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Miniature Gun for Subscale Ballistics

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14. ABSTRACT
Full-scale and microscale ballistics experiments are used extensively to probe material behavior in conditions relevant to Army applications. However, full-scale experiments are expensive and slow, while microscale experiments have questions of scaling effects. Miniature ballistics experiments fill the gap, allowing fast experiments on small, but still mesoscale, samples. Several miniature ballistics experiments are described using a novel miniature gun system. High throughput is demonstrated, with 60 experiments completed in two afternoon laboratory sessions. Multiple applications for cold spray metals, protection polymers, and soft armor concepts are shown, demonstrating the usefulness of miniature ballistics.

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1. Introduction

Ballistics experiments serve a range of purposes in material discovery and evaluation, ranging from comparatively simple measurements of performance, such as V_{50} and residual velocity after penetration, to more complex investigations of deformation and failure mechanisms under impact loading. These experiments also cover a large range of size scales from evaluations of samples measured in meters to microscale laser-induced particle impact test (LIPIT) experiments. Between full-scale laboratory experiments and the microscale, however, a space exists in which the low material requirements and high throughput of microscale testing can be combined with the accuracy of full-scale experiments (Figure 1). This space may be filled by a "miniature ballistic" high-velocity gas gun in the range of 100 µm to 3 mm.

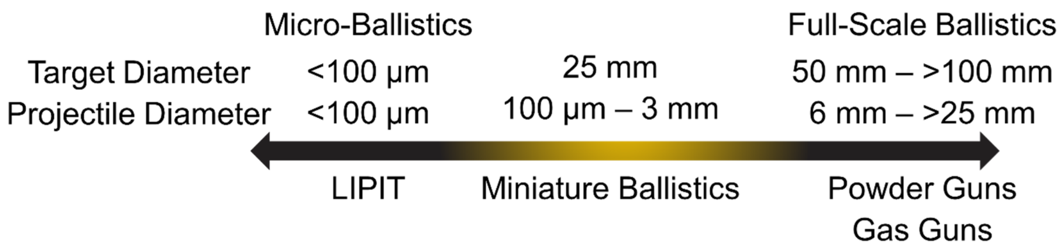

Figure 1. Relevant ballistic size scales.

Full-scale ballistic experiments typically seek to match real battlefield conditions, using gas or powder guns to fire actual threats or projectiles of similar sizes and simplified shapes. These projectiles start approximately at 6 mm (0.25 inch) and increase size to match or mirror actual threats. Size-matched targets have a diameter (or edge length, if square) of 50 mm (2 inches) and increase in size with growing projectiles. As a rule of thumb, targets are sized eight times or greater than projectile diameter to avoid the influence of edge effects on ballistic performance. These experiments are often used to collect V_{50}'s or other performance metrics to evaluate new armor materials, requiring many shots for each tested material. The significant material and time requirements involved in these test programs have driven interest in smaller, faster test methods, provided that smaller-scale experiments (typically in the microscale range) are representative of full-scale behavior.

Microscale ballistics experiments fall in the range of 100 µm or less for both projectile and target. The most common type of microscale ballistics experiment is LIPIT, in which a laser is used to excite an ablation film behind a microscale particle, accelerating the particle into a thin film target or semi-infinite block of material (Brown et al. 2012; Gangineri Padmanaban et al. 2022; Mallick et al.

2022). These experiments can reach loading rates greater than 10^8 s^{-1}, making them very useful for probing material behavior under extreme conditions (Pharr et al. 2010; Lee et al. 2012). Other microscale ballistics experiments have been carried out by using a larger scale gas gun to fire a shotgun-style blast of smaller particles, then studying the impacts that happen to land in the diagnostic area (Rogers et al. 2023, 2025).

The small projectile and target sizes make microballistics experiments attractive for the evaluation of novel protection materials, as they combine high rates of loading with low required sample sizes. Availability of novel materials in bulk scale for ballistic experimentation is a consistent stumbling block in the ceramic and metal development process. Bulk-scale brittle ceramics are typically produced using a hot press, where feedstock powder is shaped into a densified puck under heat and pressure. Metals require similarly involved processes, requiring forging, rolling, and additive manufacturing and sintering if made from powder feedstock. For brittle ceramics, the most common press sizes available to most laboratories are 1- or 1.5-inch diameter. Larger sample sizes are a significant time investment even when the equipment is available; heating and cooling times for larger presses can result in a single sample taking several days to produce.

This time issue is avoided by the much smaller size scales involved in LIPIT and related microballistics techniques. Smaller presses have lower thermal mass, thus speeding heating and cooling times and allowing creation of samples in a day or less. Additionally, several other techniques exist that can produce a small amount of novel materials quickly. Additive manufacturing is a rapidly growing field. Vapor deposition techniques can build materials with fine control of composition and microstructure, but small layer thicknesses struggle to stack up into large samples. High-throughput programs in the research community have pioneered methods of creating many high-entropy alloys and other novel metals in small quantities. All these techniques struggle to create fully dense, compositionally consistent samples on the scale necessary for full-scale ballistics.

