Elastomer–steel laminate armor

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ABSTRACT

Elastomeric coatings have been found to substantially increase the ballistic limit of underlying steel sub-strates, with an important mechanism being the impact-induced transition of the rubber to the glassy state. A composite array of elastomer–steel panels has been found to further increase the penetration resistance; moreover, the elastomer coating itself can be a laminate structure of soft and hard materials. The requirements for the laminate to function well are that the underlying substrate retains sufficient bending stiffness for the impact to induce the transition of the polymer, which in combination with break up and dissipation of the pressure wave due to impedance mismatching, leads to large increases in bal-listic penetration resistance.

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1. Introduction

The final counter-measure against bombs and ordnance is mit-igation of the effects of the blast or ballistic impact and the past several years have seen burgeoning efforts to develop new meth-ods of alleviating both explosive and ballistic threats. One success-ful approach is the application of elastomeric coatings to hard substrates. The initial work was performed by the US Air Force, with polyurea coatings applied to the walls of buildings to mini-mize fragmentation [1] and retain structural integrity during a bomb blast. The function of the coating in this application is to pre-vent building fragments produced by the blast from being pro-pelled through the interior. Such flying debris can attain speeds of 100 m/s and are the second leading cause of injury to occupants of a bombed building.

Subsequently the US Navy has pursued the use of polyurea coat-ings to mitigate the damage from ballistic fragmentation and pro-jectiles [2]. Applied to the outside of armor plate installed on the US Marine Corp's High Mobility Multipurpose Wheeled Vehicle (HMMWV), the coatings increased resistance to penetration from gunfire and fragmenting explosives. This technology was success-ful in "up-armoring" vehicles in the field [3]. The attraction of poly-urea for these applications is that it forms *in situ* by the rapid reaction of isocyanates with polyamines. The chemistry proceeds essentially independently of ambient temperature and humidity, facilitating application of the coating under diverse conditions. And at least for lower rates of impact, the extensive intermolecular hydrogen-bonding of polyureas leads to better mechanical "tough-ness". However, recently we have discovered that various non-po-lar hydrocarbon rubbers can function as well as or better than polyurea, indicating that the H-bonding of polyureas is of negligi-ble significance under the impact loadings relevant to armor coatings.

The physics of ballistic penetration of hard targets has been much investigated and reviews of the topic are available [4,5]. However, the nature of the interaction and the effect of impact de-pend strongly on the properties of both target and projectile. The origin of the blast and ballistic mitigation from rubber coatings re-mains to be fully understood, with a variety of mechanisms likely contributing [6–8]. The viscoelastic nature of polymers means that the frequency and test temperature can influence the properties of polymer-based ballistic armor [9]. Moreover, the convolution of rate and strain effects (impact penetration is highly nonlinear) makes quantitative analysis difficult [10]. One important aspect of performance is the frequency of the segmental dynamics of the polymer in comparison to the strain rate during the loading [11]. For ballistics the latter can be as high as $10^5\,\mathrm{s}^{-1}$ or more, which means that the rubber may respond in a glassy fashion; that is, reorientation and translational modes of the polymer segments are too slow to respond on the available timescale. These modes become "frozen out", leaving only vibrational and secondary mo-tions. Such proximity of the rates of the loading and of the polymer segmental motions requires that the glass transition temperature, T_g, of the material be close to, but less than, the operating temper-ature. When this condition is met, sufficiently high strain rates can induce a transition of the rubbery polymer to the glassy state, which is accompanied by large energy absorption and brittle frac-ture of the rubber [11,12]. Conventionally, brittle fracture is asso-ciated with minimal energy dissipation; however, in this case the

brittle glass is the consequence of deformation that encompasses the glass transition zone.

The ballistic resistance of the rubber-coated steel likely involves other mechanisms, such as mode conversion and strain delocalization, which can broaden the distribution of the impact pressure. As described herein, single coatings of elastomer are effective in increasing the ballistic limit and minimizing the extent of damage to the underlying substrate. In this work we also examine the use of multiple hard–soft layers as a means to further enhance the penetration resistance. The objective therein is to dissipate the shock wave through multiple reflections as it traverses the laminate.

