibrations created when the regenerative breech opens. An important point is the sinusoidal-like signals from the two gages at different locations are different, or, at best, are similar but out of phase (but that may be a coincidence based on their relative location and the frequency of the vibrations). This means that the strain signals will be different at each location on the barrel, both along the length and possibly around the circumference, and from one barrel size to the next. It is also possible that mounting gages in the axial direction (or another direction entirely)

will produce better signals for triggering, including possibly having lower jitter. Thus, each barrel and the strain gages mounted on it will have to be “calibrated” to measure the timing. If an existing gage breaks or debonds, it should be mounted in the exact same location, including around the circumference, to ensure already established timings do not change.

3. Fracture Gun Performance

The performance of the gun was characterized on a 6.35-mm nominally sized barrel with a length of 2440 mm. The exact bore size of the barrel is such that a 6.431-mm (0.2532-inch) gage pin slides freely through it with little to no frictional resistance, but a 6.436-mm (0.2534-inch) gage pin will not even enter the bore. Shots were performed at 3.45 MPa (500 psi) and every 6.89 MPa (1000 psi) up to 41.4 MPa (6000 psi). Projectiles were mostly freely sliding and made from Delrin or polycarbonate (PC), Al, and steel. Freely sliding projectiles reduce the wear on the bore but allow more blow-by. Saboted projectiles made of plastic produce minimal wear on the bore and can significantly reduce or eliminate blow-by; however, their use may be undesirable for certain types of tests. Figure 6 shows the velocity obtained as a function of pressure for three different projectiles, each with a different mass. The maximum velocity is about 1600 m/s for lightweight projectiles, and relatively long rod steel projectiles can reach a few hundred meters per second. Generally, only one shot was performed at each condition, but certain shots were repeated, and Fig. 6 shows the data points generally overlap each other. Overall, the shot-to-shot jitter is less than 1%. Finally, the trend as a function of pressure follows a power law curve fit very closely, which will give accurate interpolation of the velocities.

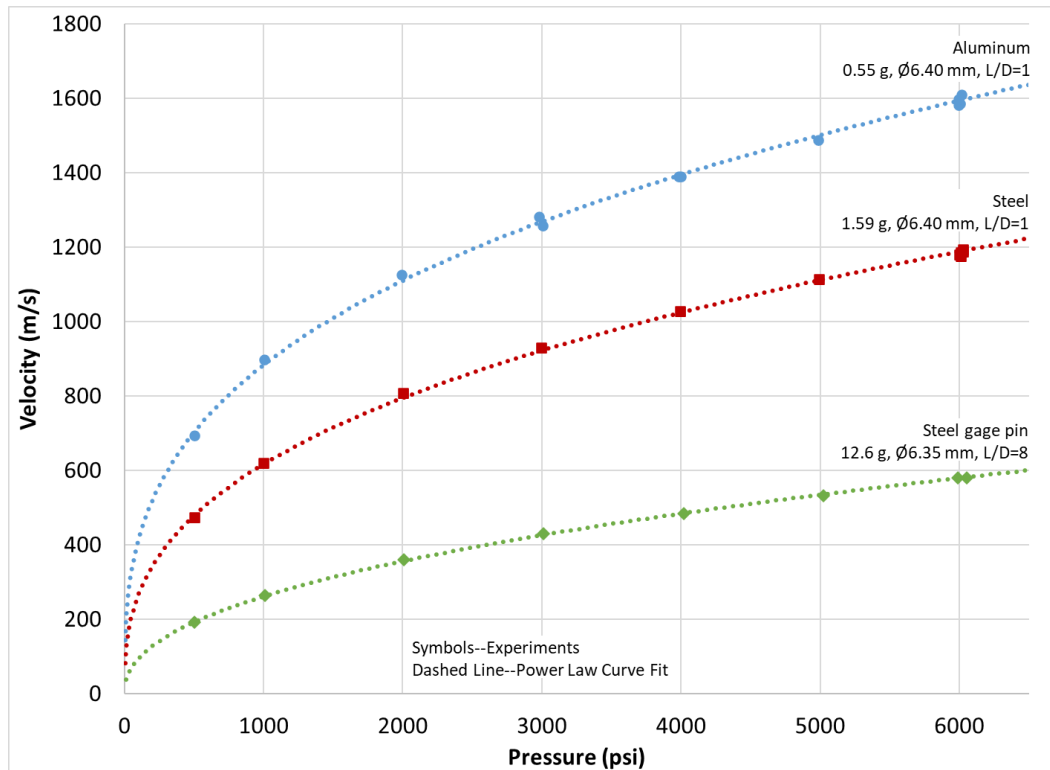


Fig. 6 Velocity of the gun as a function of pressure for different mass projectiles

