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THERMOPLASTIC MATRIX COMBAT HELMET WITH GRAPHITE-EPOXY SKIN

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ABSTRACT

An advanced molding process has been developed for manufacturing ballistic helmets comprised of thermoplastic (TP) resin matrix composite materials reinforced with para-aramid fibers, woven fabrics, unidirectional fiber architectures and structural graphite-epoxy skins. The developed TP matrix ballistic helmet design is thinner and lighter than the current PASGT helmet, meets the durability requirements of any practical helmet and has superior ballistic resistance against a range of fragmentation threats. This paper discusses the design, manufacturing and testing of these hybrid (reinforcement and matrix) composite materials that balance the ballistic performance and stiffness requirements of the ballistic helmet design utilizing thermoplastic matrix resins, para-aramid fabrics, and graphite-epoxy skins. This new TP matrix helmet molding technology is also potentially cost competitive because it takes advantage of 80% of the existing helmet manufacturing infrastructure.

INTRODUCTION

One of the US Army greatest challenges has been to reduce the weight of personnel body armor carried by a soldier, including ballistic vests and helmets. Previous studies [1] have identified material combinations that could meet both structural and ballistic requirements at lighter weights. More compliant matrix ballistic materials suggest the potential for greater ballistic efficiencies than the existing helmet materials. High ballistic efficiency fibers such as p-aramid, PBZ and ultra high molecular weight polyethylene (UHMWPE) when combined with thermoplastic matrices will improve the ballistic protection beyond that afforded by the incumbent phenolic thermoset resin systems. Hybrid designs using the new ballistic materials with structural composite skins can reduce trauma and durability limitations with these more compliant laminates. To mold helmets from this new class of materials, a thermoplastic forming process will require rapid temperature cycling and cycle times of the order of 15 minutes to compete with current thermoset based processes.

BACKGROUND

Currently, the existing thermoset (actually a 50/50 blend of the phenol thermoset and a poly vinyl butyral thermoplastic toughener) PASGT (Personnel Armor System Ground Troop) helmet has an areal density of approximately 330 oz/yd^2 (2.30 psf). It is manufactured using 1500 denier Kevlar® 29 yarn in a 2x2 basket fabric construction that weighs 14.0 oz/yd^2 (475 g/m^2) [2]. The fabric is impregnated with 16-18% by weight of Polyvinyl Butyral (PVB)-phenolic resin. The helmets are fabricated by assembling a helmet preform using 19 equivalent layers of prepreg. These layers are then compression molded at constant temperature and rather substantial compression pressures using self-trimming matched metal molds at a rate of one helmet every 10-15 minutes. Because of the thermoset (TS) nature of the PVB-phenolic resin matrix, molding of the standard PASGT helmets requires constant temperatures between 320-355 ^{o}F (160-180 ^{o}C) and pressures well over 500 psi for roughly 15 minutes on average for the resin to fully cure.

Although the MIL-H44099-A [2] specification for PASGT helmets requires a ballistic performance with probabilistic limit velocity, V50(f/s), of at least 2000 f/s, most PASGT helmets measure around 2100 f/s V50 against 17 grain fragment simulators projectiles (fsp) during quality assurance lot testing.

Since the late 1980s thru the 1990s, improvements with ballistic performance and weight reduction of PVB-phenolic aramid fabric helmet systems have been achieved. One helmet design of particular interest is the 850 denier Kevlar® KM2 fiber system developed by DuPont in 1990 [1], as described in Table 1.

Table 1. PVB-phenolic Matrix PASGT and Kevlar® KM2 Helmet Systems

Properties	***PASGT Helmet***	***Kevlar® KM2 Helmet***
Areal Density, psf	*2.30*	*1.95*
Yarn Denier / Fiber	*1500 denier, Kevlar® 29*	*850 denier, Kevlar® KM2*
Fabric Construction/Weight	*2x2 basket, 475 g/m^2*	*31x31 plain weave, 234 g/m^2*
Matrix Resin / Weight Fraction	*PVB-phenolic, 16-20%*	*PVB-phenolic, 16-18%*
Molding Process	*Compression Molding*	*Compression Molding*
Molding Cycle time, min	*10-15 min*	*10-15 min*
V50(f/s), 17 grain fsp	*2,100 f/s*	*2,200 f/s*

The KM2 helmet innovation produced a 15% lighter helmet shell with superior ballistic performance to the incumbent Kevlar® 29 PASGT helmet system. This improvement was achieved mostly by using a higher toughness Kevlar® fiber than the 1500 denier Kevlar® 29 used in the standard PASGT, finer Kevlar® yarn denier, greater ply count and a special fiber surface treatment to control the adhesion strength between the PVB-phenolic resin and the fiber surface.