2. Experimental

The elastomers were formulated in-house and mixed at Manville Rubber Products, Inc., except for the polyureas, which were prepared at NRL. The base polymers were polyisobutylene (PIB), polyurea (two variations: PU-1 and PU-2), polynorbornene (PNB), nitrile rubber (NBR), 1,4-polybutadiene (PB), and both synthetic (PI) and natural (NR) 1,4-polyisoprenes; these are all high-molecular weight, commercially-available organic polymers. The compounds were applied to the front face of steel substrates (High Hard Steel "HHS", Mil-A-46100, with hardness in the range 470–500 Brinell units). Generally an adhesive was used, although some additional tests employed other methods of attachment, as described below. Depending on the test, the thickness of the steel plates was between 5.1 and 12.7 mm, in all cases sufficient to prevent observable flexure upon ballistic impact. Elastomer coating thicknesses were varied as described below. Ballistic tests followed Mil-Std-662F, using a 0.50 caliber (1.3 cm diameter) rifled Mann barrel firing fragment-simulating projectiles (FSP); the latter had a Rockwell C hardness of 30. The velocity of the projectile, varied by variation of the gunpowder charge, was measured both with a chronograph and a laser velocimeter; typically the difference between the two measurements was <1%. The ballistic limit (i.e., penetration velocity), V-50, was determined as the average of the lowest and highest velocities for penetration and lack of same, respectively, with testing carried out until these quantities differed by no more than 15 m/s. High-speed video was obtained (Vision Research Phantom v7 camera) on the incident projectile. Failure of the plates occurred by shear plugging; i.e., shear-dominated separation of a cylindrical section of material having a cross-section that matched that of the FSP. All tests were carried out at ambient conditions.

Low frequency ($\sim$0.1 s^{-1}) stress–strain data on the elastomers were obtained in a tensile geometry using an Instron 5500R. Glass transition temperatures were measured by scanning calorimetry (TA Instruments Q100), with samples cooled below T_g at 10 K/min and data taken during subsequent heating at the same rate.

3. Results

The ballistic limit of the HHS steel plates was measured with various elastomeric coatings. Previous work has shown that using steel of lower hardness or less toughness than HHS significantly reduces the performance enhancement due to an elastomeric coating. The best-performing coatings are those based on elastomers having high and/or broad glass transitions. This is seen in Fig. 1, showing the V-50 of the HHS laminate plotted as a function of T_g of the elastomer. Note that there are differences in various properties among these elastomers and some of these properties may affect the performance; for example, the more strongly strain-crystallizing NR is superior to PI. However, an over-riding variable is the glass transition temperature. When the latter is sufficiently close to the test temperature (21 °C for the data in Fig. 1), impact
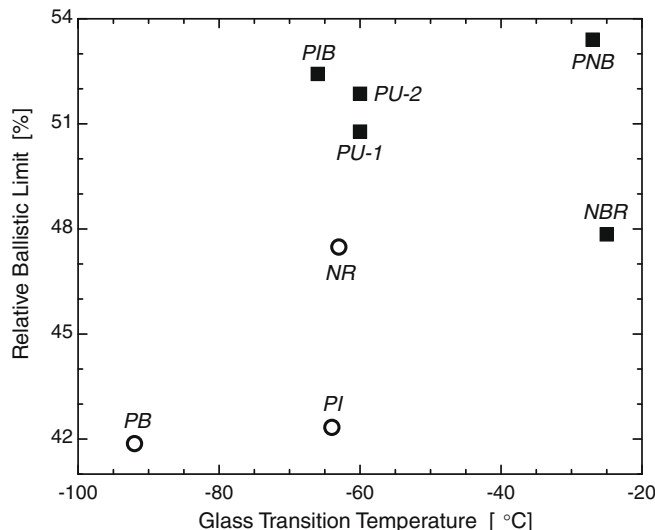

Fig. 1. Increase in V-50 over bare HHS for elastomer coatings (19 mm thick) having the indicated T_g. The hollow symbols indicate rubbery failure (substantial stretching and tearing of coating) and the solid symbols designate coatings that failed in brittle fashion (damage zone limited to immediate area of impact). The failure modes are depicted in Fig. 2.

of the projectile induces a transition to the viscoelastic glassy state. The latter is defined by the rate of the external perturbation exceeding the rate of the polymer segmental dynamics [13]. For the ballistic tests herein, the strain rate can be estimated from the ratio of the projectile velocity to the coating thickness, equal to about 10^5 s^{-1}. This falls within the frequency range of the segmental dispersion for polymers in Fig. 1 having high glass transition temperatures [11]. This transition from the rubber to the glassy state dissipates significant energy; from the V-50 changes we estimate the kinetic energy loss is about 3 kJ, corresponding to a strain energy density in the rubber of $\sim$4 GJ/m^3, assuming no delocalization. This reduction in projectile energy elevates the velocity require for penetration, with a concomitant change in the mode of failure from rubbery (large strains with pervasive rubber tearing) to brittle fracture wherein damage is limited to the immediate area of impact. These failure modes are illustrated in Fig. 2.