For certain types of tests (Taylor anvil test), sabotaging the projectile is undesirable because the sabot being present in the impact event can change the result (often because the sabot adds mass), which can extra complexity to simulations of the experiment. But there should be an optimum diameter mismatch between the bore and projectile such that velocity is maximized and would correspond to a condition of low barrel wear and blow-by. This is shown for steel gage pins in Fig. 7a, where the peak velocity occurs when the projectile diameter is about 0.076 mm (0.003 inches) less than the bore diameter. For Delrin, which will have less friction with the steel barrel, the diameter mismatch that maximizes velocity is 0.025–0.051 mm (0.001–0.002 inches). Within the ranges tested in Figs. 7a and b, the difference between the maximum and minimum is only about 4% (the largest size of the Delrin is actually press-fit into the bore, i.e., not freely sliding). Finally, Fig. 7c is a comparison between PC and Delrin projectiles, with everything else being equal. The former is about half of weight, but the latter has some lubricious qualities. Clearly, the lighter-weight PC has greater velocity, but it is only about 3%.

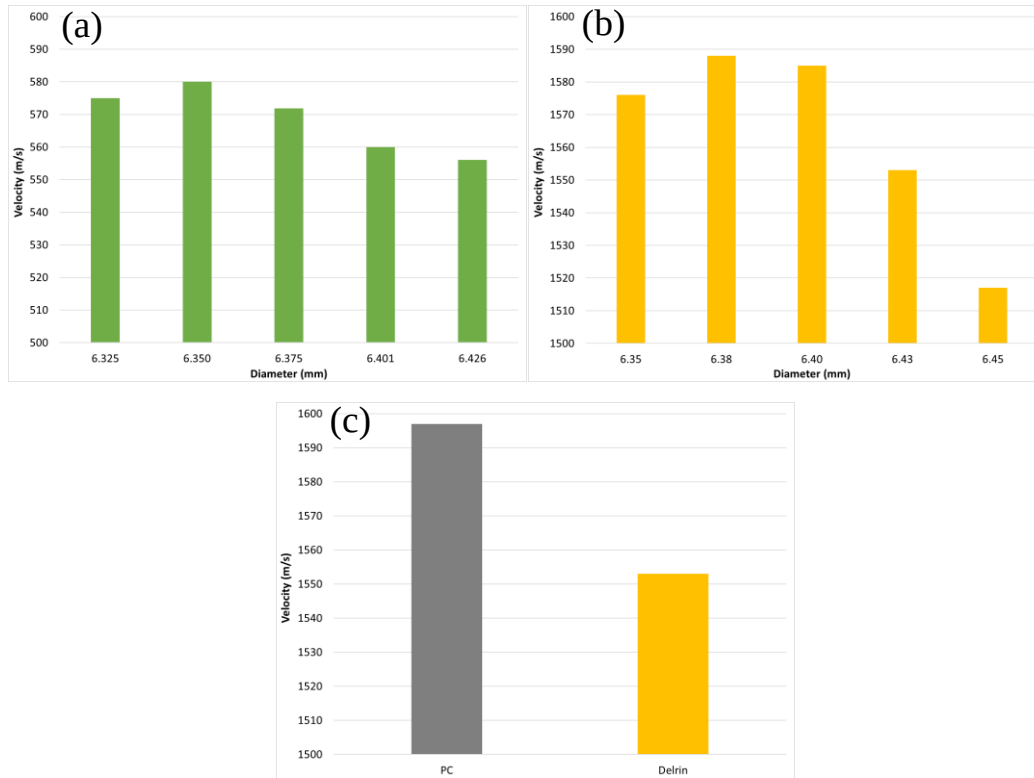


Fig. 7 Velocity of the gun at 41.4 MPa (6000 psi) firing pressure as a function of diameter for (a) steel gage pins, $L/D = 8$, and (b) Delrin, $L/D = 1$. (c) Velocity for PC and Delrin with the same dimensions and firing pressure. To magnify the small velocity differences, the velocity axes do not start at zero.

The next step was to design a PC sabot that does not allow any blow-by—for those experiments that cannot tolerate any. At the maximum firing pressure of 41.4 MPa, even a little blow-by could easily generate enough force to move, misalign, and/or blow away a “lightly” held sample prior to impact. A “lightly” held sample may be advantageous under many tests because a more “rigid” holding might change the results and make simulations more difficult. A “flared” sabot design is shown in Fig. 8a, where the back end of the sabot has a section with a slightly larger diameter, characterized by the flare diameter, D , and the flare width, W . A small chamfer was machined into the end of the barrel to accommodate the flared end of the sabot. Several different dimension combinations were tested with the velocity results shown in Fig. 8b. Blow-by was assessed qualitatively by hanging a single-ply paper towel over the muzzle and the movement was recorded with a high-speed camera in the tens of microseconds prior to and as the projectile exited the barrel. The paper towel was so light that one could slightly blow on the towel (with their mouth) and blow it out of the way of the muzzle, thus even slight gas blow-by would move the paper towel. A steel projectile was inserted into a drilled recess in the sabot to add mass to observe the response of a more “realistic” mass that might be used for real