However, recent literature has indicated that LIPIT results may suffer from size scaling effects that complicate evaluations of ballistic performance. Rogers et al. (2025) compared LIPIT experiments with full-scale ballistics results on polycarbonate and found a microscale ballistic limit of three times the full-scale performance. More work is needed to clarify how consistent this size effect is and to what degree it applies to other materials such as metals and ceramics. Miniature ballistics experiments bridge the size scale between full-scale ballistics and LIPIT experiments, creating an opportunity to clarify the size effect and understand ballistic scaling.

Miniature ballistics are also useful for direct material characterization under ballistic impact. A typical size scale for a miniature ballistics target is 1 to 1.5 inches, consistent with laboratory-scale manufacturing processes. This allows characterization of novel materials much earlier in the development cycle with less time and effort invested by both the characterization and the material science development teams. Earlier, easier characterization also results in more characterization. Many novel materials do not reach the point in a development cycle where production is feasible in quantities suitable for full-scale characterization. Evaluating these materials earlier in development with smaller quantities allows understanding of ballistic response and mechanisms that will contribute to future development in a tighter, more agile development cycle.

Previous miniature ballistics work used an electrothermal gun system developed by Uhlig et al. (2019, 2020), Bartkowski et al. (2019), Berning et al. (2020), and Wilmer et al. (2022). This system stored a charge of up to 20,000 V in a capacitor bank. During firing, this charge is released across the tip of a sharpened electrode behind the projectile, vaporizing the electrode and propelling the projectile using the resulting plasma cloud. This method had several advantages: 1) the ability to adjust the stored charge gave fine velocity control comparable with gas guns, 2) the system could fire a variety of projectile sizes and shapes so long as the projectile was conductive or backed by conductive foil, and 3) velocities of up to 2500 m/s could be reached using a light aluminum hemispherical projectile. The system did have two disadvantages compared with a gas gun of similar scale, as presented in this work: on a per-shot basis, firing was both slower and more expensive, i.e., requiring significant time from a team of scientists to operate as well as individual one-use barrel assemblies to contain the projectile and electrode.

Miniature ballistics gas gun systems have other advantages over full-scale ballistics: because of the smaller size scales and lighter projectiles, miniature ballistics systems are typically easier and faster to operate than larger gas gun systems while retaining the advanced diagnostic options not typically present in powder gun ranges. This can allow for characterizing many samples in a single test program in days (rather than weeks or months), gathering data for modern high-throughput material development programs.

2. Methods, Assumptions, and Procedures

The miniature gas gun used in this study is based on a 0.15-L breech capable of firing pressures up to 5000 psi. A ball valve actuated by compressed air is used to dump the helium in the breech to the barrel. A thin plastic dowel is inserted into a fixture attached to the valve during actuation, preventing the valve from opening until the dowel breaks, which results in a faster opening compared with actuating the valve alone (Figure 2).

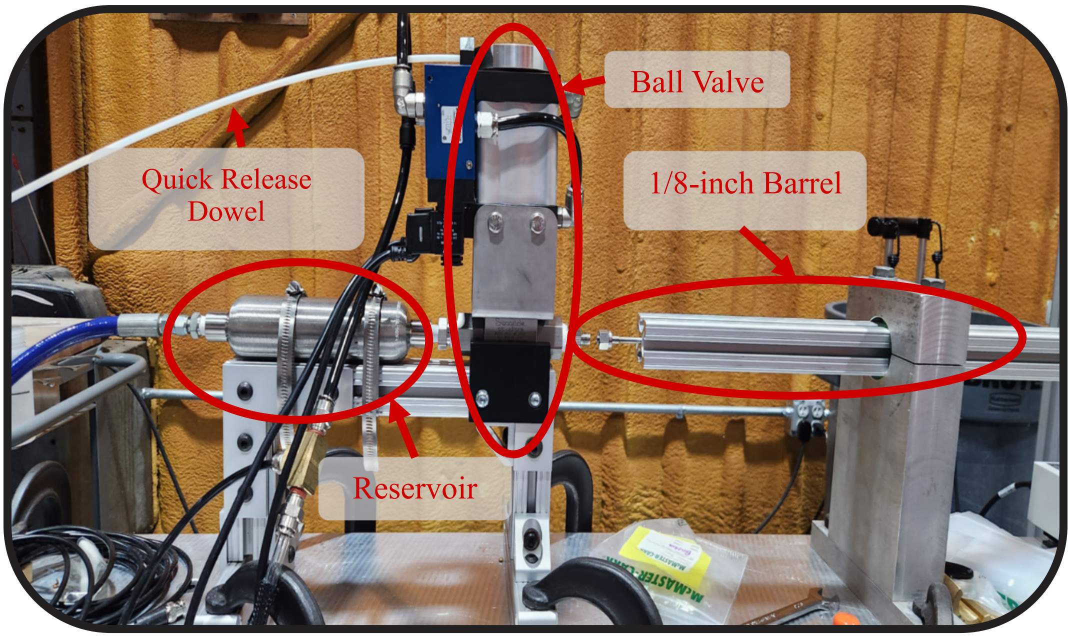

Figure 2. Breech and valve assembly for the gun used in this report.

