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Measuring the Blast and Ballistic Performance of Armor

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CONTENTS

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EXECUTIVE SUMMARY

This report relates to the discovery and development by the authors of armor designs using certain elastomers applied as coatings to the front side of rigid substrates, to increase the ballistic and blast performance of armor. This has led to much activity intended to optimize and exploit the technology for various applications, both military and civilian. Since armor improvements of even a few percent are substantial, quantifying the performance of armor materials requires high accuracy. Herein we describe test methods and analyses useful in achieving measurements of sufficient quality. Since the optimal design of any armor, conventional or advanced, depends on the threat (i.e., the nature of the projectile and its mass and energy; single- versus multiple-hit defeat), we describe how performance attributes can be quantified and valid comparisons made between different armor designs.

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MEASURING THE BLAST AND BALLISTIC PERFORMANCE OF ARMOR

1. INTRODUCTION

Research is conducted at the U.S. Naval Research Laboratory (NRL) to improve the performance of armor intended for the military and for civilian infrastructure protection. Efforts to improve armor properties must address the fact that the two main attributes of armor — performance and weight — tend to work contrary to each other: Thicker, harder, denser materials generally have better stopping power, but also weigh more, which is undesirable for vehicle and body armor applications. Moreover, the nature of the perceived threat, such as the expected projectile weight, caliber, and velocity, and whether it has a blunt tip or is armor-piercing, affects armor requirements. Thus, any armor design is invariably a compromise between performance and weight. A third consideration is cost; its importance is substantial, and the best available armor is rarely used due to its expense. Our general approach has been to employ, wherever possible, commercially available and generally low-cost materials; our strategy has been to use conventional components arranged in unconventional designs.

Armor dates to the beginning of recorded history, and modern designs are highly developed (although "mail," a metallic mesh used by the Etruscans for body protection as early as the 4th century BC [1] remains the basis for stab-resistant body armor even today). Thus, it is expected that only modest improvements in performance can be achieved; nonetheless, given the purpose of armor, increases in stopping power of just a few percent are considered significant. Quantifying such small changes in performance places a burden on the testing protocols, since accuracy and reproducibility of the measurements must be very high. For ballistic testing of armor, standard methods are available, although aspects of their implementation and interpretation are ambiguous. For blast testing, which is more limited due to its difficulty and expense, standard test methods are lacking; thus, ad hoc procedures are usually adopted.

In this report, the factors influencing the characterization of ballistic and blast performance of armor are reviewed. We describe the methods and analyses useful in achieving measurements of sufficient quality to yield valid assessments; that is, approaches that minimize or avoid potential errors. Interpretation of ballistic and blast measurements is usually based on making comparisons of different armor designs under arbitrary conditions. Such comparisons are obfuscated by the disparate requirements of performance and weight. For this reason, it is common to normalize ballistic performance to that expected for rolled homogeneous armor (RHA), a conventional armor material. However, such a normalization scheme is projectile-specific; that is, the relative merits of different designs will vary, even qualitatively, according to the bullet or projectile used in the testing.

Given the difficulties and expense of evaluating armor performance, modeling and simulations are attractive alternatives to testing. However, at least for armor incorporating polymer/steel bilayers, especially the designs in which soft polymers undergo a phase transition upon ballistic impact, modeling has proved to be of limited value. For example, polyurea, which is the focus of much recent work, has complex behavior, exhibiting a high nonlinear and extremely viscoelastic (rate-sensitive) response to mechanical perturbation, in addition to irreversible chemical changes effected by projectile impact. Moreover, the response of the polymer is coupled to the properties of the substrate, due to mechanisms that are presently

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unknown. Of course, the substrates have vastly different mechanical and failure properties than the coatings. For these reasons, existing modeling efforts, even on a strictly empirical level, can at most only describe some of the properties of hard substrates coated with soft, polymeric coatings. Lacking predictive capability, modeling does not obviate experimental testing.

The focus of the work at NRL has been armor designs that use soft elastomers applied to the front (strike) face of rigid substrates [2,3]. This technology has shown great promise for a range of purposes, including military vehicles, body armor and helmets, and some civilian applications. We review the test methods and discuss interpretation of test results.