experiments, where the total mass (1.46 g) is slightly less than the freely sliding steel projectiles in Fig. 6. Not surprisingly, the sabots with the largest flare diameters, 6.62–6.69 mm, and flare widths, 1.27 and 2.54 mm, resulted in very little blow-by. The towel slightly moved around, displacement by only a couple of millimeters, but it was not blown away from the muzzle (see Fig. 9, left column). Notice from Figure 8b that the velocity does not drop as the flare size increases, even though the press-fit with the barrel is increasing, and the velocity is a little greater than the freely sliding steel projectiles in Fig. 4. The shot-to-shot variation is about the same as what was observed with the freely sliding projectiles, so the velocity is essentially the same for all the flared sabots tested. Of the two, the flare length plays a bigger role in reducing the blow-by as compared to the flare diameter. This is exemplified by the sabot geometry that did not have any blow-by—the sabot with a constant diameter (i.e., no flare) of 6.44 mm, which is approximately a 0.025-mm (0.001-inch) press-fit with the barrel. The right column of Fig. 9 shows successive images about 100- μ s apart where there is no movement of the paper towel. The velocity of this sabot/projectile is a little lower than others by a couple percent, but the mass is higher by several percent (Fig. 8b), so it is more likely the drop is a reflection of the increased mass, rather than increased friction with the barrel.

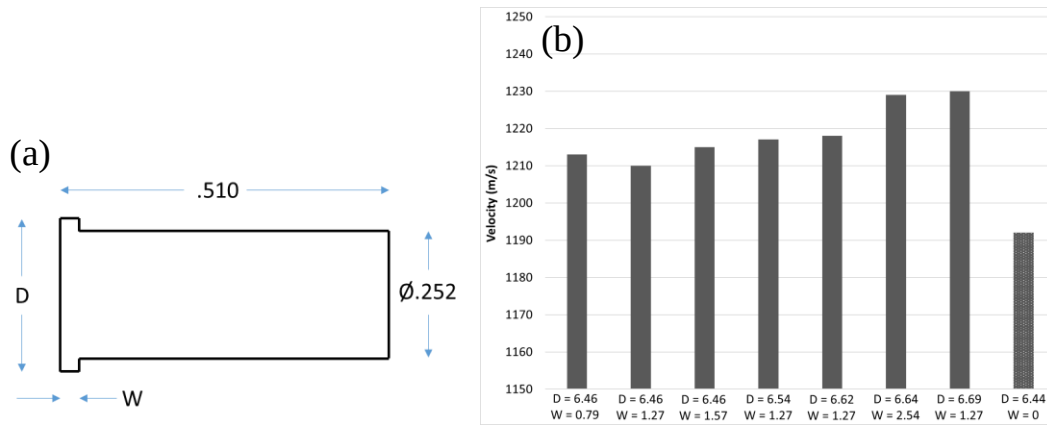


Fig. 8 (a) Geometry of the PC “flared” sabots—all dimensions in inches, and image is not to scale and (b) velocity of flared sabots with a steel projectile with different flare diameters, D , and flare widths, W (both in millimeters). The last geometry with $W = 0$ was a 6.44-mm constant diameter sabot (i.e., no flare). The firing pressure for all was 41.4 MPa (6000 psi) and the mass was 1.46 g, except for the last geometry, which was 1.56 g. To magnify the small velocity differences, the velocity axis does not start at zero.