Two types of barrels are used with this breech. One system uses a heavy steel breech interlock developed for larger gas guns. The advantage to this system is that it uses the same size connections as those of a larger gas gun in the same laboratory, expanding the range of barrels usable with this gun up to internal diameters of 1 inch, which ranges into full-scale ballistics. In the miniature ballistics size range, 1/4-inch and 7-mm barrels are compatible with this system. While the interoperability of this system is useful, a heavy steel breech connection is not necessary for the small-diameter barrels at pressures of 5000 psi or less that are of interest in this report. Smaller barrels, such as the 1/8-inch barrel in Figures 2 and 3, use a simpler screw-on Swagelok connection. The small barrels are made of off-the-shelf hypodermic needle tubing. Commercial tubing is available for inner diameters as small as 0.002 inches or 0.051 mm, and custom tubing diameters are available for significantly lower prices than typical barrel manufacturing for full-scale gas guns, allowing for cheap expansion of capabilities. As these tubing sections are thin, they are supported in a section of 80–20 to maintain alignment and protect against damage in use. A piece of adapter tubing is welded to the end of the hypodermic tubing to provide an interface for standard 1/4-inch swaged connections. This results in a robust, cheap method to manufacture barrels smaller than typically used in ballistics applications where traditional tooling is not available.

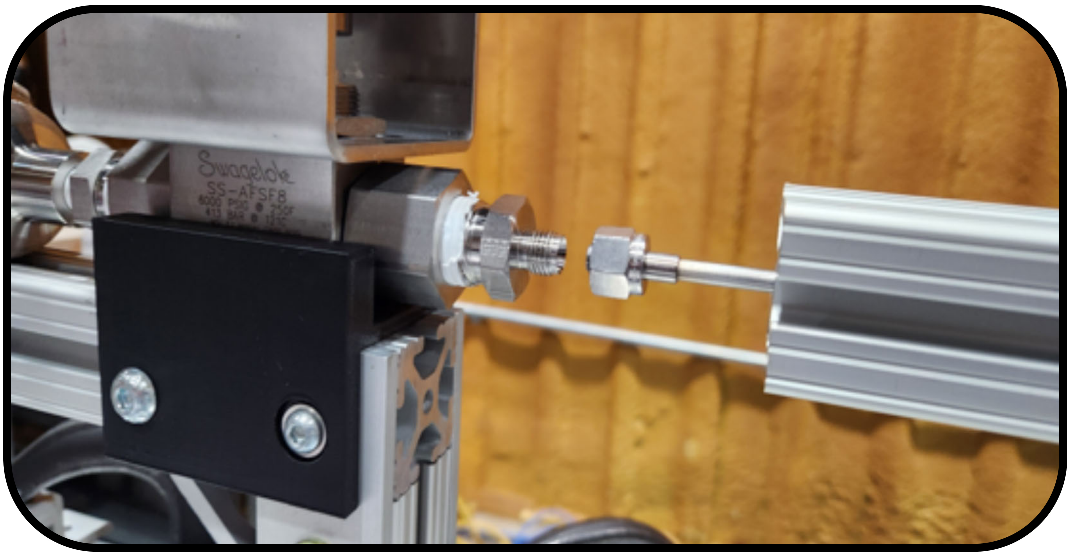

Figure 3. Swagelok breech connection and 1/8-inch barrel.

Compared with full-scale gas guns, the miniature gas gun's small gas volumes reduced the quantity of gas that ultimately discharged from the barrel during a shot, and smaller projectiles result in less energy during impact. This allows the use of a polycarbonate enclosure at the impact site rather than a larger steel catch tank, such that high-speed cameras can be positioned easily at any point around the target with full visibility of it. High-speed photography is used from multiple angles in this study to capture impact from both side and front views. Images captured confirm that the projectile does not pitch from a side view and are used to measure the back-face deformation profile of high-density polyethylene (HDPE) panels. Projectile velocity is captured for each shot using a laser velocimeter consisting of an 8-mW laser split into two photogates and recorded via an oscilloscope. This system is also used to trigger the high-speed camera and may be used to trigger any other diagnostics as needed for an experiment.