2. BALLISTIC TESTING

The most common metric of ballistic performance is the V-50, which refers to the projectile velocity that has a 50% probability of completely penetrating the target (an average calculated after conducting a series of firings at different velocities). Other quantities used to assess performance include ballistic limit, an ambiguous term akin to V-50; V-0, the velocity at which there is zero probability of complete penetration (thus, V-0 is lower than V-50); and residual velocity, the velocity of the projectile after transit through the target. Although these and other criteria are employed for specific applications (such as when protection from a certain threat must be guaranteed) or for certain test methods, V-50 is the most generally useful parameter for armor assessment. Military specification MIL-STD-662 provides guidelines for determination of V-50; our implementation of this standard procedure is described below.

2.1 Equipment and Test Protocols

Typical ballistic test instrumentation is depicted in Fig. 1. The gun system employs a Mann barrel, available in a range of calibers[1] (e.g., .22 cal to 20 mm). A Mann barrel (the name refers to F.W. Mann, a medical obstetrician who pioneered the science of ballistics [4]) is a heavy-walled test barrel designed for accuracy. The barrel interior has helical grooves ("rifling") to induce spinning of the projectile; the consequent angular momentum stabilizes the flight by minimizing yaw. The barrel is usually mounted with concentric rings, rather than using a manually held stock. A recoil mechanism incorporating hydraulic dampening is used for projectiles larger than .50 cal.

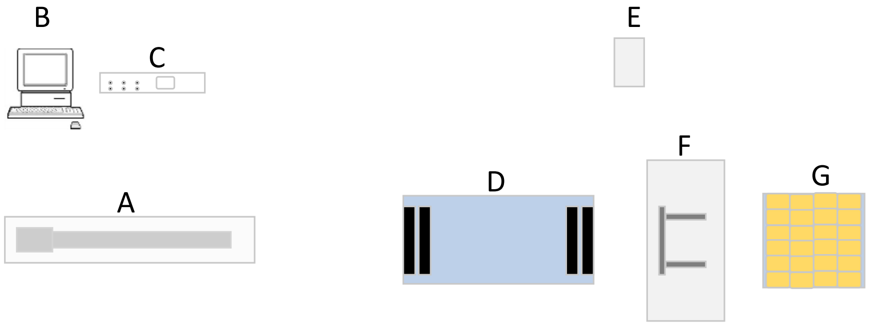

Fig. 1 — Schematic of ballistic test setup. (A) Mann barrel gun system; (B) computer and data acquisition interface; (C) remote, manual trigger; (D) velocity screens; (E) high speed video camera; (F) mounting stand, which allows movement of target to position the impact locus; (G) sand-filled box to catch projectile and spall.

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[1] Caliber corresponds to the diameter of the gun barrel, usually expressed in inches; e.g., .30 cal refers to a 0.30 inch bore.

The gun system is remotely fired through electrical initiation, using either percussion-primed cartridges initiated by a solenoid-driven striker (for smaller calibers) or electric primers (for projectiles larger than .50 cal). Barrel lengths from 4 to 6 feet are typical. Although in principle the muzzle velocity of a bullet increases in proportion to barrel length, the gain from a longer barrel is minimal for typical gun powder burn rates. Other considerations related to barrel length, such as weight, accuracy, and noise, are not relevant for V-50 tests. Higher velocities can be achieved with a larger bore; this requires the use of sabots (French *sabo*, wooden shoe) to seal around the sub-caliber round and carry it through the barrel.

Determination of V-50 requires systematically changing the projectile velocity until the minimum value required for complete penetration is obtained. Typically in our tests we require at least two penetrations and two stoppages (partial penetration), with a velocity spread that does not exceed 2%. For bullets having speeds close to the V-50, both complete and partial penetrations may occur for apparently identical conditions. Multiple shots on the same target makes selection of the impact points critical to avoid artifacts due to edge effects or damage from prior shots. During testing, the gun barrel is maintained in a fixed position, with the target holder translated to alter the shot location.

The projectile velocity can be changed by varying the type (e.g., burn rate) and amount (charge weight) of gun powder. Figure 2 shows data for the velocity of a .50 caliber fragment-simulating projectile (fsp; described below) versus the amount of IMR 4895 gun powder. The incident velocity can also be changed by varying the distance between the gun barrel muzzle and the target, with very short standoffs used to maximize bullet velocity.

