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The effect of polyacrylate microstructure on the impact response of PMMA/PC multi-laminates

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Polymer armor is widely implemented in many military and commercial applications, particularly where optical clarity is required. The impact mechanics and energy absorption mechanisms of these multi-layered structures are not well understood. This experimental study focuses on the impact response of three-layered structures consisting of poly(methyl methacrylate) (PMMA) and polycarbonate (PC) outlerlayers with various polyacrylate adhesives. Specifically, the effect of varying the microstructure of a soft interlayer incorporated into all-polymer multi-laminates is investigated. Four polyacrylates (VHB 4905, VHB 5925, VHB 4930 and VHB 4936) having a common acrylic base matrix with microstructural variations including combinations of compressible air gaps and rigid microsphere inclusions. To examine how interlayer microstructure affects impact resistance, an instrumented, compressed air driven, experimental setup is utilized to conduct intermediate velocity (9–30 m/s) normal impact testing. The setup is unique in that both force and displacement during impact are recorded independently using a shock accelerometer embedded impactor and optical displacement sensors measuring contact force and out-of-plane deflection, respectively. Quantitative metrics from the data are used to characterize and assess impact response between various configurations. Two impact velocities are tested: 12 and 22 m/s. Several correlations between adhesive microstructure and impact response are observed, including a secondary contact force decrease in multi-laminates having interlayers with microspheres and delamination in multi-laminates having interlayers without air gaps. The multi-laminates with VHB 5925 adhesives (air gaps only) showed the longest cracks and largest fracture area, which directly relates to the greatest displacements and pulsewidths, and smallest second force peaks. Increased fracture compromises structural integrity resulting in more deflection, prolonged impactor contact with the multi-laminate, and decreased elastically stored energy lessening impactor reload. It is demonstrated that this experimental methodology is capable of consistently probing and assessing the local impact response and modulation of an impact load when a multi-layered polymer includes a soft middle layer. Quantitative and qualitative effects of the interlayers' microstructure on overall impact performance are presented.

1. Introduction

The purpose of this research is to examine the role of soft polyacrylate adhesives with varying microstructures on the impact response of three-layered PMMA/PC multi-laminates using an instrumented gas gun. Researchers utilizing gas guns are typically unable to measure contact forces or sample deflection, and rely on analysis through measuring incident/residual impact velocities, and post-impact visual inspection [1–8]. Due to signal transmission issues as well as the intensity of collisions, possible target perforation, and resulting fracture of high speed impact, instrumentation can be difficult. Therefore, only a few research groups have attempted instrumentation of gas gun projectiles. Delfosse et al. used a 1.83 m long gas gun (44.5 mm inner diameter) capable of intermediate impact velocities of 7–50 m/s with an impactor instrumented with a piezoelectric accelerometer [9]. Their projectile had a trail wire leading to a digital oscilloscope as well as a relief valve to prevent double impact and to facilitate rebound of the impactor back into the launch tube. Levy and Goldsmith's gas gun was 1.37 m long with interchangeable barrels of inner diameters 6.35 and 12.7 mm capable of impact velocities from approximately 25–300 m/s. A silver-plated X-cut quartz disc instrumented the projectile and the signal is read by an oscilloscope [10]. In this paper, it is shown that an improved

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instrumented gas gun developed by this group is capable of repeatedly recording contact force and displacement data, as well as synchronizes the output of multiple sensors using LabVIEW. Using this novel instrumented experimental setup, the intermediate velocity impact response is characterized both qualitatively with fracture and energy absorption observations, and quantitatively with force and displacement sensor output. This paper examines how the impact response of a three-layered structure is modulated by the introduction of different polyacrylate adhesive interlayers. This research is of immediate value to understanding property-structure-performance relationships in developing multi-layered polymer armor.

Transparent armor is utilized in military defense applications such as personnel protection (visors/shields/goggles) and air/ground vehicle windows. Typically, these optically clear, multi-laminates are required to defeat incoming threats, withstand multiple impacts, and maintain optical clarity with minimal fragmentation and visual distortion for the user [11–13]. While glass is still implemented extensively for transparent armor because of its cost, availability, and high stiffness/hardness, the high weight and possibility of dangerous back-face spall have led researchers to investigate lighter polymer alternatives. For example, a typical 0.1 m^2 area glass-based structure could weigh on the order of 13.6 kg, but by replacing glass layers with polymers, areal density reductions of 20–30% may be achieved [14]. A typical configuration of all-polymer transparent armor consists of multiple tough thermoplastic outerlayers with rubbery interlayers. For many years, the component materials have consisted of the glassy polymers poly(methyl methacrylate) (PMMA) and polycarbonate (PC) with thermoplastic polyurethane (TPU) adhesives [15,16]. The transparency, toughness, and rate dependence of these three materials are the main reasons they are excellent choices for use in transparent armor to withstand projectile impact. Previous research by this group has compared the impact mechanics of multi-layered, impact resistant, polymer structures with two TPU interlayers and an optically clear polyacrylate with no discernible microstructure (VHB 4905) [17]. When compared to the TPUs, it was observed that the substantially more compliant polyacrylate had comparable (or superior) impact performance. Further correlation is sought between microstructure and quasi-static mechanical response of three other polyacrylates to impact performance and energy absorption mechanisms. Relationships of this sort would be useful in tailoring future polymer outerlayers and interlayers with superior impact performance for transparent armor.