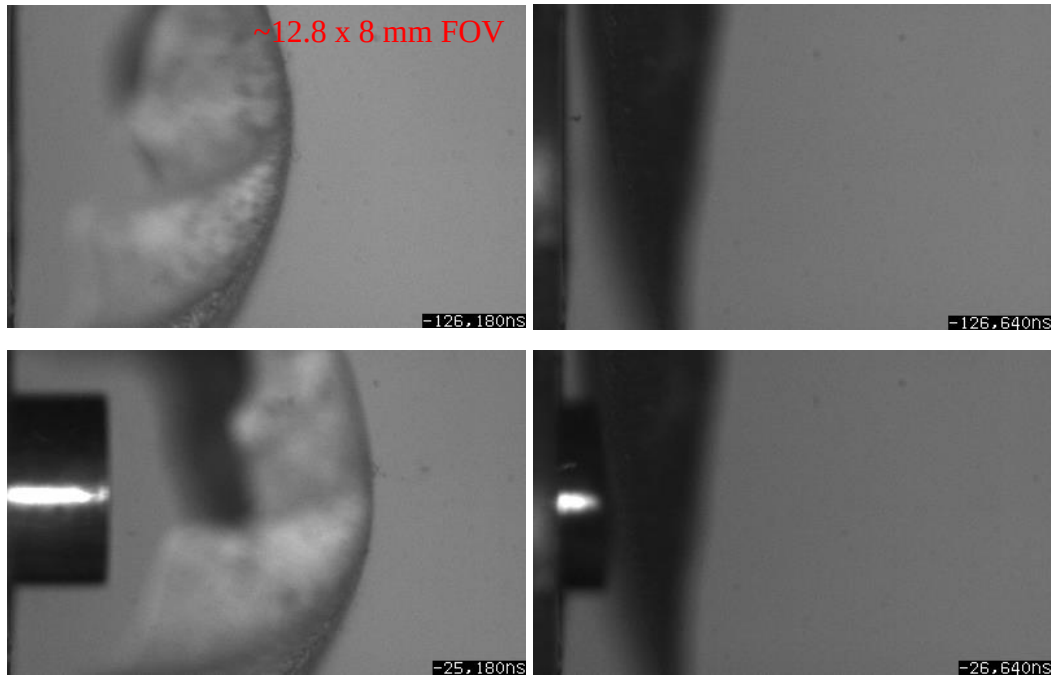


Fig. 9 Paper towels hanging in front of the muzzle as a qualitative method to assess gas blow-by in front of the sabot/projectile at the maximum breech pressure of 41.4 MPa (6000 psi). Left column: slight blow-by, where the paper towel moves a couple millimeters in approximately 100 μ s. Right column: no evidence of blow-by. The projectile velocity for both columns is about 1200 m/s and the FOV for all images is approximately 12.8×8 mm.

Finally, Fig. 10 is a plot of all the shots as a function of pressure/mass, where all the data collapses down into a single curve for this nominal 6.35-mm bore size. Thus, if one knows the mass of the projectile to shot and the desired velocity, the required firing pressure can be accurately determined if the barrel size is the same. This saves significant time because it minimizes the time of doing practice shots. All the shots in Fig. 10 are freely sliding, except for the flared PC and press-fit Delrin sabots with a steel projectile. This is good evidence that using press-fit and flared sabots does not reduce the performance. It is expected that each barrel size would have its own curve that needs to be determined. For the entire suite of shots, only a few conditions have been shot multiple times. Those conditions that have been shot at least three times have a standard deviation in the velocity of about $\pm 0.71\%$, which is very good.