For the PIB and PU coatings, T_g is not especially high ($\sim$−60 °C); nonetheless, impact still induces a glass transition because the breadth of the transition zone is unusually broad for these polymers. This is illustrated in Fig. 3, showing the dispersions in the dynamic mechanical loss tangent [14,15]. These are significantly broader than found for most polymers (the peak for 1,4-polyisoprene [16] is included if Fig. 3 for comparison). This breadth means that well above the nominal T_g, there remain a significant number of segmental modes at frequencies associated with the rate of impact; thus, the glass transition mechanism remains operative at temperatures well above T_g. Note that the estimate of the nominal impact strain rate as the ratio of the projectile velocity to the coating thickness, on the order of 10^5 s^{-1}, assumes that the projectile maintains a constant velocity [17].

In Fig. 4 are stress–strain curves for the five elastomers in Fig. 1 that perform well as ballistic coatings. Conventional mechanical properties such as stiffness, strength, and toughness, measured at usual laboratory (slow) strain rates, bear no relationship to the material's ability to enhance the penetration resistance of armor. For example, the polyurea compounds differ by a factor of 2 in strength, but have quite modest differences in performance as a coating. In fact, a slightly higher V-50 is obtained with the lower strength PU-1 coating. The reasons for the decoupling of rubber
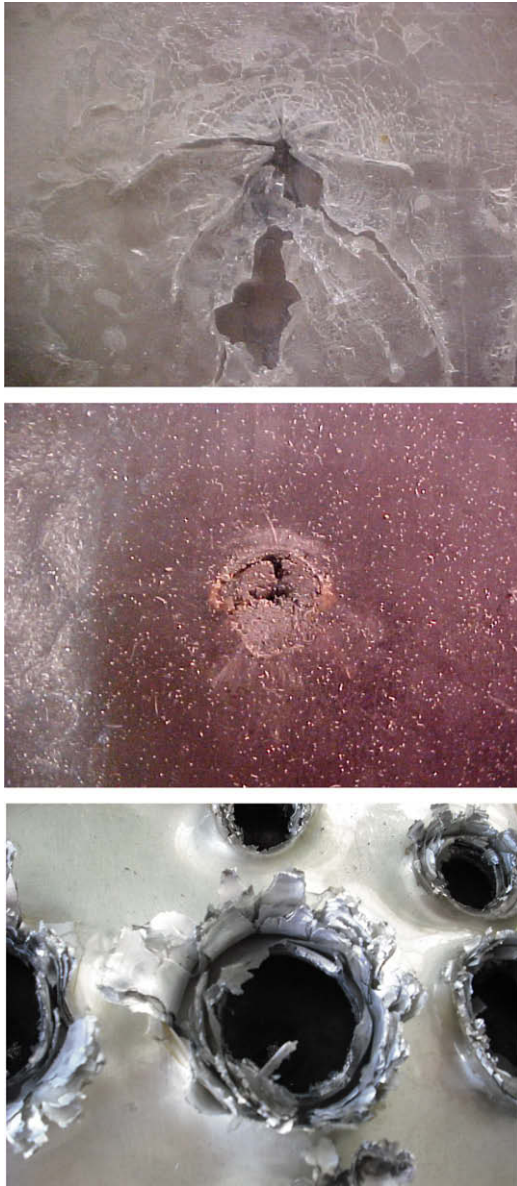
Fig. 3. Mechanical loss tangent for: (Lower) polyurea [15]; the plot is the superposition of measurements over a range of temperatures. Although the material is thermo-rheologically complex, so that the shape of the curve is only approximate, time–temperature superpositioning (abscissa scale is reduced frequency) gives an indication of the breadth of the dispersion. (*Middle*) polyisobutylene [14]; the data were obtained over a broad frequency range by combining transient and dynamic mechanical spectroscopies. (*Upper*) 1,4-polyisoprene [16]; the dispersion is narrow, so that it can be measured in a single experiment without time–temperature superpositioning. Note that the height of the loss tangent peak varies with temperature (decreasing in proximity to T_g), a consequence of thermo-rheological complexity.