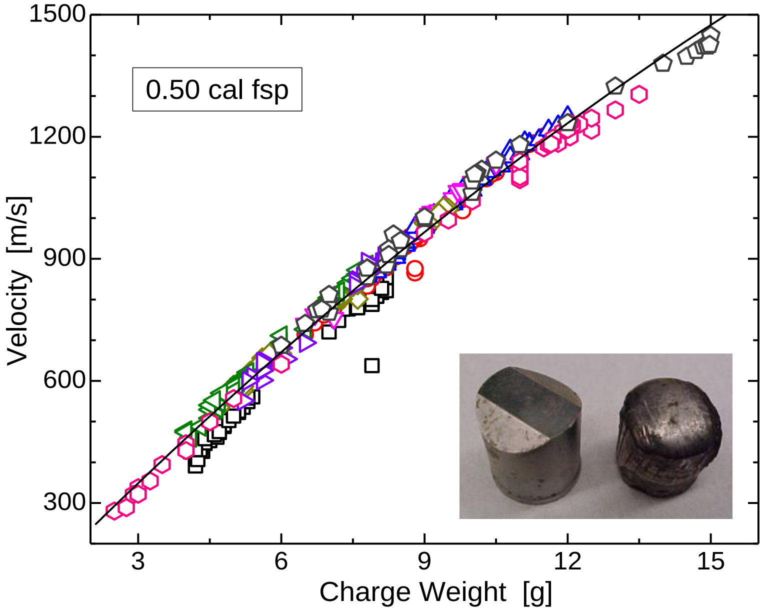

Fig. 2 — Projectile velocity, using a 5 ft rifled Mann barrel, as a function of the quantity of IMR 4895 gun powder. Different symbols correspond to tests on different dates; the solid line is the best-fit of a quadratic function. The projectile, a .50 cal fsp, is shown in the lower corner, before and after passage through a high hard steel (HHS) plate.

Usually, experiments are carried out with the target oriented normal to the projectile path. (Minuscule deviations in projectile path arise due to gyroscopic drift and precession of the rotating bullet [5].) Since the interaction of the projectile with the front surface can change qualitatively with angle, a complete characterization of ballistic performance also requires measurements at oblique angles. This is achieved by tilting the target. Typical results are shown in Table 1 for the relative performance of bare and elastomer-coated steel at three angles of incidence. Note that the effect of obliquity cannot be predicted from a simple calculation of the incident vector. For coated targets, the effect of obliquity is more complex, because the effectiveness of the coating decreases with decreasing angle of incidence. Presumably this is caused by attenuation of the rapid compression of the polymer that underlies the mechanism for ballistic enhancement; nevertheless, as seen in Table 1, bilayers with certain elastomers yield higher V-50 even at 45° incidence.

Table 1 — Effect of Obliquity on V-50 (Values Normalized to Bare Steel at Normal Incidence)

Target	Angle of Incidence		
	90°	60°	45°
Bare Steel	1	1.24	1.37
Coated Steel	1.39	1.41	1.49

The accuracy of a V-50 determination depends directly on the accuracy of the measurement of projectile speed. Various measurement techniques can be employed, and with modern instrumentation the measurable range of speeds spans at least 5 orders of magnitude [6]. Common to most methods is a time-of-flight calculation. For our experiments, Ohler chronographs are used, in which passage of the projectile is detected from reflection of infrared light. The sensitivity of the chronograph improves with higher bullet caliber and velocity. Data are collected at sampling rates of $1.25 \times 10^6\ s^{-1}$. The output from the chronographs is displayed on-the-fly and also stored in a PC for subsequent processing using custom (in-house) software.

Typically we employ four screens arranged in series to obtain two independent velocity measurements. This enables assessment of the reproducibility of our data and detection of spurious readings. The latter are usually caused by light emitted from the gun barrel; collimators help suppress this “muzzle flash.” To illustrate the reliability of our speed determinations, 100 shots were measured simultaneously by two chronographs. There was only one outlier (a reading high by a factor of 10); for the two data sets, the mean differed by 0.6%, with a correlation coefficient between the two instruments essentially equal to unity.

Alternate methods of measuring projectile velocities can be employed. Break-screens are conductive papers placed a known distance apart, with timing obtained from creation of an open circuit by passage of the projectile. A variation on this technique is the use of make-screens, which are panels of two conductive sheets separated by a dielectric material. When a projectile penetrates the panel, the circuit is temporarily completed, providing electrical detection. The advantage of make-screens over break-screens is the former can be reused, at least until the damage is too extensive and causes a short in the panel. High-speed photography can also be used to measure projectile velocities. The method can be very accurate; however, the results are not obtained until after the ballistic tests, so the primary value of photography is to validate the calibration of chronographs and detection of any spurious events during target impact.

