Army Research Laboratory

The Development of a Hybrid Thermoplastic Ballistic Material With Application to Helmets

by Shawn M. Walsh, Brian R. Scott, and David M. Spagnuolo

ARL-TR-3700 **December 2005**

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14. ABSTRACT

U.S. helmet material technology has changed relatively little since the introduction of aramids in the 1970s. All U.S. Army ballistic helmets use woven aramids with a thermoset (toughened phenolic) resin system. The current research explores the use of thermoplastic (polyolefin-based) matrix material. Although thermoplastic aramid systems have been evaluated for specialty applications, they have often failed to meet all the stringent criteria required of a U.S. Army helmet system. The present work seeks to remedy this by investigating hybrid ballistic material solutions. The combination of mass efficient ballistic and independent structural materials provides a means of meeting the spectrum of performance requirements demanded by U.S. Army helmet specifications. In addition to this, a series of helmet prototypes has been produced, which explore alternate design methods for selectively stiffening the core ballistic shell. Preliminary normalized performance data are presented that demonstrate the improved mass efficiency of the hybrid ballistic material solutions. This work summarizes the U.S. Army Research Laboratory's initial development of a candidate ballistic material solution to meet the Future Force Program requirements.

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1. Introduction

U.S. Army transformation is one of the largest efforts in modern times to reshape the overall structure and function of ground forces. It is designed to respond to a host of new and emerging threats, and it explicitly recognizes the need for and vulnerability of electronically based systems on and off the battlefield. Indeed, U.S. Army transformation features the Future Combat Systems (FCS), which is a "system of systems." The prominent theme in this new reshaping of the Army is emphasis on strategically arraying and integrating as many technologies together to provide an overwhelming and decisive advantage in hostile environments.

The emergence of electronics on the battlefield has been incremental. The impact of this is being re-thought as part of the U.S. Army transformation. The goal is not only to ensure overall integrated system effectiveness but to minimize any potential weight and human performance penalties associated with incorporating this technology on and around the Soldier. Many mobile electronic systems bring a concomitant requirement for power, and thus battery weight and efficiency, together with other novel power-generating and storage technologies, are a key focus of Army transformation goals.

The addition of state-of-the-art electronics systems and power systems has stimulated a total redesign of the overall Soldier system ensemble. The goal is to provide an effective, flexible, and lightweight system that enables the Soldier to rapidly and successfully do his or her mission. The challenge is integrating the lethality, survivability, and other technologies onto the Soldier without causing the overall system weight to impede the Solider's ability to execute a wide variety of tasks.

New designs for the Soldier-borne uniform and equipment are being developed, tested, and revised, based on a variety of human factors and other types of testing. Key to this system development is the use of alternate materials to shed weight from conventional systems. The U.S. Army transformation has provided a stimulus for pushing the limits of conventional materials and has opened the opportunity for the consideration of new materials and material combinations. These materials may also include hybrids to maximize the overall system performance while minimizing weight.

2. Background

Helmet materials and designs have evolved primarily in light of prevailing threats and the invention of new and improved ballistic materials. Figure 1 is a basic summary of U.S. helmet designs and materials since World War (WW) I. For example, the helmet designs in WW I were significantly different than in WW II. WW I was characterized by an unprecedented amount of trench warfare, and the hot, sharp debris falling from relatively high angles was typical. This gave rise to the fairly wide "brim" that gave the WW I helmet its distinctive look.

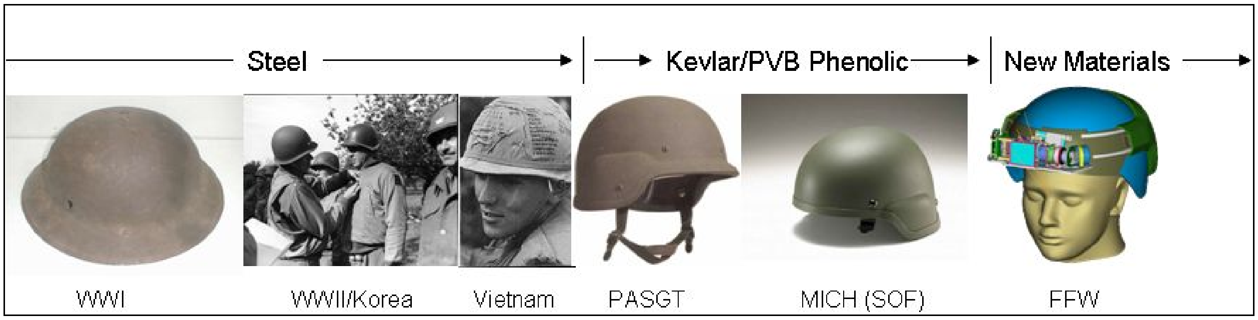

Figure 1. Historical perspective of U.S. Army helmet design and materials.