THERMOPLASTIC MATRIX COMBAT HELMET

Design

Based on the known better ballistic performance of TP matrix composite materials, a helmet area density of 1.75 lbs/ft^2 was selected as an objective to provide the US Army with a weight reduction of almost 25% from the US Army PASGT helmet standard.

The PVB-phenolic matrix was chosen as the control composite system and the PASGT helmet as the standard geometry. The use of the PASGT geometry was selected for several reasons. First, a large database of ballistic performance and combat experience has been collected for this geometry. We would like to compare performance of the new materials to the current material without introducing effects related to shape. Second, expensive matched metal compression tooling exists and is readily available. And lastly, the PASGT geometry is conservatively complex so that one could argue that if capable of molding the PASGT, then one would be capable of molding most other geometric variants.

Once the area density of 1.75 lbs/ft^2 was defined as the helmet weight, the wall thickness of the helmet was estimated. By utilizing woven aramid fabrics and knowing that the standard 2.30 psf PASGT Kevlar® helmet is currently fabricated with a 350 mils (0.350”, 8.9 mm) wall thickness, the estimated wall thickness of a helmet that weighs 1.75 psf is calculated at 280 mils (0.28”,7 mm). Of course some of these estimates are approximations since the later will require the use of structural skins of higher density.

Thermoplastic Matrix Helmet Composite Materials.

To achieve the required ballistic performance we selected two different thermoplastic matrix composite systems with para-aramid fiber reinforcement: a) 600 denier Kevlar® KM2 woven fabric coated with a DuPont proprietary thermoplastic resin with a weight ratio of 16-18%; and b) 850 denier Kevlar® KM2 fabric coated with an INTER Materials proprietary thermoplastic resin.

INTER Materials selected the 850 denier Kevlar® KM2 fiber to facilitate the comparison and improvements on ballistic and structural performance between the KM2 helmet systems previously developed by DuPont and the new TP matrix combat helmet.

INTER Materials selected its proprietary thermoplastic resin because of the ballistic performance improvement achieved during a research program of composites for vehicle armoring [3]. Although the objective of the car armoring research program [3] was to develop a thin, flexible and thermo-formable ballistic composite panel to stop hand gun bullets at the NIJ Level IIIA, a statistically significant increase in ballistic performance was obtained when using INTER Materials thermoplastic resin compared against the ballistic performance of PVB-phenolic composites with identical reinforcement architectures.

For the structural reinforcement, we selected a 2 ply 0/90 IM7 graphite-epoxy prepreg that weighs 448 g/m^2 (13.2 oz/yd^2) as the skin on the striking face and two layers of 850 denier Kevlar® fabric with PVB-Phenolic resin on the outside. Other fiber materials and other resin systems were considered, but this particular prepreg was readily available, had compatible cure requirements (250^{o}F) and provided very high flexural stiffness once cured. Chemical compatibility with the class of TP resins used in the ballistic layers was confirmed by simply molding flex bars and visually inspecting for resin migration and performing short beam shear tests to confirm adequate interlaminar adhesion between ballistic core and structural skin. The ballistic resistance of the structural skin is assumed to be negligible, and when the requirement to keep the areal density to the set limit of 1.75 psf is maintained, this requires a reduction in the amount of ballistic material that remains. This only complicates the design by requiring higher performance from the remaining ballistic layer. We also knew that having structural skins on both inside and outside shell surfaces would have improved the structural rigidity, but recognized that the stiff layer on the inside would negatively affect the ballistic resistance of the entire hybrid shell. Further design candidates limited the structural skin to the outside of the shell. We later concluded that while this location had least detrimental effect on ballistic performance, the particular graphite systems we considered actually improved the ballistic performance slightly for the smallest, fastest fragment simulators.

For most of the helmet prototypes, we used the graphite/epoxy skin as a sandwich of 2 ply 0/90 graphite/epoxy prepreg between two layers of Kevlar® KM2 fabric coated with PVB-phenolic resin for better chemical compatibility and for easier surface release during the forming and molding steps. The graphite/epoxy skin with the two layers of 850 denier KM2/PVB-phenolic weighs 30.0 oz/yd^2 (1.0 kg/m^2). This structural "pack", like the remaining ballistic core involves pinwheel geometries that unfortunately include several legs of narrow width. These cut edges of the pinwheels are distributed evenly through the preform by staggering the orientation of one ply after another. The objective of avoiding such need to cut and overlap in order to form the shell with minimal wrinkling remains a challenge to the preform assembly.

Testing

Based on the Advanced Combat Helmet (ACH) solicitation first article testing requirements, the TP matrix helmet ballistic performance was required to meet or exceed the same minimum ballistic limits, V50 (f/s), listed in Figure 1.