Determination of V-50 also requires evaluating target penetration. Projectiles invariably penetrate the target to some degree. Complete penetration is defined as any perforation of a back-side witness plate that is sufficient to allow passage of light. This perforation can be caused by the projectile itself or by spall (fragments of material broken from the back side of the target). Figure 3 shows the large hole in the front side of a target caused by penetration of three .50 cal bullets; however, there was no damage on the back side of the target beyond a small bulge, and no damage to the witness plate. Since the witness plate was unaffected, this shot is a partial penetration, and the inference is that the bullet speed was less than the V-50 of the target.

The witness plate is typically placed ~15 cm behind the target, centered along the projectile line-of-flight. A 0.5 mm thick 2024 T3 Al plate (areal dimensions 12 in. × 12 in.) is sufficient for most tests, although for applications in which a secondary barrier would be present, the witness plate can be varied to simulate the barrier. For example, a 2 mm sheet of mild steel has been used in testing armor that will protect a container; the steel sheet used as the witness plate is the same material and thickness as the container.

(a) (b)

Fig. 3 — (a) Front side of target after penetration in lower left corner by three .50 caliber armor-piercing projectiles. (b) Intact witness plate demonstrating the absence of complete penetration of the target.

2.2 Projectiles

The type of ammunition used for armor testing depends on the application. A comprehensive evaluation of armor would include testing for the following:

(i) Ball ammunition refers to conventional bullets having a round or flat nose. The ogive may have a jacket covering a lead core (e.g., total- or full-metal jacket) or be the expanding type.[2] The term “bullet” derives from the French word for ball, and the term “ball ammo” is similarly historical — ammunition typically had a spherical shape up through the early 19th century.

(ii) Fragment-simulating projectiles are blunt bullets composed of soft steel (30 Rockwell C per MIL-DTL-46593) that are intended to mimic the fragments produced from the casing of an exploding bomb. They are used to evaluate the effectiveness of armor against bombs, such as improvised explosive devices

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[2] Bullets designed to expand on impact, which date to the mid-19th century, include hollow-points, which have a hollow depression in the nose, and soft-points, having a deformable, usually lead, tip.

(IEDs), for example. Fragment penetration is the primary cause of injury from bombs exploded in open space, and the lethality range of the fragments is much greater than that of the blast itself [7].

There are both U.S. military (MIL-DTL-46593) and international (STANAG 4496) specifications for fragment testing. Typically, bomb fragments have a broad range of mass and velocity, and fsp are available in sizes ranging from .22 caliber to 20 mm diameter. Armor that performs well against fsp is usually effective against ball ammo also; thus, testing with fsp is an efficient means to assess armor capabilities more generally. Since fsp are relatively soft, they deform substantially on impact, as shown in Fig. 2.[3]

(iii) Armor-piercing (AP) bullet is a generic term, strictly defined by federal statute (18 U.S.C § 921). As the name implies, AP ammunition is designed to penetrate armor. This is accomplished by using a sharp tip (small frontal area and thus elevated impact pressure) in combination with a dense, hard core. Originally the core material was tungsten carbide, but more common nowadays are steel alloys of comparable hardness.

(iv) Incendiary ammunition has combustible material in the front, which detonates on impact. The principal intent is to ignite the target, with the blast facilitating armor penetration.

2.3 Data Analysis

To quantify ballistic performance, the V-50 is determined as the projectile velocity that has a 50% probability of completely penetrating the target. This is calculated as the mean of the highest velocity for incomplete penetration and the lowest for complete penetration. For bullets having speeds close to the V-50, both complete and partial penetrations may occur for apparently identical conditions; such results are incorporated in the average. The V-50 calculations are performed subsequent to the ballistic tests.

Since armor design is almost always a compromise between performance and weight, both properties must be assessed. The usual metric for weight is areal density, defined as the weight per unit (presented) area of the armor. Since most armor applications have a performance specification that must be met, “improvement” often implies meeting the specification at a lower weight and an acceptable cost. The “best” design depends on the intended application.

For evaluating the balance between performance and weight, the mass efficiency is commonly used, defined as the reduction in weight that maintains a given level of performance. RHA is a common standard for comparison; thus, the mass efficiency of a candidate armor can be calculated as the areal density of RHA having sufficient thickness to achieve the performance of the candidate armor, divided by the areal density of the latter.