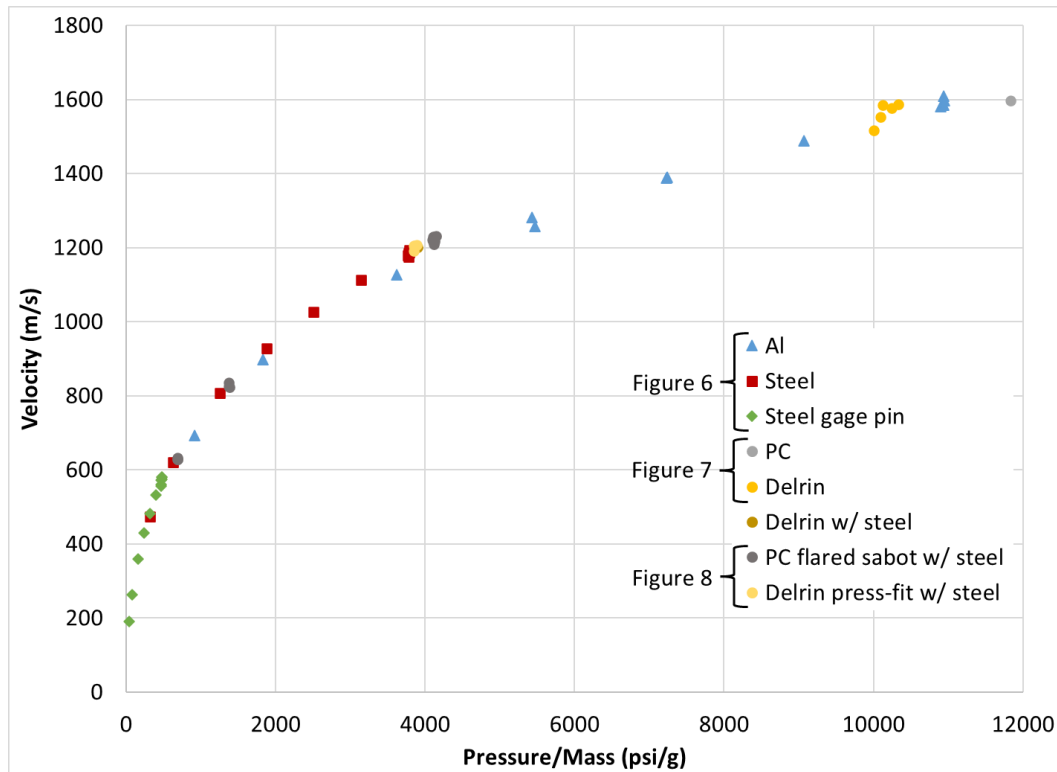


Fig. 10 Velocity of the gun as a function pressure/mass for all the shots conducted. All the projectiles are freely sliding, except for the PC flared and Delrin press-fit sabots. Shots presented in previous figures are referenced.

4. Potential Experiments

There are several potential experiments where the fracture gun could provide a wealth of quantitative data from the use of high-speed cameras (including 2-D/3-D DIC) and Photon Doppler Velocimetry (PDV) that the lab already possesses. This section describes a few such experiments for both brittle and ductile materials and the data that could be measured and quantified.

For brittle materials, generally individual cracks at relatively low velocities, or completely damaged regions or fronts due to relatively high-velocity impact, can be tracked with high-speed cameras. These types of experiments have been performed for decades (Figs. 11a and b), but the data was mostly qualitative. Using advanced imaging analysis techniques allows significantly more data to be extracted and quantified, such as the area of damaged versus undamaged material (Fig. 11a) or crack versus not a crack on the surface of a sample (Fig. 11b). The latest high-speed cameras can image at over 1 million fps with over 100 images, which allows for measurements as a function of time. The extent of damage, damage-front velocities, wave-front velocities, crack lengths, crack branching, angle of cracks, crack velocities, and so on, can be determined in time and

quantitatively compared to simulations of the experiment. Historically, this has not been done. These experiments are not necessarily the most amenable to DIC measurements because the damage may render the speckle useless, with potential debonding of the speckle pattern, or the pattern may obscure the very narrow cracks that would not be resolved from DIC. However, under certain circumstances the fracture properties, such as Mode I and II stress intensity factors, can be measured during a well-controlled experiment (Fig. 11c) using a modification of typical DIC called digital gradient sensing.⁷ This can be used to parameterize material fracture models, where the aforementioned impact experiments could be performed and compared to simulations. Digital gradient sensing is a powerful technique for measuring the crack propagation and fracture properties of transparent and opaque materials under certain simplified loading conditions and where less than a few cracks are present in the FOV.