3. Results and Discussion

At the time of writing, 170 shots have been completed. All but eight of those experiments were carried out using the 1/8-inch barrel. One series of shots was done on candidate cold spray materials, which were fired as right circular cylindrical samples into a steel anvil and evaluated for further development dependent on behavior during impact as captured by high-speed photography. Larger-scale impacts have been used in prior works studying the critical velocity of bonding for materials in cold spray (Schmidt et al. 2006). Although much larger than micrometer-scale projectiles, millimeter-scale impacts still exhibit characteristics important to cold spray, such as interfacial jetting and evidence of adiabatic shear instability (Schmidt et al. 2006). Brittle failure indicates that the material is not suitable for cold spray use, while ductile behavior suggests that the material will stick during the cold spray process. Figure 4 shows examples of these shots, in which Figure 4A shows plastic deformation representing a successful material screened for further investigation for cold spray, while the remaining Figures 4B through 4D demonstrate increasingly brittle failures. Over the course of two afternoons of testing, 63 shots were completed, reaching a rate of fire comparable with other high-throughput techniques. The full dataset, as well as material science portion of the cold spray investigation, will be published as a separate report.

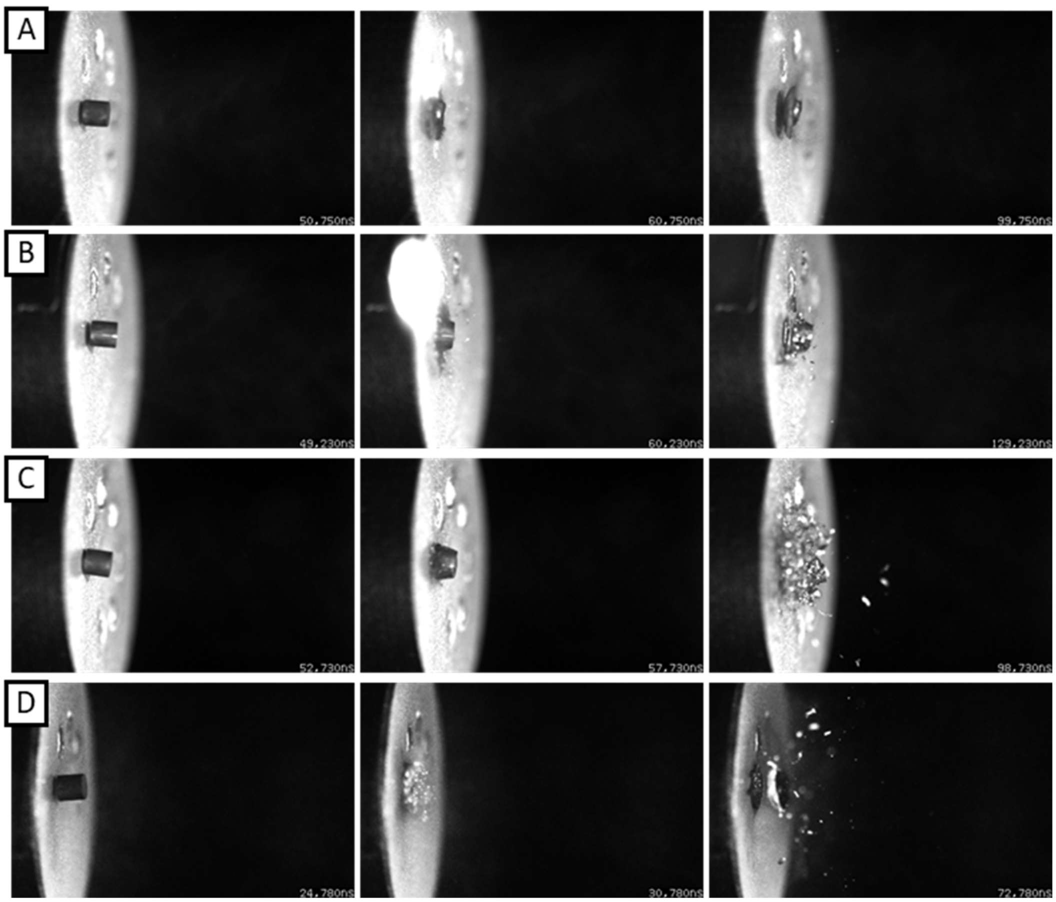

Figure 4. Example cold spray evaluation shots. Row A demonstrates a plastic deformation, suggesting that specific composition will perform well as a cold spray material. Rows B–D show increasingly brittle and destructive failure.

Figure 5 shows projectile velocity at a given firing pressure normalized by projectile mass for the remaining shots. The majority of the experiments shown were conducted using steel dowel pins with diameters of 1/8-inch and lengths of 1/8-inch (L/D = 1) and 3/16-inch (L/D > 1). These pins are commercially available right circular cylinders with a small bevel on one edge, which was always used as the target-facing end during experiments.