3. BLAST TESTING

In a typical blast test, an explosive charge is placed in the center of a circular arrangement of targets (Fig. 4). This “arena testing” enables multiple targets to be evaluated with a single blast. Common explosives include C4 and pentolite, with blocks of the material arranged in a symmetric pattern such as shown in Fig. 5. The maximum pressure (i.e., overpressure) is a critical aspect of the potential of a blast wave to create damage, and is measured with pressure transducers interspersed among the targets. To verify uniformity of the blast wave, multiple transducers are used, placed at the same radial position as the targets. These gauges are either piezoelectric or piezoresistive; the former have higher temporal sensitivity, but are

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[3] Note that frangible bullets, or “frags,” differ from fragment-simulating projectiles; frangible bullets are ball ammo designed to fracture on impact, yielding a wider but shorter penetration channel. The term “frag,” however, is also used for fsp and other projectiles that mimic fragments from the casing of an exploding bomb.

affected by temperature. The output from the transducers is conditioned and recorded as a function of time. As an example, 5 to 8 lb of C4 was measured to produce blast pressures 1 m away in the range from 65 to 100 kPa. Pressures exceeding ca. 100 kPa are associated with serious injury [8].

Fig. 4 — Typical arena blast test configuration, with test plates mounted in a semicircle, 0.94 m from the explosive. Interspersed between these test panels are four pressure transducers to measure the blast pressure incident on the targets.

Fig. 5 — Blocks of C4 explosive arranged to give a symmetrical blast pressure at the targets

Accelerometers, linear variable displacement transducers (LVDTs), and strain gauges can be used to measure deformation resulting from the blast. These are affixed to the back side of the target. Accelerometers have a fast transient response, which avoids clipping of the signals, although their output is usually noisier. Representative data for LVDTs and strain gauges are shown in Fig. 6. Both have limitations, the former a lower frequency response and the latter a limited range, which can also be affected by edge conditions. Differentiation is required to obtain speed and acceleration results from LVDT and strain gauge data, and this introduces scatter. On the other hand, velocity and displacement can be obtained from accelerometer data by integration, which reduces noise. If the mass and exposed areal dimensions of the target are known, the force and pressure from the blast can be calculated, although this requires the assumption that motion of the target is not restricted, for example by the mounting system.

An alternative for measuring deformation is to use a high-speed video camera, placed at a right angle to the target. From the images, the deflection is obtained as a function of time, with the corresponding velocity and acceleration obtained by differentiation. The primary value of video is to provide redundancy; for example, it avoids loss of data if the accelerometer detaches during exposure to the blast pressure. Figure 7 shows a comparison of velocity and acceleration measurements obtained from an accelerometer and from video images.

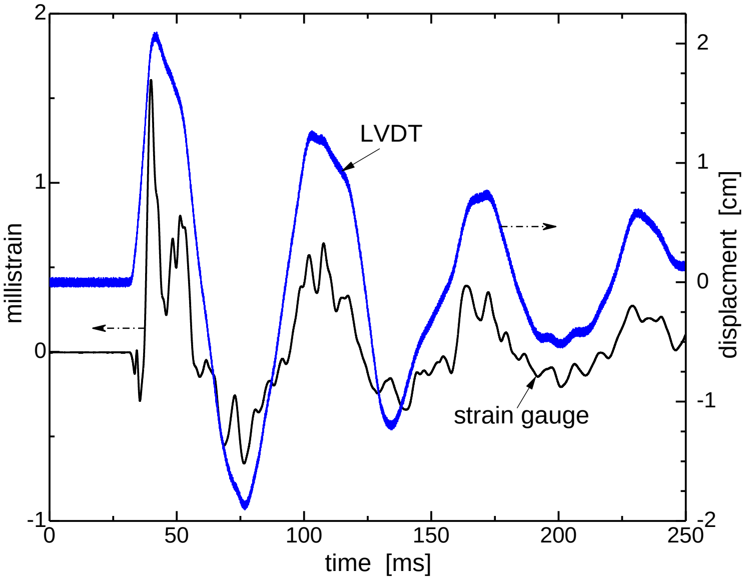

Fig. 6 — Response at the center on the back side of an elastomer-coated steel plate: strain measured by a strain gauge (left axis) and displacement measured with an LVDT (right axis). As can be seen, the strain gauge has significantly higher temporal resolution; the higher frequency oscillations are absent in the LVDT response.