Ballistic helmets today reflect combat experiences learned from WW I to contemporary deployments of personnel and equipment. With the advent of trench warfare, fragmentation from exploding ordnance was the predominant source of injury and death to troops on the front line. The randomness of the shrapnel threat forced the design of protective head gear to cover not only the very top but also the sides, front, and back of the Soldier's head. The original French and British designs of WW I were adapted by the U.S. Army and involved formed Hadfield steel bowls with web-based suspensions. Weight, comfort, and protection level influenced the eventual redesign of the fragmentation helmet to become the famous M1 helmet of WW II. This steel outer shell used a molded inner shell to attach the suspension made of cotton webbing and leather. The composite inner liner nested into the ballistic steel shell. The inner liner, introduced in 1941, was made of cotton fabric-reinforced phenolic laminate. An improved ballistic version of the liner, fielded in 1961, used nylon fabric to replace the cotton. The combined shells provided higher protection levels over a greater coverage area than the previous M1917 copy of the British Mk I "Brodie" helmet of WW I. The one-size M1 helmet weighed 1.55 Kg, had 0.12 square meter of surface coverage, and protected against the 0.45 caliber round at 244 m/s with a 50% ballistic limit of 396 m/s against the standard NATO (North Atlantic Treaty Organization) 1.1-gram fragment simulator.

In the early 1960s, the U.S. Army embarked on an experimental effort to replace this two-part helmet design with a single-walled, lighter and more protective configuration. Composite materials were considered because of their known higher ballistic efficiencies. Glass fiber and nylon reinforcements were evaluated in the same toughened phenolic as was used in the earlier liners. With the invention of Kevlar[1] in 1965, it became immediately obvious that what could be done with nylon would be done better with this high strength polymer. Kevlar was commercially available in 1972, with the U.S. Army already evaluating it late in the 1960s. As is most often the case, a direct substitution of the newer, stronger fiber from the previous one showed less-than-optimal improvement. With considerable development effort, the "steel pot" M1 helmet

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[1] Kevlar is a registered trademark of E. I. DuPont de Nemours & Co., Inc.

was gradually eliminated from the U.S. inventory in the late 1970s and replaced with the improved Kevlar design called the Personal Armor System for Ground Troops (PASGT) in 1976 (*1*). The PASGT originally had three sizes, now four. Throughout the development, improvements in protection level (50% ballistic limit now 610 m/s), area of coverage (0.14 square meter) and better fit (1st to 99th percentile of the U.S. military population) were achieved while the same weight was maintained as for the M1.

The PASGT has found much praise from the troops; it has saved many lives, including the civilian police forces who have now adapted it. It has proved itself in field use, which suggests that its durability is also adequate. The laminated material from which it is formed is not ideal structurally, however. A low resin content (roughly 20% by weight), multi-ply fabric architecture and high porosity was selected primarily for its ballistic attributes, and one would expect that it could exhibit problems with durability or blunt trauma (lower flexural rigidity would suggest more deflection and lower structural capacity). With its standard wall thickness of 9 mm, it barely meets the practical requirements.

Since this very successful introduction, the desired trend has been related to weight reduction. Complaints related to comfort, hearing acuity, and relative motion or mobility and the desire to mount additional devices as noted earlier have required the shell material to provide equivalent protection at reduced weight. Research into higher efficiency materials has moved toward more compliant laminates with stronger reinforcements. The advanced combat vehicle crewman (ACVC) helmet was fielded in the late 1980s with less coverage but equal protection at reduced weight where it did cover. The U.S. Army type classified this new helmet material with the newest Kevlar KM2 fiber (*2*), but several design details were also changed. Besides the shell thickness being reduced to 7.6 mm, the fiber denier was reduced, the fabric style changed, the ply count increased, and fabric interface was adjusted to include a flouropolymer coating. The amount and type of laminating resin remained the same, but the overall trend was toward higher compliance of the final laminate. The KM2 fiber was stronger and tougher than the previous Kevlar 29 fiber. It is believed that both of these changes resulted in the higher performance. The identical material modification was evaluated for replacement of the PASGT and actually followed through the necessary evaluation cycle but was not selected for major procurement because significant weight reduction was less than perceived (15%). Its field durability has not been demonstrated to the same extent as PASGT.