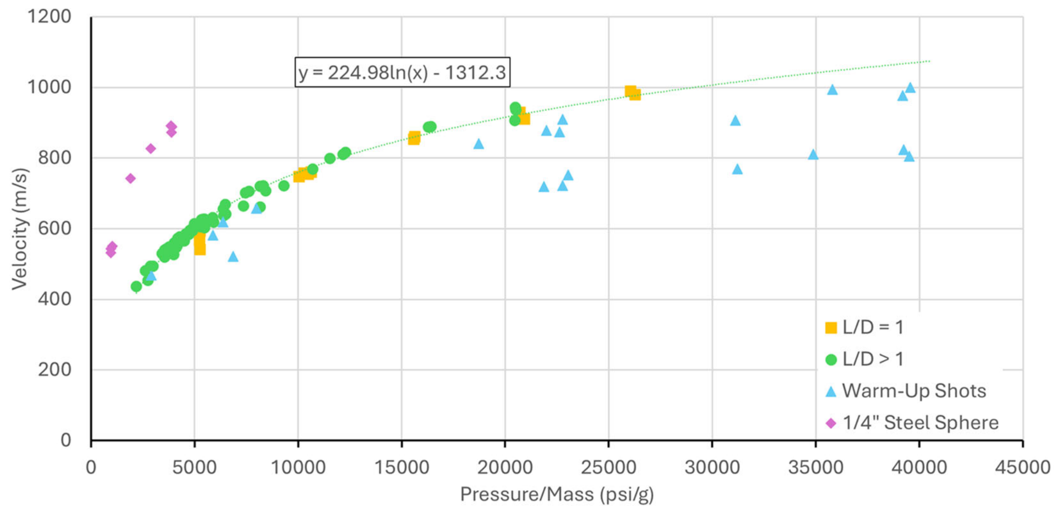

Figure 5. **Velocity vs. firing pressure normalized by projectile mass for the minigun system.**

During the first several experiments on the gun system, it was observed that the first two shots fired each day would underperform. Subsequently, these shots were done with 1/8-inch-diameter steel spheres into a steel plate. These are shown separately in Figure 5 as “warm-up shots.” Two distinct clusters can be observed relative to the trend line of the full experiments: one slightly below the trend line or other experiments at a given pressure/mass, and one significantly below, demonstrating how performance increases from shot to shot. This behavior was only seen with the 1/8-inch barrel and not present for the 1/4-inch barrel experiments. This indicates that the issue does not lie with the ball-valve system. It is unclear how much time is required for the gun to cool down and again warm-up before coming to full performance. Shots performed before and after a lunch break showed loss of performance, but not as much as an overnight pause. The exact cause of the warm-up behavior is still uncertain but is mitigated with warm-up shots. Since firing can be performed in a matter of minutes, it does not currently impede operations. However, as the issue is believed to be related to gas flow dynamics, it is likely to increase in effect at smaller scales. Additional work is needed to determine the magnitude of the scaling effect and if the performance decrease can be prevented.

The eight shots conducted on the 1/4-inch-diameter barrel are also shown in Figure 5. They reach velocities comparable with the 1/8-inch-diameter shots at significantly lower pressure/mass, or—phrased differently—the 1/4-inch barrel can reach similar velocities at similar pressures to the 1/8-inch barrel, despite firing projectiles with a mass approximately four times greater than the 1/8-inch dowel pins. The 1/4-inch barrel is therefore much more efficient. This loss of performance is a result of gas dynamics as the barrel diameter scales down and is inherent to light gas guns. It is one of the reasons using gas guns with miniature ballistics has not been pursued before. The decreased gas flow down the smaller barrel cross section, as well as the increased boundary layer thickness compared with the size of the gas plume, reduces the projectile velocity. It is unclear how this performance drop will scale with smaller-diameter barrels, as smaller projectile masses partially offset the drop. As barrels made from stainless steel tubing are very cheap to manufacture compared with full-scale barrels, the authors hope to address this question in future work. However, the velocities obtained for both the 1/4-inch and 1/8-inch barrels demonstrate that while there may be a performance drop, the obtained velocities are fast enough for useful data to be collected.

As the main use case of the miniature gun is for subscale ballistic experiments, it is important to verify that there are no pitch or yaw effects prior to impact. Pitch and yaw are not typical issues for gas guns in the same way they are for powder guns because there is no combustion by-product or soot expelled during firing. Thus, the target may be placed very close to the barrel with only a few inches of separation or less. In the case of plate impact experiments, it is typical for the projectile to not fully exit the barrel prior to impact. This is true of the minigun as well. In all the experiments discussed in this report, the target was approximately 3 inches from the barrel, with only enough room left to fit the two beams of the laser velocimetry system. However, high-speed video was taken prior to impact on the target for several experiments to verify there was no pitch and yaw. A typical sequence from these experiments is shown in Figure 6. The video was taken at 100,000 fps using a steel dowel pin with L/D greater than 1 as the projectile. A cylindrical projectile was chosen, as pitch and yaw are not a problem when firing spheres. LED backlights were used to illuminate the video through a diffuser plate.