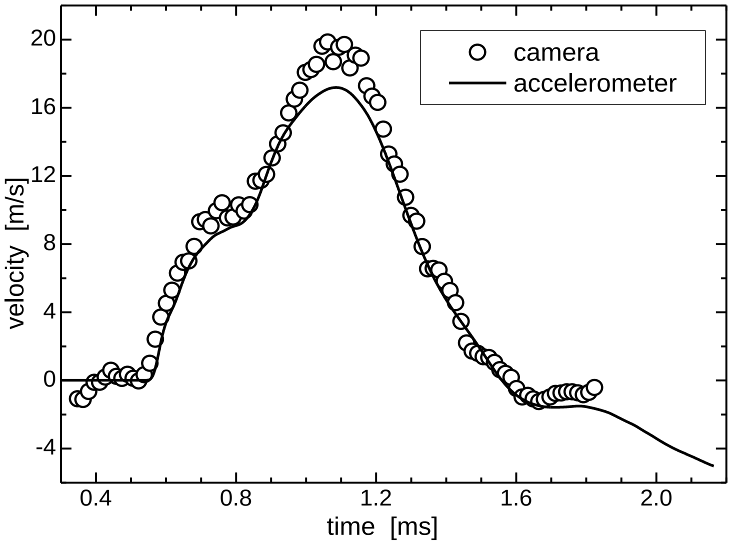

Fig. 7 — Velocity obtained from the first derivative of the displacement of the back side of a target measured with a Shimadzu HPV-2 high-speed camera (circles) and from integration of the output of an accelerometer (line)

4. TEST MATERIALS

Armor materials are usually designed for specific applications. Here, we discuss an example of armor for ballistic protection of light vehicles: a rigid steel substrate coated with polyurea.[4] The polyurea for this application is an elastomeric material having particular dynamic properties [9]. There are several other elastomers that perform very similarly to this polyurea [2,3]. The property that makes these materials suitable for use herein is having a glass transition temperature roughly in the range from −60° to 0° C, with the exact value depending on the breadth of the glass-rubber transition zone in the polymer’s viscoelastic spectrum. This property ensures that the ballistic impact frequency is commensurate with the frequency of the polymer segmental dynamics [9], which give rise to a resonant condition with large energy absorption [10]. The thickness of the coating is 2 to 3 mm, to optimize the mass efficiency.

The polymer coating is applied to the front (strike-face) of the substrate, which can be metal or a rigid polymeric material or composite. For our tests, we employed RHA (Brinell hardness ≈ 300), high hard steel (HHS, MIL-DTL-46100E; Brinell hardness = 500 ± 28), ultra high hard steel (UHHS; Brinell hardness = 600 ± 35), and a polymeric resin reinforced with Kevlar aramid fabric. Polyurea has sufficient inherent adhesion, both chemical and mechanical, to remain in place on most substrates. More generally for the elastomer-coated armor construction, the method of attachment, whether adhesives, mechanical fasteners, or other, had no influence on ballistic performance.

The elastomeric coatings enhance the performance of steel substrates for fsp and ball ammunition, but bullets with a sharp tip cut and tear the coating, significantly reducing the coating effectiveness. Thus, to defeat AP ammunition, we embed ceramic in the polymer, to deflect and fracture (or erode) the bullet. Ceramics are very hard and have lower densities than metals, and for these reasons have found application in a wide range of military platforms [11]. Conventional use of ceramic suffers a drawback due to its low

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[4] A polyurea-based coating from Specialty Products Inc. known as DragonShield was used to up-armor Humvees during the Iraq War.

tensile strength. When the pressure wave reaches the back side of the target, it reflects as an extensional wave. Since the wave speed is typically 3 to 4 times faster than the projectile velocity, this reflecting tensile wave destroys the ceramic before the incoming bullet can be disrupted by the ceramic. The usual solution to this problem is to use thicker ceramic. However, by embedding discrete ceramic objects (e.g., spheres) in the polyurea or another ballistically effective elastomer, the fracturing ceramic is held in position, so that the particles can continue to erode the projectile. Discrete ceramic is less prone to damage from being dropped, which is another advantage over ceramic plates.

For blast protection, armor designs must address the expected blast pressures, which are governed by the amount of explosive and the standoff distance. Design strategies to break up or disperse the blast wave and its associated momentum include venting, sacrificial materials, shock impedance matching or mismatching, blast wave reflection, and energy absorption. The effectiveness of some of these mechanisms depends on the blast pressures. Bomb fragments are a part of blast protection that is addressed through ballistic tests using fsp.