Fig. 2. *Upper*: Substantial stretching and tearing of low T_g coating that failed in rubbery fashion. Tests with failure modes of this type are indicated by the hollow symbols in Fig. 1. *Middle*: Brittle failure of high T_g elastomeric coating via shear-dominated separation of a cylindrical section of material having a cross-section matching that the projectile. This failure mode corresponds to the filled symbols in Fig. 1. *Bottom:* Profuse damage accompanying penetration of HHS coated with 21 alternating soft and hard layers (see Table 4).

Fig. 4. Uniaxial extension measurements on elastomers in this study that undergo a glass transition under ballistic impact.

properties and armor coating performance are twofold: The viscoelastic behavior of the materials is different, so that their response to changes in strain rate can be quite different. More importantly, substantial increases in the ballistic limit of the armor are associated with an impact-induced transition to the glassy state. This transition is related to the T_g of the elastomer (Fig. 1), whereas mechanical properties measured at conventional strain rates are not.

Clamping methods are known to influence the ballistic resistance of materials [4], and if the functioning of the composite were dependent on the interaction between the substrate and coating, the nature of their interface should exert a role on performance. However, this is not the case. As seen in the data in Table 1, the method of attachment has no measurable effect on V-50. Mechanically-fastened (with screws) elastomer coatings performed equiv-
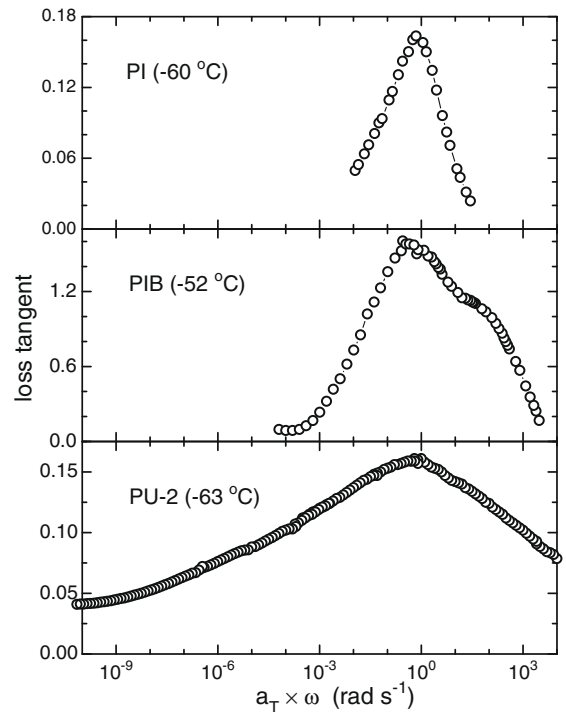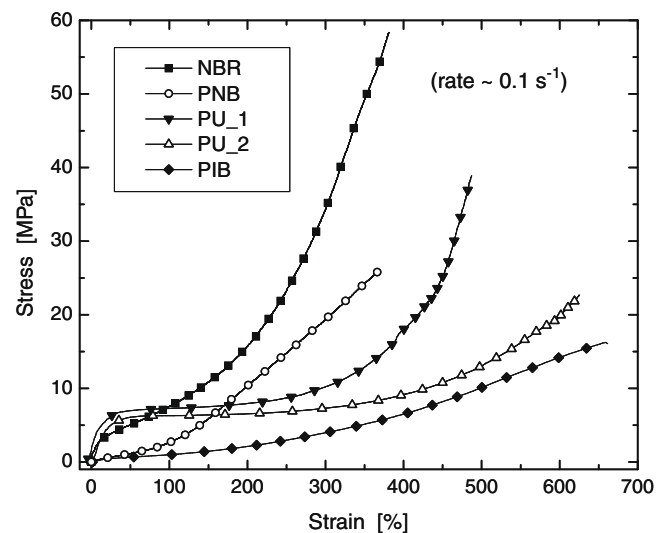
alently to sheets attached with an adhesive. Similar results were obtained using clamps. The only requirement is that the polymer be in physical contact with the steel, so that projectile impact compresses the material, rather than causing flexure. The implication is that the hyperelastic response of the steel is largely independent of

Table 1
Effect of attachment method on *V-50* (m/s).

Coating[a]	Attachment method	
	Adhesive	Mechanical fasteners
PIB	869	855
NBR	848	852

[a] 6.2 mm HHS substrate.

the coating, other than encountering a projectile of reduced velocity after passage of the latter through the dissipative rubber.