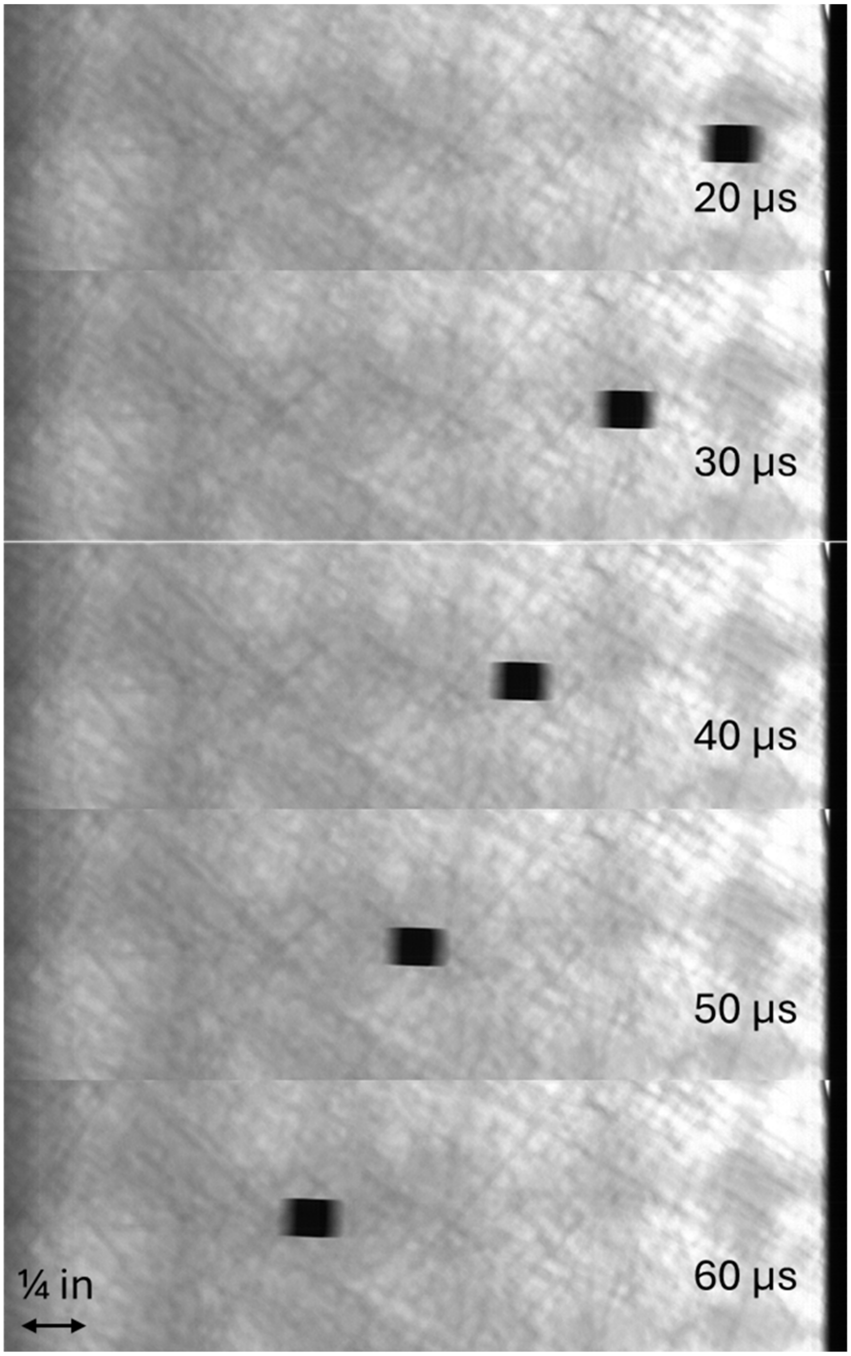

Figure 6. High-speed video of a 1/8- × 3/16-inch steel dowel pin projectile prior to impact, verifying there is no change in orientation and no pitch. As there is no significant pitch observed, it is also likely there is no yaw in the short distance prior to impact.

Computer vision techniques were used to measure pitch angle relative to the projectile trajectory. A reference background image was subtracted from each test image and the projectile detected using a threshold. With the projectile location and shape known, shape fitting tools were used to measure the centroid and projectile angle relative to the camera x-axis. The trajectory angle was calculated from the projectile centroid frame to frame, giving the trajectory in each frame relative to the camera x-axis. Subtracting the trajectory from the pitch gave the final measurement of pitch relative to trajectory (Figure 7). Motion blur and resolution, in this case both limited by the performance of the high-speed camera, complicate projectile detection and increase error in the final measurement. However, the measured pitch angle was still approximately –2°, which is within the useable tolerance for most gas gun experiments. This analysis is only intended to provide a rough estimate of pitch and operates under the assumption that pitch and yaw behavior will be similar for a radially symmetric projectile. If higher accuracy is needed for future experiments, a pair of orthogonal cameras with better resolution and lower exposure time can be put in place with a smaller field of view to better capture the projectile.