5. REPRESENTATIVE RESULTS

Figure 8 shows V-50 results for elastomer coatings on steel (different alloys and tempers) as a function of areal density. Performance variations of the elastomer/steel bilayers can be achieved by varying the materials or their thickness. Since there is a trade-off between ballistic properties and weight, the requirements of the intended application become paramount. In evaluating the armor, the performance of RHA can be used for comparison; however, there is some variation in the literature for the ballistic properties of RHA. In the figure, we show results for RHA taken from the military standard (MIL-DTL-12560), which is a linear regression of various test data, and the (somewhat higher) V-50 values reported by Gooch and Burkins [12]. By either measure, the elastomer-coated steel bilayers offer substantial improvements over uncoated RHA. The performance level of conventional steel can be obtained with bilayer armor that approaches twofold reductions in weight.

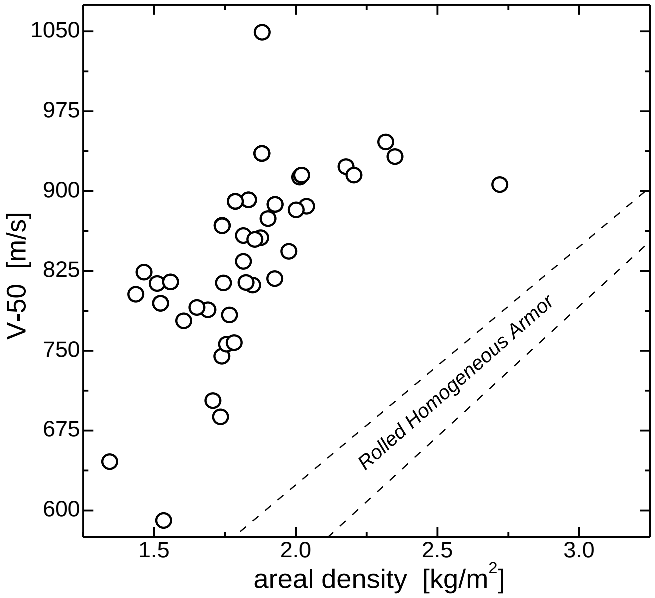

Fig. 8 — The ballistic performance of various elastomer/steel bilayers made of different materials and layer thicknesses (circles). Dashed lines indicate the range of reported performance of RHA.

Table 2 compares the results of blast tests on Kevlar-based panels both with and without an elastomeric front coating. Two tests were carried out, with different distances between the explosive (1.25 lb pentolite) and the targets. For the shorter stand-off, the pressure incident on the target was about 300 kPa. For both tests, the coated panels deflect less, and have lower velocity and acceleration values (as measured on the back side) than the uncoated control at equal areal density.

Table 2 — Blast Results for Coated and Uncoated Panels

	Velocity (m/s)		**Acceleration (km/s^2)**	
Stand-off (m)	0.6	1.1	0.6	1.1
Uncoated	21.3 ± 0.5	13.6	110 ± 5	32.0
Coated	16.5 ± 0.4	9.0 ± 0.3	75.5 ± 0.11	17.5 ± 0.04

6. CONCLUDING REMARKS

Using the test methods described here, armor coatings have been developed at NRL that increase the resistance of substrates to ballistic penetration and blast wave deformation. These materials provide the performance of current armor but with substantial reductions in weight. The mitigation of bomb blasts has been demonstrated with tests employing a range of overpressures, demonstrating the robustness of the armor. The ballistic data presented here are limited to V-50 measurements for fsp projectiles; however, the coatings can be modified to defeat AP bullets by embedding ceramic elements within the elastomer coating [13].

Several applications for these materials are currently being investigated, including helmets, body armor, light military vehicles, amphibious vehicles, civilian transport, and rail tank cars.

Although the improvements measured in tests of these coatings are significant, more generally the accuracy of armor testing and the reliability of the results have to be verified. Since ballistic and blast tests tend to be expensive and can be carried out only in specialized facilities, it is imperative to employ sound experimental methods, including adherence to any relevant test standards. Although such standards help to make the methods more reproducible, important aspects of armor testing remain subjective, potentially introducing variability into results from different facilities. This problem can be minified by documenting the details of the procedures used, although in practice this is rarely done.

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