RCC Fragment Simulator Projectile (fsp), grains	Ballistic Limit, V50 (f/s), Minimum
2	4075
4	3450
16	2425
64	1700
17	2200
9mm RTP/BFD	1400+50, no penetration

Figure 1. ACH First Article Ballistic Testing Requirements

Before any candidates of various hybrid skin / core combinations were evaluated ballistically, they were first subjected to mechanical screening tests. Rectangular bars, sectioned from flat plates were flexed in short beam shear and 4 point flexure to compare relative stiffness to the PASGT system. All of the TP materials are lower in both flex strength and stiffness, but the use of the structural skins brings the behavior closer to what we feel is necessary. From the highest flexural performing material combinations, we selected several for molding into prototype shells. These shells were then subjected to cyclic loading representative of what real helmets would experience. Those candidate systems that were found to be reasonable from a durability perspective were then selected for subsequent ballistic evaluation. Preliminary ballistic testing of flat plates and helmets was performed by both INTER Materials at H.P. White in Street, Maryland and the US Army Research Lab at Aberdeen Proving Grounds.

In addition, one of the ACH structural requirements was to meet the side-to-side ASTM D-76 Compression Test. The test procedure includes placing the helmet in a 2.5” flat loading anvil, centering the helmet on the widest part of helmet shell, compressing the shell at a rate of 12 inch/min until 300 lbs are reached, and releasing the load down to 5 lbs and repeating this loading cycle for another 24 times. After the loading cycle, measure the change in dimension to be less than 0.125” immediately after the 25 loading cycles (within 5 minutes) and to be less than 0.100” after 24 hours. This test is performed on shells conditioned at room temperature and humidity. Other mechanical tests and environmental exposure are required of helmets purchased under the ACH specification, but for this development effort, we selected the test above as the sole structural screening procedure. Any candidate hybrid system which clearly failed this test was excluded from subsequent ballistic evaluation.

BALLISTIC PERFORMANCE

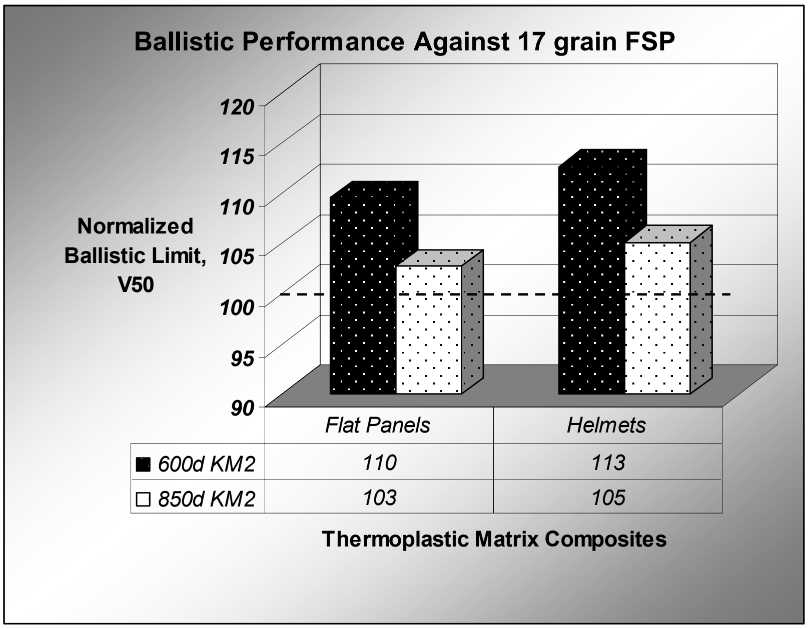
Flat Panels and Helmets

Preliminary ballistic testing with 17 grain FSP and 2 grain RCC fragment simulators using 15”x15” flat panels and molded helmets of areal density 1.75 lbs/ft^2 are very encouraging and are summarized for the 17 grain FSP in Figure 2. In Figure 2, the Normalized Ballistic Limit, V50, of 100 corresponds to the V50 of 850 denier KM2 with PVB-phenolic flat panels at 1.75 psf areal density.

The same trends are exhibited with the 2 grain fragment simulator. One should note that ballistic testing involves considerable variation from many sources. Before scientific comparisons can be made, sample set sizes need to be increased and proper statistical interpretation then allowed. These two fragment sizes represent the middle and smallest of the entire distribution, but classically the smaller sizes at higher velocities are usually the more difficult to accommodate. We chose to do the preliminary screening with these and expect to test with the remaining fragment sizes and 9 mm 124 grain full metal jacket (FMJ) bullets once a final material combination is selected. This same screening approach will be applied when we explore the many variations of molding process, with a complete test series following final process selection.