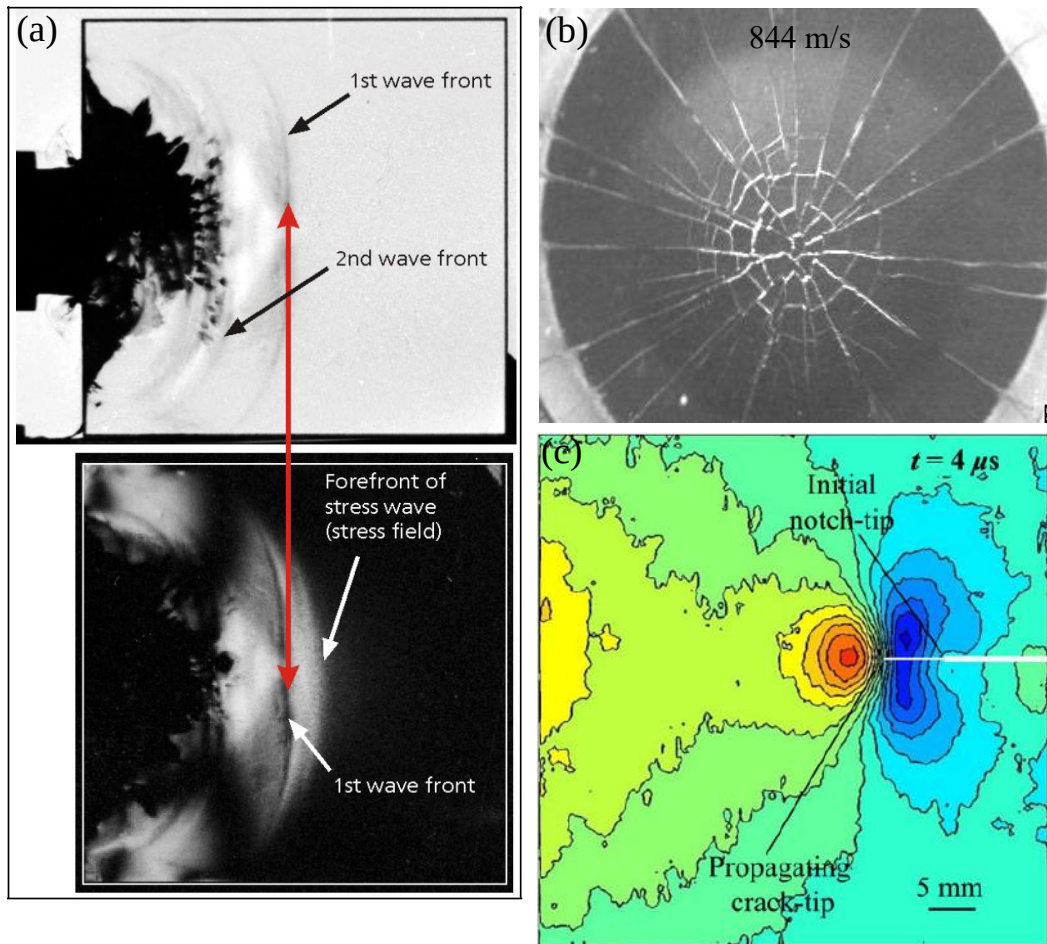


Fig. 11 (a) Edge on impact at ~ 400 m/s of soda-lime glass using backlighting (top) and crossed polarizers (bottom) $8.7 \mu\text{s}$ after impact,⁸ (b) backface cracking of a ceramic tile at 844 m/s (image courtesy P Jannotti, DEVCOM ARL), and (c) angular deflection contour plot using digital gradient sensing of a soda-lime glass under Mode I crack propagation subjected to dynamic edge loading⁷

Finally, all these experiments could easily use PDV velocity measurements at one or more points on the sample surface. The velocity data is compared to simulations of the experiment as a direct comparison where deviations and error associated with the material and fracture models can be assessed. A significant advantage of this gun is the ability to precisely control the projectile–target alignment, which will reduce significant data scatter that may be present in historical data sets using traditional guns where projectile pitch and yaw cannot be controlled. Additionally, studies where the angle between the impact surface and projectile is purposefully varied to understand the effect on performance can be easily performed with this gun, which has received significantly less study.

In many ways, the fracture gun is most suitable for the impact testing of ductile materials because their ductility allows for a wide range of DIC configurations for which to measure strains, strain rates, and so on. The classic Taylor anvil impact experiment¹ immediately comes to mind, but the symmetric Taylor impact experiment removes most of the downsides of the classic experiment and is straightforward to do with this gun. The author has made initial attempts at performing this experiment with the gun using 3-D DIC.⁹ Another use of 3-D DIC is to measure the backface deformation of a metal plate subjected to projectile impact and penetration. This has been done before,¹⁰ but it is not widely used; however, the author believes this data can be more routinely measured and compared to simulations. Using this data to parameterize and/or validate constitutive and damage models used in the simulations could significantly improve prediction capabilities because the experimental data are obtained under ballistic conditions, so there would potentially be less extrapolation of the parameters from the nonballistic conditions for which they are often fit from.

Another potential type of experiment is one that induces adiabatic shear localization, which commonly is observed in ballistic scenarios. Two variants are shown in Fig. 12. In the first experiment, Fig. 12a, a “pill” is driven by an impactor into a target disk that is backed by a ring. A shear-dominated stress state is generated in the target in a narrow region indicated by green dotted lines. The total amount of deformation is controlled by using a washer of precise thickness, which only allows a desired amount of deformation. Over multiple experiments with different washer thicknesses, the evolution of the shear localization can be determined via microstructural analyses techniques. In-situ velocimetry measurements (PDV) can be made on both the free surface of the backup ring and at the middle of the target free surface (red lines in Fig. 12a) to give the deformation of the target as a function of time. The PDV data can be compared to simulations of the experiments for validation of a constitutive model. Schematically the stepped projectile impact looks very similar to a top-hat geometry that has been used with

Kolsky bars to study adiabatic shear localization for decades (Fig. 12b). The main difference is the top-hat geometry is a single piece that combines the pill, target, and backup washer; however, the top-hat can be directly impacted in a similar manner with similar PDV measurements to measure the deformation. The author speculates that directly impacting the top-hat geometry might produce a stress state that is closer to that found in plugging failure of armor—the formation of an adiabatic shear band. But the stepped projectile impact experiment could better inform ballistic failure by a combination of shear localization and dishing, where the latter is a delamination of the armor near the backface along a plane parallel to the impact face, which is generated by bending of the armor plate generating tensile stresses near the backface. The speculation is the stepped projectile geometry will develop more bending stresses than the top-hat geometry as the sample deforms under impact.