Beginning in the early 1990s, the desire was to reduce the weight of the PASGT by at least 25%. The U.S. Marine Corps started a development program that evaluated several candidate materials with higher ballistic efficiency. Materials such as Spectra Shield[2] or Kevlar Mark III[3] used alternate resin systems, fiber materials, or laminate architectures. Both were successfully molded into PASGT geometry and found to meet the ballistic and weight goals. Both failed to address the less-defined durability requirements, largely because of the higher flexural

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[2] Spectra Shield is a registered trademark of Honeywell.

[3] DuPont proprietary coated fabric prelaminated material

compliance of either material. Brief attempts to resolve the structural limitations were not able to satisfy the program schedule, but initial ideas to make the final structure a hybrid with structural skins or rib reinforcement were proposed.

Since then, two new helmets have been produced for the U.S. military. The first is now called the advanced combat helmet (ACH) and was previously provided by the Army for special operations as the modular integrated communications helmet (MICH). This helmet uses a higher strength Kevlar K129, lower content phenolic resin (thus higher fiber content for the same weight), modified edge cut for lower protection surface, and a new suspension system for better comfort and possibly trauma reduction. With a shell thickness of 7.8 mm and lower resin content, it will have higher structural compliance and potentially the same limitations of the earlier lightweight helmets. The other helmet in current U.S. production is the new lightweight Marine Corps helmet. This helmet uses a higher strength fiber, Twaron[4], with properties similar to Kevlar 129, and with the same phenolic resin, is expected to perform ballistically and structurally similar to the ACVC material described earlier. The geometry is the same as the PASGT, but the wall thickness is less, so the overall performance is similar to the lightweight PASGT.

The future in helmet design may follow what we are describing in this report. The Kevlar Mark III and Spectra Shield materials noted before involve thermoplastic resin matrices and are relatively flexible. If the ballistic requirements at reduced weight can be met with these materials, then future development efforts will likely focus on meeting the structural (durability) and trauma (transient deflection) constraints. Hybridization with structural skins is logical and should have a high probability of success. How to manufacture finished helmets from these new material systems in a practical, cost-efficient manner also remains to be demonstrated. One such example is with the Tepex[5] (*3*) system now in production for the Norweigan military. Claims are made of complete molding cycles of less than 5 minutes, without the need of extensive hand pre-forming. Certainly the existing manufacturing infrastructure will have a significant influence in defining the initial capital investment and subsequent unit cost. What may be of particular interest is how to modify existing production equipment to allow for the thermoforming of thermoplastic matrix composite materials. Identifying the proper combination of fiber, resin, reinforcement architecture, and manufacturing process for specific requirements is the goal of our present study. Some trends have already been identified. Beyond the increased compliance, we know that higher ply count and lower basis weight layers will improve ballistic efficiencies. Reducing the frequency of cutting and tacking will increase effective fiber length but will introduce wrinkling issues. Lowering the resin content or weakening the resin-fiber interface will promote delamination and deflection which introduce positive and negative attributes. Through-the-thickness reinforcement will similarly control the extent of the deflection. The most obvious parameter is the ratio of ballistic to structural material used in any hybrid architecture. The orientation of each is also a variable. Fabric architectures that allow for

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[4] Twaron, which is a registered trademark of Teijin, is a synthetic fiber made from aramid polymer.

[5] Tepex is a registered trademark of Bond-Laminates GmbH, Germany.

conformal draping without tacking is highly desirable, but the amount of necessary in-plane distortion may have limitations.

Certainly as new high strength reinforcement fibers are introduced, they need to be evaluated in this ballistic application. It is somewhat universally agreed that higher specific strength fibers with sufficient toughness (strain energy capacity or high elongation) should be good candidates for lighter weight helmets. Newer polymers such as pyribenzamine (PBO[6]), MePPD-TA (*4*) or M5[7] (*5*) may suggest great potential but may exhibit other limitations or may simply not be commercially available. The resin systems may also exhibit similar limitations, especially around thermal stability and environment degradation. In addition to the subject areas of structure and ballistics noted already in this report, the practical issues around cost, availability, and environmental susceptibility will ultimately factor into what materials are good candidates to replace the incumbents.

