Materials and Design 111 (2016) 362–368

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Elastomer-metal laminate armor

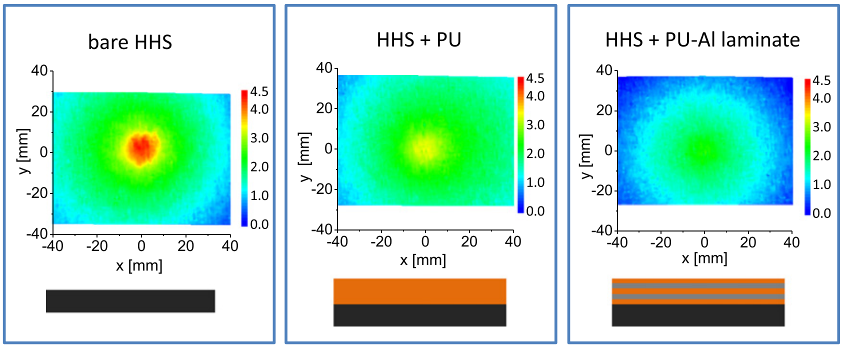
R.M. Gamache [a], C.B. Giller [b,c], G. Montella [b], D. Fragiadakis [d], C.M. Roland [d,*]

[a] *Naval Postgraduate School, Monterey, CA, United States*
[b] *American Society for Engineering Education postdoctoral fellow, United States*
[c] *MITRE, McLean, VA, United States*
[d] *Naval Research Laboratory, Chemistry Division, Code 6100, WA 20375-5342, United States*

HIGHLIGHTS

- Polymer-aluminum laminates on the strike-face of steel plates enhance ballistic performance.
- With judicious selection of substrate and laminate, a broad range of performance and weight combinations can be obtained.
- There is both a reduction in magnitude of the substrate deformation and spatial dispersion of the impact.
- The main function of the metallic layers is to stiffen the polymer without affecting the latter's viscoelasticity response.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form 23 August 2016
Accepted 24 August 2016
Available online 26 August 2016

Keywords:
Laminate
Wave transmission
Ballistics

ABSTRACT

A study was carried out of pressure wave transmission and the ballistic penetration of steel substrates incorporating a front-face laminate, the latter consisting of alternating layers of thin metal and a soft polymer; the latter undergoes a viscoelastic phase transition on impact. The ballistic properties of laminate/steel structures are substantially better than conventional military armor. This enhanced performance has three origins: large energy absorption by the viscoelastic polymer, a significant strain-hardening of the material, and lateral spreading of the impact force. These mechanisms, active only at high strain rates, depend on the chemical structure of the polymer but not on the particular metal used in the laminate.

1. Introduction

Reflecting the need to meet the disparate requirements of military armor (e.g., performance, size, and weight), the use of layered and laminated structures is not uncommon. The impact resistance of multiple thin metallic plates has been found to be better [1,2] or worse [3,4] than that of fewer thick plates, the relative performance depending on the materials, their arrangement, and the shape of the projectile ogive [5,6,7]. Polymers are eight times less dense than steel and thus an obvious route to lighter structures. A prominent example of their application is transparent armor, a laminate of inorganic glass and polymer layers that affords rigidity, toughness, and resistance to crack propagation [8,9,10,11]. Fiber composites are often layered with harder materials such as steel to yield better performance for a given weight [12]. A key to obtaining good ballistic properties with laminates is to maximize any available energy absorption mechanisms [13,14,15,16]; these can include friction between the projectile and the armor material, deformation (e.g., shearing and back side deflection) of the components, and layer delamination. For composites, especially fiber-reinforced

---

* Corresponding author.
E-mail address: roland@nrl.navy.mil (C.M. Roland).

http://dx.doi.org/10.1016/j.matdes.2016.08.072
0264-1275/Published by Elsevier Ltd.

materials, the primary modes of energy loss are fiber strain and breakage, and debonding from the matrix [17,18,19,20]. Cuniff [21] proposed a performance metric for fiber composites that indicates the ballistic limit (minimum projectile velocity for complete penetration) depends sublinearly on the modulus, strength, and failure strain of the fibers. For laminate armor, shear deformation promoted by the layering can have a substantial influence on the impact response [22], as can interaction between the layers [12]. The presence of a front-face polymer structure can even alter the failure mode of the underlying steel substrate [23,24]. Shear-plugging and spallation are the usual failure mechanisms for hard steel subjected to the impact by a blunt projectile. In addition to attenuating the stress waves, front layers broaden the impact area with consequent reduction in impact pressure [25]. These effects reduce the tendency of the steel substrate to form a shear plug. Multiple layers also afford a method of mitigating ballistic impact through management of the shock wave (e.g., deflection and spreading) [26,27,28]. For these reasons, the stacking sequence can exert a significant influence on performance [29,30,31,32].

Herein results are presented for armor incorporating alternating thin layers of metal and a rubbery polymer, with this laminate structure placed on the front side of a steel substrate. The work evolved from earlier studies on bilayers consisting of steel with a thin elastomer coating [33,34,35,36,37], the unique feature therein the large contribution of viscoelasticity to the absorption of impact energy. The particular polymers employed have segmental dynamics occurring on the time scale of the ballistic impact (ca. 10^{-5} s), so that the impact induces a rubber-to-glass viscoelastic phase change [38]. This phase transition corresponds to the mechanical regime in which polymers are most energy dissipative. The mechanism is only operative in polymers having a glass transition temperature close to, but below, the test temperature, whereby local motion of the chain segments coincides with the ballistic impact. One curious feature of the polymer-coated steel is the dependence of penetration velocity on coating thickness [33,34]. There are two regimes: a steep linear increase up through thicknesses in the range 1–3 mm, followed by a second linear range with a much weaker dependence. This suggests employing multiple substrate-coating assemblies to take better advantage of the coating; that is, use a laminate design. In addition, by incorporating the polymers in multiple layers, the mechanical stiffness of the coating is increased, which affects transmission of the pressure wave and promotes its spatial and temporal dispersion. Different laminate designs were tested, and the results compared to the ballistic performance of Rolled Homogeneous Armor (RHA; MIL-DTL-12,560), a traditional material which served as the primary military armor through the Second World War.