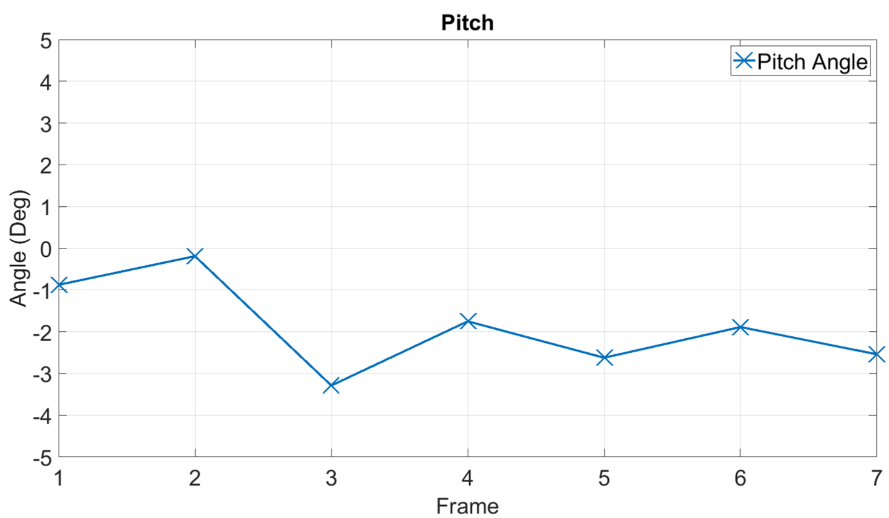

Figure 7. Computer vision techniques are used to measure pitch angle relative to projectile trajectory. The measured pitch angle is approximately –2°, which is in tolerance for most gas gun experiments.

Similar high-speed videography techniques were used to capture the 2D side view back-face deformation profile of 1/2- × 6- × 6-inch HDPE panels when impacted by a 1/4-inch steel sphere at nominal velocities of 890 m/s. The goal of this type of experiment is to validate material modeling of HDPE by comparison with the high-speed video and connect the results to postmortem examination of damage and failure mechanisms present in the panels. The experiments described in this report were used to develop the technique and do not use novel HDPE formulations or include the modeling component. Figure 8 shows frames from the best video of the test series, in which diffuse backlighting, a frame rate of 50,000 fps, and a corresponding resolution of 672 × 456 gave the clearest view of the back-face deformation. Figure 8 shows every other frame for the portion of the video covered, so twice as much data is available to modeling efforts. Fiber pullout from the matrix material is also visible, demonstrating a key failure method. The projectile did not fully penetrate, and the frames shown cover the entirety of the development of the back-face profile. The back-face profile is initially pyramidal and changes in shape to a dome as the outer edges of the material deform, as well as recovering slightly from its furthest extent, demonstrating that a postmortem analysis of deformation would not capture the entire process and that in-situ high-speed video is necessary to capture the behavior of interest.