Another promising impact experiment on ductile materials is to investigate the dynamic failure of pre-notched plates (either single- or double-notched) under shear (Mode II) loading conditions, as shown in Fig. 12c. Shear loads are generated at the notch tip and multiple materials have a transition in the failure mechanism at a critical impact velocity. At projectile velocities below the critical velocity, a tensile crack propagates at an angle with respect to the notch direction, but above the critical velocity a shear band propagates straight back in the same direction as the notch. There is potentially some discrepancy as to the exact nature of the crack propagation below the critical velocity, even for the same material,¹¹ and not every material shows the transition; that is, only a shear band propagates at all velocities^{12,13} (however, the critical velocity is influenced by the notch tip radius¹³). This experiment can take advantage of time-resolved DIC to measure the full-field strains under the different failure mechanisms. Impacted samples can be recovered, and the crack or shear band can be probed using microscopy to inform on the underlying deformation mechanisms active in each failure regime. The full-field strain data can be quantitatively compared to simulations of the experiments, which would be a challenging exercise for constitutive and damage models to accurately predict. Additionally, PDV velocimetry data from both sides of the shear band could give valuable experimental data that can be compared to simulations.

The experiments mentioned in this report may not be the best experiments for this gun, so the author welcomes discussion on the best projectile–target configurations and measurement probes that will best interrogate fundamental dynamic fracture and failure phenomena under ballistic loading events.

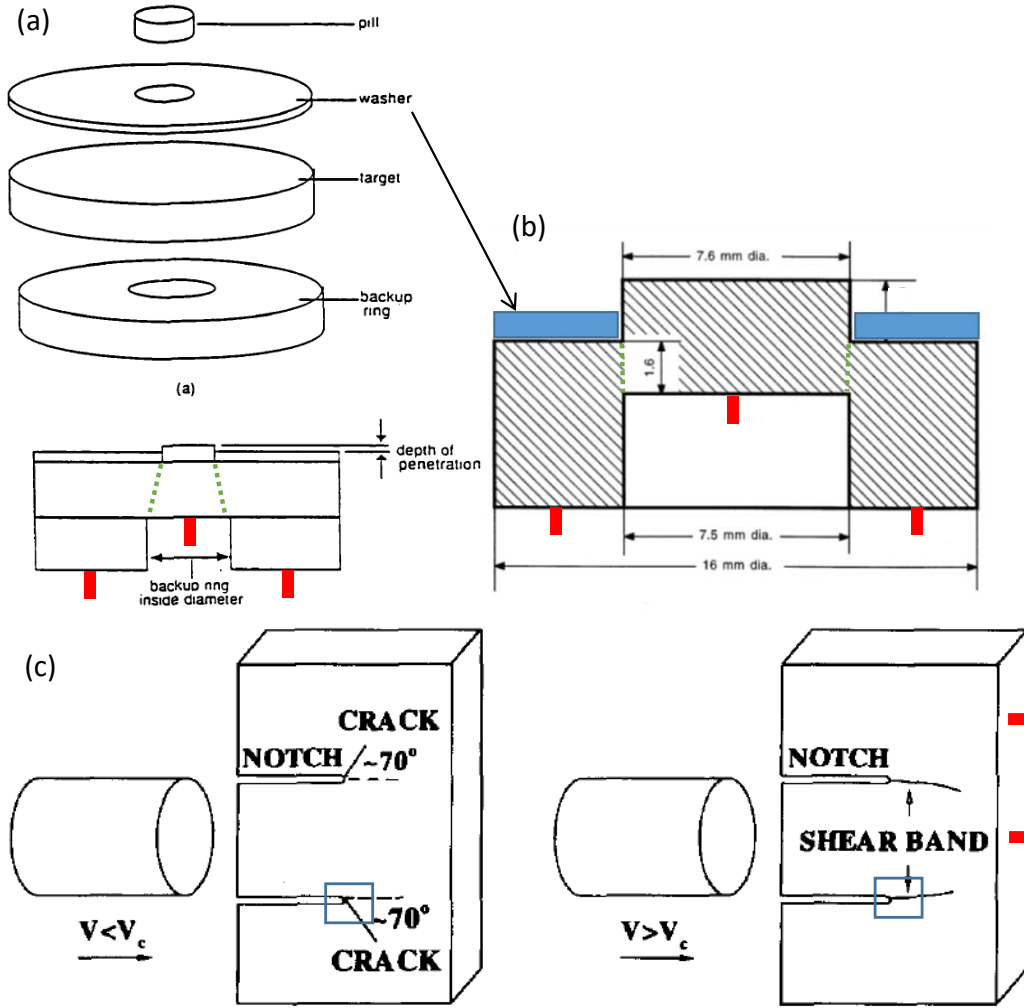


Fig. 12 (a) Stepped projectile impact experiment¹⁴ and (b) top-hat specimen,¹⁵ which can be directly impacted. The impact direction is vertical in both images, and the green dotted lines show the region of shear localization. (c) Edge on impact of a pre-notched plate where there is a transition between a tensile crack and shear band propagation at a critical impact velocity.¹¹ The blue boxes represent the FOV for time-resolved DIC measurements. In all images, red lines represent surface velocity measurements via PDV.