An obvious variable in the use of coatings is thickness, since optimal armor is always a compromise between performance and weight. In Fig. 5 the *V-50* measured for the PIB coating is plotted as a function of its thickness. Two data sets are shown, corresponding to HHS substrates of different thickness. Both curves have a modest slope, corresponding to a change in *V-50* of less than 200 m/s per cm of coating. Extrapolating to zero thickness gives a ballistic limit more than 50% higher than actually measured for the bare HHS. This means that the surface of the coating is dissipating a disproportionate amount of the projectile kinetic energy. This insensitivity to thickness is maintained down to *ca.* 0.3 cm thick coatings.

This near invariance of performance to thickness can be exploited with a multi-laminate structure. Toward this end various combinations of HHS–elastomer layers were incorporated into armor structures. Results are tabulated in Table 2 comparing a single coated HHS target to the same weight materials distributed over multiple bi-layers. The latter are clearly superior, the *V-50* for two bi-layers being 23% higher than a single bi-layer at equal weight. For comparison also shown are results for an equivalent thickness of Rolled Homogeneous Armor (Mil-A-12560). With the use of four bi-layers, there is some decrement in ballistic performance. Evidently the substrate has to maintain a certain level of stiffness to avoid flexure, which prevents compression of the polymer coating sufficiently rapidly to induce a glass transition. A similar effect is observed replacing the HHS with aluminum, the elastomer coating yielding much smaller increases in *V-50*.

As a variation on the structures in Table 2, the total mass of the target was reduced by using thinner HHS substrates. As illustrated
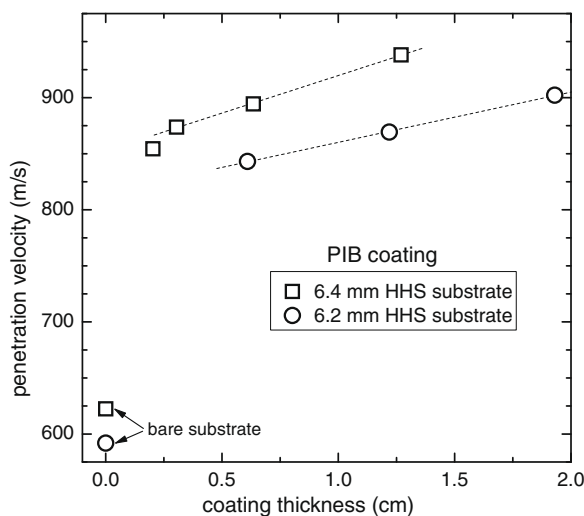

Fig. 5. Variation in *V-50* for two steel plates as a function of the thickness of the PIB coating. The dashed lines are the fits to the linear portion of the data, with the obtained slopes equal to 170 ± 4 and 114 ± 2 m/s per cm for thicker and thinner HHS substrate, respectively. Extrapolation of these lines gives a *V-50* much larger than measured for the uncoated HHS.

in Table 3, this does not compromise ballistic performance. Significant increases in *V-50* are still achieved, along with a substantial reduction in weight.

We can extend this approach by introducing multiple layers into the coating itself (Table 4). A single HHS substrate was coated with successive layers of 0.25 mm thick aluminum and 0.33 mm thick, low modulus PU-1. Despite the negligible increase in weight, there is an increase of over 60% in the ballistic limit (Table 4). Note that equivalent performance from Rolled Homogeneous Armor would require about twice the thickness (or weight).

4. Discussion

The degree of improvement in the ballistic protection of HHS armor coated with soft elastomer is surprising and not predicted by any model. The mechanisms responsible for the performance are not entirely understood; however, certain aspects of the required material properties for the elastomer are known, and by inference mechanisms contributing to the performance can be identified. The impact loading resulting from the arrival of a high speed projectile induces a viscoelastic transition of the rubbery polymer to the glassy state. The evidence for this transition is threefold: (i) The failure mode of the elastomer coating changes from rubbery to brittle. (ii) The impact strain rate ($\sim 10^5$ s^{-1}) falls within the frequency range of the local segmental relaxation dispersion of the elastomer. (iii) The ballistic limit of the laminate increases significantly, consistent with the fact that the glass transition zone of polymers is the viscoelastic regime of greatest energy dissipation. This transition significantly reduces the kinetic energy of the projectile because this transition in the viscoelastic regime of polymers is associated with maximum energy absorption. Note that the change is completely reversible; after the impact the polymer is completely elastomeric.