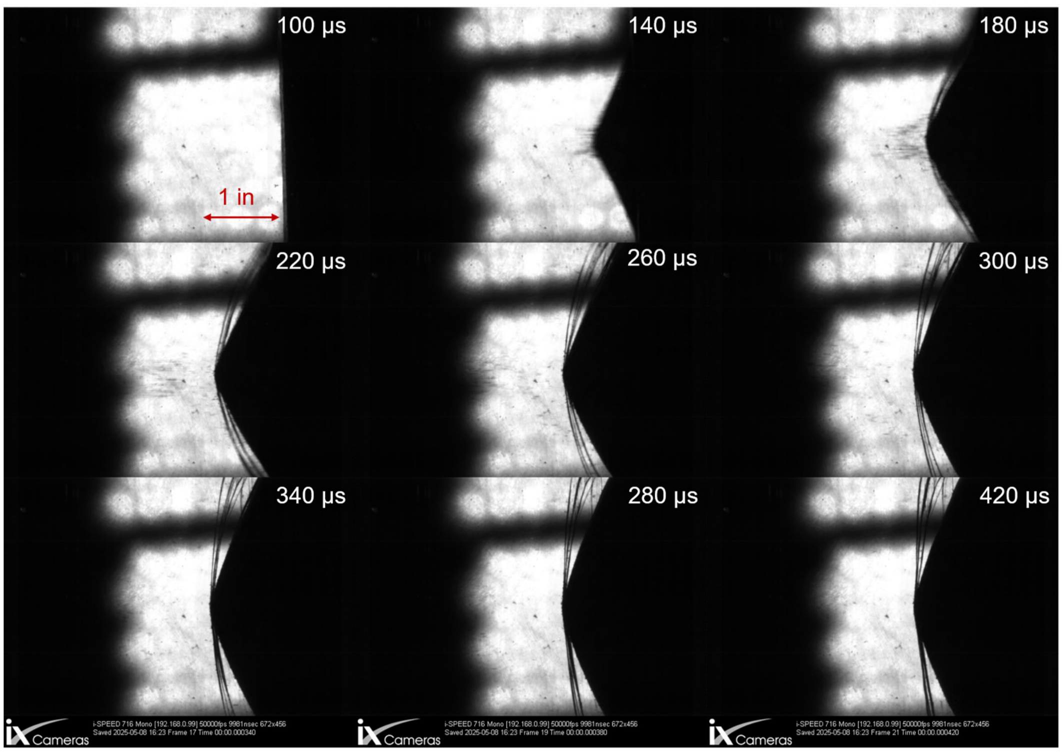

Figure 8. The back-face deformation profile of HDPE is shown for a 1/4-inch steel sphere with a striking velocity of 889 m/s.

4. Conclusions

Miniature ballistics work occupies an underserved niche between full-scale ballistics and microscale techniques like LIPIT. Historically, researchers have been wary of pursuing miniature ballistics due to a combination of concern over decreased performance in small-scale gas guns and perceived lack of benefit. This report demonstrates that miniature ballistics can be done cheaply and effectively.

Fabrication of barrels for miniature ballistics experiments can be done using off-the-shelf components at costs far under those of full-scale ballistics, greatly reducing the necessary investment to pursue experiments in this space. Despite the loss of efficiency with decreasing scale, projectile velocities are still high enough to provide useful ballistic impact information. Shots can be done quickly, reaching rates of testing of more than 60 shots in two afternoon testing periods—on par with high-throughput testing techniques and exceeding larger, more complex full-scale gas gun systems while still retaining the wide range of diagnostic methods available to laboratory gun systems. Miniature ballistics experiments will provide a method to shorten the development cycle from material fabrication to ballistic testing.

5. References

Bartkowski PT, Berning PR, Uhlig WC, Coppinger MJ. Electrical arc driven hypersonic projectiles. DEVCOM Army Research Laboratory (US); 2019 Apr. Report No.: ARL-TR-8683.

Berning PR, Bartkowski PT. A high voltage capacitor bank design with a built-in spark gap switch. DEVCOM Army Research Laboratory (US); 2020 July. Report No.: ARL-TR-8995.

Brown KE, Shaw WL, Zheng X, Dlott DD. Simplified laser-driven flyer plates for shock compression science. Rev Sci Instrum. 2012;83(10):103901.

Gangineri Padmanaban A et al. Molecular-weight-dependent interplay of brittle-to-ductile transition in high-strain-rate cold spray deposition of glassy polymers. ACS Omega. 2022;7(30):26465–16472.

Lee J-H et al. High strain rate deformation of layered nanocomposites. Nat Commun. 2012;3(1):1164.

Mallick DD, McKee PJ, Wetzel ED. Laser-driven impacts to characterize protection materials. Proceedings of the 2022 16th Hypervelocity Impact Symposium; 2022 Sep 18–22; Alexandria, VA. American Society of Mechanical Engineers; c2022.

Pharr GM, Herbert EG, Gao Y. The indentation size effect: a critical examination of experimental observations and mechanistic interpretations. Annu Rev Mater Res. 2010;40:271–292.

Rogers JA et al. Mechanics of hypervelocity simultaneously launched distributed particles. Int J Impact Eng. 2023;180:104671.

Rogers JA et al. Size matters: impact energy absorption across five decades of length scale. Int J Impact Eng. 2025:105478.

Schmidt T, Gärtner F, Assadi H, Kreye H. Development of a generalized parameter window for cold spray deposition. Acta Materialia. 2006;54(3):729–742.

Uhlig WC, Bartkowski PT, Berning PR, Coppinger MJ. Controlling chamber expansion in miniature electrothermal guns for increased velocity and efficiency. DEVCOM Army Research Laboratory (US); 2019 June. Report No.: ARL-TR-8722.

Uhlig WC, Coppinger MJ, Berning PR, Bartkowski PT. Overcoming erroneous erosion of electrically launched projectiles in ALEGRA simulations. DEVCOM Army Research Laboratory (US); 2020 Jan. Report No.: ARL-TR-8888.

Wilmer BL, Uhlig WC, Berning PR, Coppinger MJ. Optimizing performance of compact hypervelocity electrothermal guns: electrode composition and bore diameter. Proceedings of the 2022 16th Hypervelocity Impact Symposium; 2022 Sep 18–22; Alexandria, VA. American Society of Mechanical Engineers; c2022.

List of Symbols, Abbreviations, and Acronyms

2D	Two-Dimensional
HDPE	High-Density Polyethylene
L/D	Length/Diameter
LED	Light-Emitting Diode
LIPIT	Laser-Induced Particle Impact Test
V_{50}	Ballistic Limit Velocity at Which a Specific Projectile Has a 50% Probability of Penetrating a Material

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