5. Conclusion and Future Work

The fracture gun is fully operational, and all the basic “functional” aspects required for actual experiments (target holding and alignment, velocity measurement, sabot design, performance, and triggering, especially regarding triggering of lighting) are figured out. Quantifying 2-D distortion errors due to a window with one side under vacuum is ongoing; 3-D errors with 3-D DIC also must be analyzed. The maximum velocity with the 6.35-mm bore size is about 1600 m/s using a low mass, but still realistic, projectile. The first experiments will consist of edge-on-impact experiments of ceramics to measure fracture morphology and of metals to probe

cracking versus shear band localization. We believe this gun will provide significant advancements in quantifying deformation and fracture mechanisms under ballistic loading.

Barrels up to 25.4 mm exist but the performance has yet to be measured. This is a work in progress. The barrels directly relate to the first performance upgrade. The current barrels are 2440 mm long, but the gun platform can accommodate lengths up to 3660 mm, which is the best “bang-for-the-buck” upgrade. A theoretical velocity calculation shows a 33% increase in velocity under one configuration.

In terms of instrumentation, we have a four-channel PDV system but the maximum oscilloscope bandwidth in the lab is 2.5 GHz, which limits the maximum velocity that can be measured and is less than the capability of the gun. This would add a lot of data synchronized in time with the high-speed images. A more thrilling velocimetry investment would be a line-VISAR system that would allow heterogeneous velocity measurements across a heterogeneous deforming/fracturing surface. These types of velocity profiles have never been made before in a ballistic environment (as far as the author is aware). Currently, the laboratory has two Shimadzu HPV-X2 cameras that can go to 5 million fps at full resolution. To capture fracturing ceramics at the tens to hundreds of nanoseconds, a gated intensified high-speed camera with a framing rate up to 400 million fps and megapixel resolution would be a worthwhile investment. Additionally, with the current setup we have an idea for an “insert” window that places the window inside the target tank, closer to the shot axis. This would allow the camera lens to be even closer to the target. A high-zoom lens we have for the cameras has an FOV down to a couple millimeters but has a working distance of only 90 mm. That is very close when the shot has a 41.4-MPa firing pressure and a 1600-m/s projectile velocity and proving that a very expensive camera will not be damaged or destroyed will be challenging. Another instrumentation add-on could be flash X-rays. Since the target tank has four windows, the horizontal windows can be used with high-speed cameras and the vertical ones could have flash X-ray heads. With DEVCOM Army Research Laboratory’s plethora of flash X-ray units, this can be done without a large investment. A more expensive flash X-ray investment, but one that would greatly increase the types of experiments that could be performed, would be a “multi-anode flash X-ray tube,” which closely spaces several X-ray sources into a single housing so that parallax is eliminated. Current multihead flash X-ray systems require that the sources be placed at different angular orientations (parallax), which is a huge disadvantage when fracture and failure processes are usually nonuniform and this limits extracting quantitative information. Currently, the aforementioned investments are theoretical since no funding has been sought.

6. References

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List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
Al	aluminum
ARL	Army Research Laboratory
DDG	digital delay generator
DEVCOM	US Army Combat Capabilities Development Command
DIC	digital image correlation
DOM	drawn over mandrel
FOV	field of view
fps	frames per second
PC	polycarbonate
PDV	Photon Doppler Velocimetry
VISAR	Velocity Interferometer System for Any Reflector

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D KRAYTERMAN
J MCDONALD
P MCKEE
K RAFAELS
S SATAPATHY
L SHANNAHAN
M TEGTMEYER
T WEERASOORIYA
T ZHANG

FCDD RLW TB
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M COPPINGER
J NESTA
S TURNAGE
C WILLIAMS
W UHLIG
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FCDD RLW TD
A BARD
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R DONEY
R GUPTA
S HALSEY
M KEELE
D KLEPONIS
B KRZEWSKI
K MASSER
F MURPHY
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G WATT

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N GNIAZDOWSKI
B HOMAN
S KUKUCK
C PECORA

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R FRANCA
J HOGGE
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P PATEL
W SHOULDERS
J SWAB
L VARGAS-GONZALEZ

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B BARNETT
B BUTLER
T CAIN
K DARLING
K DOHERTY
D FIELD
A GIRI
C HAINES
B HORNBUCKLE
K LIMMER
H MURDOCH
M WALOCK

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J COLBURN
S HOWARD

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A RAWLETT
S KARNA
J NEWILL

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