Strain-induced transition of a rubber to the glassy state is the basis for other applications requiring energy dissipation at high strain rates, such as the wet-skid resistance of automobile tires [18,19] and sound attenuation [20]. Recent results on the vitrification of polymers under pressure also reveal two relevant effects: The transition is associated with greater energy loss than the corresponding transition at low pressure [21]. And the resulting material is more ductile, due to a broader distribution of local relaxation times [22]. Since locally there is an increase in hydrostatic pressure upon impact, both these effects should be operative to increase the toughness of the elastomer, contributing to greater enhancement of penetration resistance when used as a ballistic or impact coating.

When the elastomer–steel configuration is present as multiple layers, the viscoelastic glass transition operates in conjunction with an enforced longer path-length for the pressure wave through the dissipative rubber, due to impedance mismatching with the steel. The improvement in performance for multiple layers is consistent with the data in Fig. 4, which yields an extrapolated value of *V-50* at zero coating thickness that is much larger than actually measured for the bare substrate.

The behavior of the multi-laminates requires further study, although the effectiveness of armor having more than one layer has been reported previously for other structures [4,23–26]. Separation of rigid layers with softer material has been shown to cause breakup of the compression waves within the layers [27,28], inducing multiple reflections of the incoming wave with the potential for greater attenuation prior to penetration of the substrate. This likely underlies in part the increased *V-50* for the laminated coating. Each sublayer has a significantly different acoustic impedance (=1.7 × 10^{-6} kg m^{-2} s^{-1} for the polyurea, versus 17 × 10^{-6} for the aluminum and 47 × 10^{-6} for the steel [29]), giving rise to

Table 2
Effect of front-surface elastomer layers on ballistic limit of steel plates.

Construction	Steel layers (mm)	Elastomer layers (mm)	Areal density (kg/m^2)	V-50 (m/s)
Single layer	One 12.7[a]	None	99	1097 ± 15
Single layer	One 12.7[b]	None	99	1184 ± 5
Bi-layer	One 12.7[b]	One 12.7	113	1483 ± 7
Four layers	Two 6.4[b]	Two 6.4	113	1819 ± 2
Eight layers	Four 3.2[b]	Four 3.2	113	1579 ± 7

[a] Rolled Homogeneous Armor.
[b] High Hard Steel.

Table 3
Effect of elastomer layers on ballistic limit at reduced laminate weight.

Construction	HHS layers (mm)	Elastomer layers (mm)	Areal density (kg/m^2)	V-50 (m/s)
Single layer	One 12.7	None	99	1184 ± 5
Bi-layer	One 12.7	One 6.4	106	1365 ± 6
Four layers	Two 5.1	Two 3.2	86	1398 ± 7
Four layers	Two 5.3	Two 3.2	90	1457 ± 1

Table 4
Effect of lamination of elastomer coating on ballistic performance.

Construction	HHS layers (mm)	Elastomer layers	Areal density (kg/m^2)	V-50 (m/s)
Single layer	One 11.5[a]	None	90	999 ± 8
Single layer	One 5.3[b]	None	42	622 ± 7
21 layers	One 5.3[b]	6.1 mm total (21 soft)	48	869 ± 1
21 layers	One 5.3[b]	6.1 mm total (11 soft/10 hard)	51	1006

[a] Rolled Homogeneous Armor.
[b] High Hard Steel.

repetitive reflections of the pressure wave. This impedance mismatching also serves to break up the compression wave, resulting in a series of lower amplitude impacts. These result in more profuse, fragmented damage to the impact surface (Fig. 2).

It has also been suggested that the failure mechanism of hard substrates can be altered by layering [6,7,30]. For example, increases have been observed in the micro-cracking of ceramic plates when layered in certain configurations [31]. The protection from penetration by multi-layering is greater for blunter projectiles, ascribed to additional energy expended in bending strains prior to fracture [32]. With respect to the projectile geometry, only relatively blunt FSP were studied herein. However, we have observed [33] that the penetration resistance conferred by the elastomer coating decreases with both projectile hardness and sharpness of its tip (reduced front-surface area).

Finally we note that the elastomer may delocalize the impact stress, which would contribute to a higher ballistic limit. Quantifying this effect requires pressure gauges with a GHz response and such experiments are currently in progress.

5. Summary

Elastomeric coatings are shown to enhance the resistance of HHS to penetration by high speed (10^3 m/s) projectiles. The requisite property of the elastomer is a T_g sufficiently close to the test temperature that impact induces a transition to the glassy state. The ballistic limit of the coated steel increases further when constructed as multiple bi-layers. Layering of the coating itself similarly enhances the V-50. Although the mechanisms underlying these improvements in performance remain to be completely identified and quantified, breakup and attenuation of the compressive wave by impedance mismatching within the laminate layers are believed to be important aspects.

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