There are a number of promising materials on the horizon, most notably a relatively new organic fiber with a complex molecular structure known as M5 (*6*). M5 is attractive based on initial properties (strength 4 GPa, modulus 330 GPa, and elongation 1.5%). However, to date, M5 has been produced in only small, laboratory production runs. There are still significant issues to resolve. Even when M5 does become commercially available in sufficient quantities, it will likely be expensive, given the capital investment and development costs. As such, the U.S. Army Research Laboratory (ARL) has proposed an incremental approach that will first establish thermoplastics and thermoplastic-based matrices as viable candidates for fabricating helmet shells. The advantage of this approach is the ability to reap the near-term benefits of commercially available thermoplastic matrix aramids, such as Tepex (*3*) and Mark III as well the ability to "spiral in" new fibers such as M5 (figure 2).

The Future Force Warrior (FFW) is a major element of the Army transformation. FFW is responsible for defining not only the type of materials, equipment, and systems that the Soldier will wear and use but also the hardware and software necessary for the Solider to be part of a larger "network." Current Soldiers configure their equipment, depending on the mission (figure 3a). While this flexibility is desirable, a major problem with this approach is the tendency to burden the Soldier with too many discrete systems. Such systems include IR cameras mounted on the helmet, communication devices on the side of the helmet, and so on. FFW is focused on streamlining these functions by determining what hardware is to be integrated into or onto a helmet as well as those devices that will be modular in nature. More importantly, FFW is focused on redesigning a helmet that allows for optimal integration and modularity, as shown in figure 3b.

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[6] PBO (ZYLON) is a new high-performance fiber developed by TOYOBO; ZYLON is a registered trademark of TOYOBO and consists of rigid rod chain molecules of poly(p-phenylene-2,6-benzobisoxazole)(PBO).

[7] poly{2,6-diimidazo[4,5-b:4',5'-E]pyridinylene-1,4-(2,5-dihydroxy)phenylene}

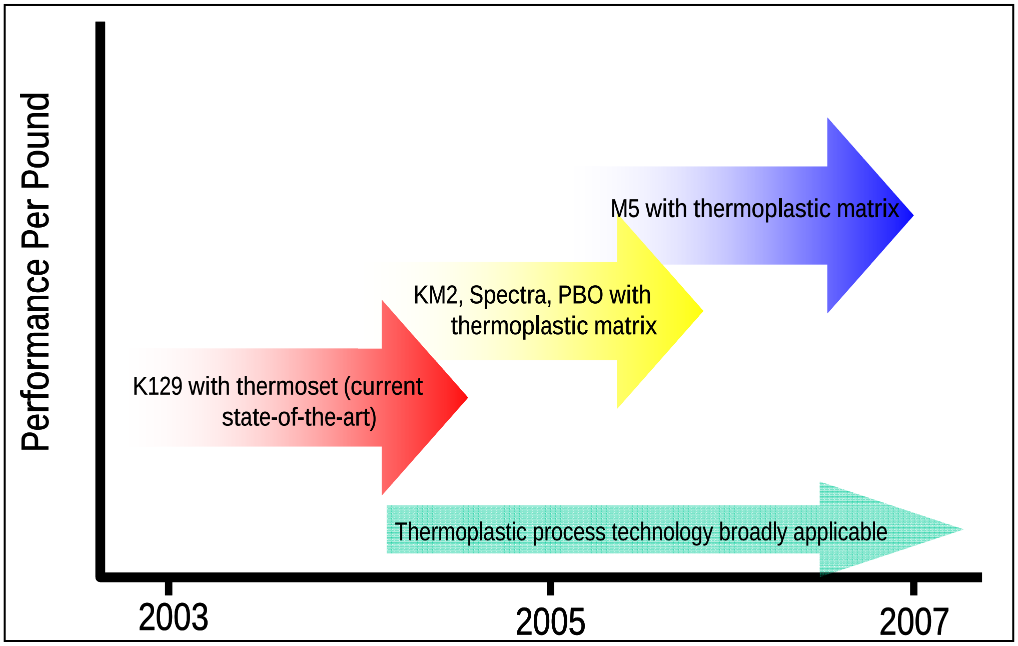

Figure 2. Transition of new helmet materials.