STRUCTURAL CHARACTERISTICS

Preliminary structural testing of molded helmets was performed at the USARL. Depending upon the graphite-epoxy reinforcement layout and helmet molding conditions, several of the helmets were found to meet the structural requirements of less than 0.100” permanent deformation following completion of 25 loading cycles under compression at a rate of 12 inch/min from 300 lbs load down to 5 lbs. Several shells failed miserably. It appears that the molding process has significant influence upon the subsequent flexural response. We infer that the structural skin is fragile



	Flat Panels	Helmets
■ 600d KM2	110	113
□ 850d KM2	103	105

Figure 2. Ballistic Performance Comparison between TP Matrix Composite para-Aramid Flat Panels vs. Molded Helmets.

and requires care in molding to avoid damage prior to the finished shell. Having a preform of relatively dense constitution prior to high pressure forming is preferred. A complete bond between skin and core is necessary, especially near the cut edge of the shell. If delamination in this region is created by either the molding or trimming, it must be repaired in a subsequent step. Fiber continuity between the outside layer and the inner ballistic layer will result in better structural response. The molding process will likely require careful application of the higher pressures to ensure that the fragile skin is properly coupled to the core but not damaged during this step. For this reason, it appears that structural performance can only be determined on shell geometries from well-controlled molding cycles, including control of the pre-forming step. This observation is repeated for ballistic performance.

DISCUSSION

Within the statistical distribution of the ballistic limit V50 (ft/s) results with the 17 grain fsp, the two composite materials with thermoplastic matrix using para-aramid fibers in woven configurations met or exceeded the ballistic requirement in panel and helmet form. Those TP matrix composite material systems are 600 denier Kevlar® KM2 and 850 denier Kevlar® KM2. The two woven fabric systems have different basis weight and ply count with two different TP matrices. A common molding process was used because we wanted to avoid having the molding conditions be a parameter when we compared the different materials and architectures.

As suggested in Figure 2, there appears a difference in ballistic performance of the TP matrix composite materials between the groups of flat panels and molded shells. In general, ballistic limit increases with decreasing ply basis weight of the laminate. Lower ply basis weights and greater ply count for the same final areal density seems to suggest better ballistic efficiency, at least for the fragment sizes and velocities we considered.

Taking into consideration that both the fiber and the TP matrix are different for each composite system, preliminary data shows that both TP matrix composite systems, 850d Kevlar® KM2® and 600d Kevlar® KM2®, not only performed well as a flat panel but their ballistic performance increased as a molded helmet. However, the 850d Kevlar® KM2 TP matrix composite system performs against 17 grain fsp similarly as the 850d Kevlar® KM2 system with PVB-phenolic matrix.

Curiously enough, at similar areal densities, para-aramid fabrics with PVB-phenolic have previously [1] displayed on average 100 ft/s higher ballistic performance V50 (ft/s) against 17 grain fsp as a molded helmet than as a flat panel. The leading explanation for this trend is that especially around the sides of these ballistic shells, the effective ply count is greater than the number of pinwheels due to overlap of the pinwheel legs, hence higher areal density. These observations suggest that the molding process, preform design, and material combinations are all coupled. The final ballistic performance cannot be independently correlated to any one of these. While during screening these trends may identify optimums, we will have to adjust the designs following testing performed on finished shells from various process adjustments. This is compounded by the need to hybridize the ballistic and structural requirements in a common molding cycle that makes economic sense.

CONCLUSIONS

We provide a preliminary demonstration of the ballistic performance of flat panels and helmets that meet or exceed the ballistic requirements of a minimum 2200 ft/s V50 against 17 grain FSP with the two composite material systems under investigation. These TP matrix composite material systems are woven 600 denier Kevlar® KM2 and woven 850 denier Kevlar® KM2.

Most important, USARL and INTER Materials have now demonstrated that the ballistic and structural performance of some hybrid TP matrix ballistic helmets as shown in Figure 2 met or exceeded at least some of the ballistic and structural requirements.

Particularly consistent were the TP matrix ballistic helmets made with 600 denier Kevlar® KM2. They met the structural requirements of a change in dimension to be less than 0.125" immediately after the 25 loading cycles (within 5 minutes). They also exceeded the ballistic requirement of a minimum V50 (ft/s) of 2200 ft/s against 17 grains FSP and 4075 ft/s against 2 grain RCC.

We may have identified some material combinations that have the potential to replace the incumbent PVB-phenolic systems, but the manufacturing process required to produce the finished helmet remains to be developed. We have identified some molding options that require further optimization with attention to both cost and performance [4]. It's also quite likely that other fiber reinforcements such as UHMWPE would benefit from such process developments.

Efficient and consistent processes to employ the hybrid TP/TS materials in the helmets manufacturing industry have not yet been demonstrated. Therefore, a business opportunity exists to develop a new manufacturing process to mold thermoplastic matrix composite ballistic helmets with structural TP or TS skins. The innovative INTER Materials approach to this process will utilize much of the existing PVB-phenolic helmet manufacturing base infrastructure as a means to make it economically viable.

ACKNOWLEDGEMENT

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