2. Experimental

The polymer was a polyurea (PU) obtained by reaction of 1 part isocyanate (Isonate 143L from Dow Chemical) with 4 parts polydiamine (Air Product's Versalink P1000, having a molecular weight of 1 kg/mol). The elastomeric material had a calorimetric glass transition temperature equal to −60 °C. The application of the polymer for ballistic armor is described in several publications [39,40,41,42]. The metal for the laminate was either aluminum (2024-T3 alloy) or titanium (grade 2). Plates of High Hard Steel (HHS, Mil-A-46100E; Brinell hardness ~500) or Ultra High Hard Steel (UHHS; Brinell hardness ~600) served as the substrate.

Very generally, the performance of multi-layer armor is affected by the shape of the projectile, with blunt ogives being more easily defeated [1,43]. The impact-induced phase transition, which is a primary source of energy dissipation for the designs herein, relies on rapid compression of the polymer coating by the projectile. For this reason the present experiments were limited to flat-faced projectiles; specifically, 0.50 caliber fragment-simulating projectiles (fsp; Mil-DTL-46593B). Their Brinell hardness is 285 ± 1; that is, the fsp are softer than either steel substrate, and become highly compressed and highly distorted by passage through the target. The details of the ballistic testing can be found elsewhere [44]. Briefly, projectile velocities, determined using tandem chronographs, were varied over the range 300–1500 m/s, according to the quantity of gun powder (2 to 15 g of IMR 4895). The measure of ballistic performance was V-50 (Mil-Std-662F), the projectile velocity for which there is a 50% probability of complete penetration of the target, calculated as the average of the lowest and highest velocities for complete penetration and partial penetration, respectively. The former requires perforation, either by the projectile itself or from spall, of a 0.5 mm aluminum (2024 T3) witness plate located 15 cm behind the target. Some ballistic results herein are reported after normalization by the V-50 of RHA; (Brinell ~380). A metric that include the armor weight in assessing performance is mass efficiency, defined as the inverse fractional weight reduction achieved relative to the use of RHA having the same V-50; for the latter is obtained from interpolation of data in MIL-DTL-12560J, Table A-IV.

Digital image correlation (DIC) experiments [45] were carried out at the Army Research Lab to measure deformations during ballistic testing. Two high-speed video cameras (150,000 frames/s) were used to stereoscopically track the displacement of a fiducial pattern on the backside of the target; spatial resolution was 2 mm. The projectile was the 0.50 cal fsp at a speed on impact equal to 610 ± 30, which is 84% of the V-50 of the 7.3 mm HHS substrate. This speed corresponds to a strain rate for the coating of ca. 10^5 s^{-1}. Data were acquired every 6 μs.

High strain rate compression tests of the laminates at room temperature were carried out using a split Hopkinson pressure bar apparatus (SPHB) [46,47]. All bars were 6061-T6 aluminum with a diameter of 15.9 mm and a specific acoustic impedance measured to be to 16.9 ± 1 MRayl at 1 MHz. The incident and transmission bars had a common length of 1830 mm; the striker bar was 304 mm long. An annealed copper disk was employed to shape the incident pulse and allow a more gradual rise in the applied stress. Two sample configurations were tested using the SHPB: homogeneous polyurea and a laminate made of four alternating layers of the PU and aluminum 1100-O adhered with cyanoacrylate. The areal densities (weight per unit strike-face area) were the same, with the sample geometry chosen to have a height to diameter ratio <0.5 to minimize inertial effects and friction between the sample and bar. Silicone lubricant was applied to the faces to ensure slippage. The axial strains in the bars were monitored at two locations: 900 mm from the bar/specimen interface on the incident bar and 300 mm from the bar/specimen interface on the transmitted bar.

3. Results

3.1. Ballistic testing

In Fig. 1 are ballistic results for HHS with a front-surface laminate, the latter having different numbers of component layers, with the layer thickness varied to maintain a constant areal density (=55.3 kg/m^2). Optimal performance was obtained for 8 bilayers of 0.4 mm aluminum layered with 0.2 mm PU; however, variation in ballistic performance for the different constructions was only ca. 10%. Substitution of Ti for the Al slightly reduced the V-50 (by <4%), even though the former is almost 40% higher in ultimate strength at equal weight. This minor effect on performance of the inherent strength of the layer materials is illustrated by comparing ballistic performance of identical laminates, except that the metallic layers were either 1100-O or 2024-T3 type aluminum (Table 1). The latter has fivefold higher tensile strength and an order of magnitude higher yield stress; however, it yields only a 3% increase in V-50. These results clearly indicate that it is not the strength of the laminate per se that governs the enhanced resistance to ballistic penetration.

Other details of the laminate configuration similarly have only a modest effect on performance. For example, introducing a gradient in laminate thickness increased V-50 by 2.4% at constant weight (Table