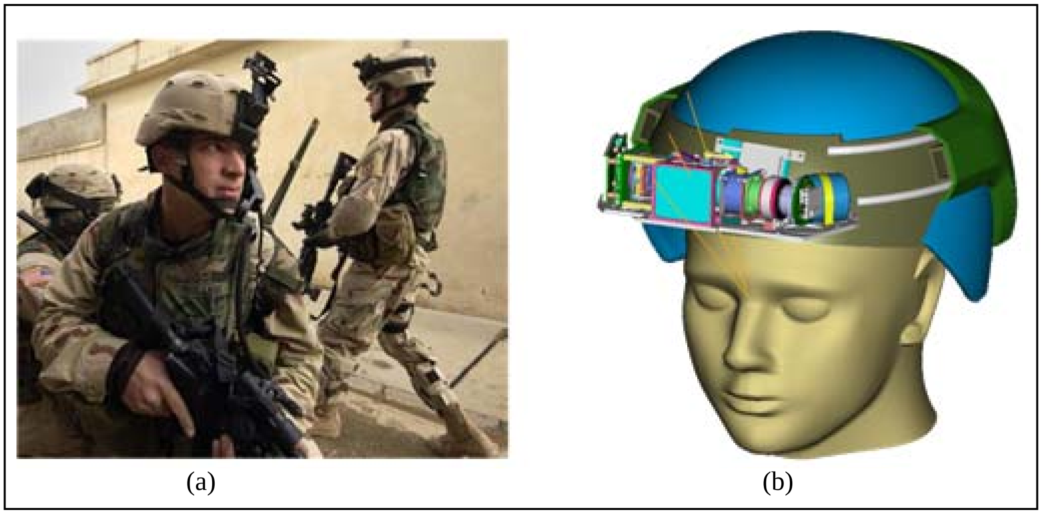
(a) (b)

Figure 3. Current and a future U.S. Army helmet systems.

The new helmet architecture, together with the integrated electronic sensors and other devices, will demand a balance between the enhanced functionality and the overall weight of the helmet. Indeed, in the FFW program, the helmet is now referred to as "headgear" and as such implies a system rather than materials or assembly of discrete components. Furthermore, the FFW ensemble is divided into two basic parts: "neck up" which includes all the systems and functions associated with the headgear, and "neck down," which encompasses the uniform and other equipment attached to the Soldier's body and extremities. An early prototype of this type of integrated system, known as Scorpion, is shown in figure 4. Weight reductions will be achieved in at least two ways. The first is by shrinking the active devices by further miniaturizing the electronics, power, and packaging of these sub-systems. The second will be in developing materials (and combinations of materials) that will enable weight reductions in the helmet shell, suspension system, comfort liners, etc. The design and material selection for the FFW headgear is a highly coupled process, especially when one considers the physical linkages to neck-down systems.

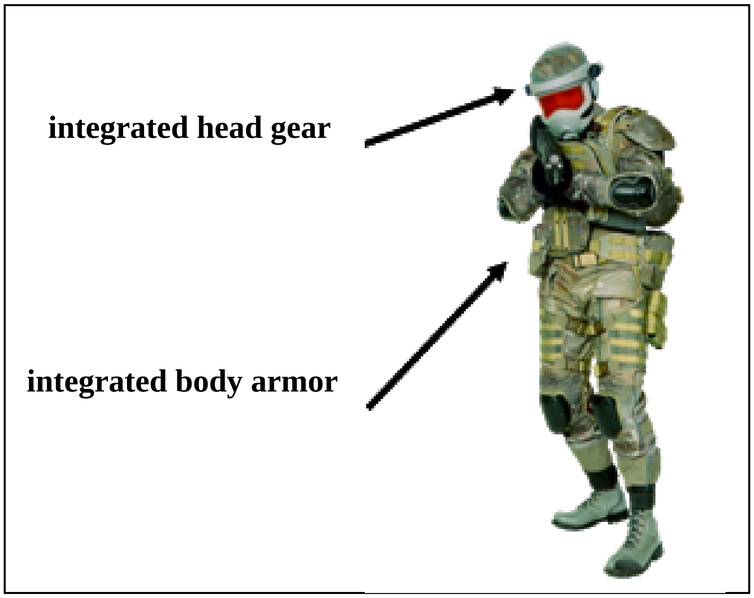

Figure 4. Coupling of headgear and body-borne systems.

3. Helmet Design and Material Considerations

3.1 Ballistic Resistance

The primary goal of the helmet shell is to protect the Soldier from a variety of threats. First, the requirement is to limit the perforation of fragments or bullets through the helmet. Even if the fragment is stopped, the deflection of the shell can engage the skull and cause injury. The current PASGT uses an effective air gap of approximately 13 mm between the inner shell wall and the Soldier’s head to accommodate any deflection during projectile arrest. Deflections greater than this will likely engage the skull, but whether this engagement is lethal is unclear. Recent studies at the University of Virginia and Natick Soldier Center, Massachusetts, have suggested that there is a threshold of impulse or force that is likely to cause serious trauma. An alternate test protocol is proposed that would measure such an impulse delivered to the skull during controlled test conditions. It is obvious that lower impulse and extent of deflection is desirable in order to minimize the probability of death.