The specific mechanisms responsible for improved performance of a multi-layered structure bonded by filled polymeric adhesive layers are not known. In order to improve understanding, there have been research efforts to investigate the impact performance and failure modes of multi-layered glass, metal, opaque polymer, and fiber reinforced composites [1,18–21], but few have examined all-polymer multi-layered plates. Some researchers have studied the impact response of optically clear co-extruded PC/PMMA [3,22] and various configurations of PMMA, PC, glass, and soft adhesives (polyurethane or polyvinyl butyral) in multi-laminate samples [2,14,23–29]. Experimental impact tests did not record contact force or deformation, with post-impact visual inspection and V_{50} used as performance metrics [2,14,23–26]. Therefore, other methods and metrics for quantifying impact performance are more desirable. With advancements in modeling capabilities, several of these groups numerically simulated impact, predicting fracture, perforation, and ballistic limits for various sample thicknesses and component materials [25–29]. This is helpful in determining what modes of failure/energy absorption mechanisms exist and give insight into predicting multi-laminate impact resistance. However, capturing information during impact can further contribute to understanding the dynamic response, impact mechanics, and specific energy absorption mechanisms of samples, as well as validate numerical models [30,31]. Furthermore, using both contact force and displacement data facilitates more definitive validation of computational codes, when compared to displacement data and post-impact analysis alone. Therefore, it is beneficial to have an instrumented impact experimental setup, such as described in this paper, capable of recording data during impact which characterizes both force and deflection.

This experimental work presents a systematic analysis relating polyacrylate microstructure to impact response when integrated into multi-layered polymer structures. Four polyacrylate adhesives provided by 3 M with varying material properties and microstructures (VHB 4905, VHB 5925, VHB 4936, and VHB 4930) are investigated (Section 2). Intermediate velocity (12 and 22 m/s) impact testing on three-layered multi-laminates consisting of a PMMA front, polyacrylate adhesive interlayer, and PC backing is discussed. The instrumented experimental setup and impact results, as well as energy absorption mechanisms, are outlined in Section 3. In Section 4, force/displacement metrics and interlayer microstructure are correlated to impact response, with research conclusions stated in Section 5.

2. Polyacrylate properties and microstructure

The interlayers are soft (low modulus) polyacrylates of varying microstructures and conformabilities commercially available from 3 M in the VHB family. They are used in as-received condition being tacky at room temperature. Fig. 1a shows the reported and measured material properties for the materials. Since they are polymers displaying strain rate dependence, the moduli are calculated from the linear portion of the quasi-static tensile testing results (Section 3.1). The Poisson ratio reported by 3 M for the VHB polyacrylates (0.49) is typical for elastomeric, rubbery materials and reflects near incompressibility [32]. The properties for the four VHB polyacrylates vary substantially, although VHB 4930 and VHB 4936 have comparable values for tensile moduli (0.553/0.559 MPa) and densities (800/720 kg/m^3). The densities reported by 3 M are reflected in slight variations between the masses of assembled samples with different interlayers (averages of 10). This illustrates how little the adhesive layer affects the total mass of the multi-layered PMMA/PC structure. Therefore, multi-laminate masses are relatively similar and are not considered a significant variable in the scope of this work.

Through visual inspection using an Omano OM3344 stereomicroscope, the microstructure of each material is visualized and components are identified[1]. Despite a common acrylic matrix material, the VHB polyacrylates have quite differing microstructures. Pictures shown of the top surface (45 times zoom) and representative schematics of the four polyacrylates' microstructures are shown in Fig. 1. Note that VHB 4905 has no appreciable microstructure (control) because it is a solid acrylic adhesive and may be considered incompressible (Fig. 1b). VHB 5925 has collapsible air bubbles of varying sizes ($\sim$100 μm) with a distribution of approximately 44.4 per mm^2 and therefore is considered somewhat compressible (Fig. 1c). VHB 4930 is similar to VHB 4905 in that it is solid acrylic and may be considered incompressible, but has rigid microspheres of equal diameter ($\sim$70 μm) dispersed at approximately 100 per mm^2 (Fig. 1d). Like VHB 5925, VHB 4936 has compressible spaces but also has microspheres (Fig. 1e). In summary, VHB 4905 and VHB 4930 may be considered incompressible with a solid acrylic structure, VHB 5925 and VHB 4936 are

[1] Microstructures were verified through several discussions with a 3M technical service scientist.