The current study described in this report simply measures the relative amount of free field deflection in a consistent impact loading condition. We are using high speed video techniques to measure the peak deflection during the arrest of a 1.1-gram fragment simulator at an impact velocity just below the limit velocity of the candidate material system. This testing has been performed on flat plate samples with partial lateral support. Whether this configuration can be related to the needed trauma requirement is uncertain. We can surely identify relative differences in the extent of transverse deflections for various material combinations and quantify the relative trade-offs among weight, structural durability, and the extent of lateral deflection.

The general method for characterizing a material's ballistic performance is to conduct a V_{50} ballistic test. A V_{50} is defined as the velocity at which there is an equal probability of a partial or a complete perforation for the given armor and threat. Security classification becomes critical when both the threat and armor are discussed or presented simultaneously, especially if the mass efficiency of the armor is significant. Screening monolithic and hybridized materials can be a lengthy and costly undertaking, given that an extensive amount of data needs to be generated in order to build requisite confidence in the performance of a given ballistic material "solution." As such, researchers tend to choose threats that are known to be difficult to defeat, such as small fragments at high speed. Bullets such as the 9 mm are also difficult to arrest with particular challenge of the transient deflections from the relatively large mass of the 9-mm projectile. Note that Europe tends to emphasize a 1.1-gram fragment simulator rather than a 1-gram right circular cylinder surrogate. In general, the required V_{50} for U.S. fragment simulators is higher than that required by European standards. Ballistic testing can be complicated by hot and cold testing requirements. Thermoplastics, for example, tend to soften at higher temperatures. This softening can translate into improved ballistic performance; however, it can also undesirably increase the transient deformation and reduce the structural rigidity of the helmet.

3.2 Transient Deformation

Transient deformation is a direct result of the kinetic energy being dissipated within the ballistic material. It is concomitant with the ballistic impact and it plays a very significant role in determining the design and materials selection of a helmet system. Fabrics, although extremely ballistically resilient at areal densities around 0.975 gram per square centimeter, tend to deform significantly. The fragment or bullet could conceivably be arrested by the fabric, but the resulting deformation could still result in a fatal injury by adversely engaging the skull. By contrast, thermoset composites such as polyvinylbutyral (PVB) phenolic-aramid systems reduce the transient deformation, even though their ballistic performance may be less than that of a pure fabric system. Thermoplastic composite materials offer a compromise of fabric and thermoset composite performance. That is, the thermoplastic tends to deform but not as much as pure fabric, and it tends to have better ballistic resistance than a thermoset-based composite material.

3.3 Static and Dynamic Structural Performance and Stability

Practical durability is a necessary trait for any article used in combat. Helmets must also pass static structural tests as well. “Ear-to-ear” loads of 2000 to 3500 kPa must be withstood by the helmet for several cycles without any permanent deformation of the helmet structure. Thermoset composites tend to do well, given the higher matrix modulus (as compared to a thermoplastic matrix). It is expected that the trends we identify for structural stiffness will track what we observe with the extent of transient lateral deformation. One exception to this correlation is obvious. If the material combination behaves in a brittle fashion (low tensile strength at high rates of loading), then it is possible that if brittle failure occurs prematurely, inelastic deflection will dominate and not necessarily track what we observe in the low rate structural testing. That is one strong argument for performing both types of tests on all material candidates. One additional comment: the transient testing ought to be performed at full scale because of the uncertainty of temporal scaling of the ballistic event.

3.4 Human Factors and Other Considerations

Comfort, hearing, weight distribution, and a host of other factors also influence design and material selection of a typical helmet. Many of these factors are weighted evaluations through models and experimental testing to reveal possible issues or concerns with the helmet system. For example, using a spiral design cycle strategy, researchers are constantly refining the design of attachments so that they optimize interfacing with weapons (figure 5) while still providing the desired electronic communication and optical systems in an ergonomically and mass-efficient design.

Figure 5. Weapons interface evaluation of prototype headgear.

4. Thermoplastic Based Helmet Materials, Specimens, and Helmets

4.1 Thermoplastic Aramid Systems

During the development of an effective thermoplastic-based aramid ballistic recipe, it was determined that transient deflection quickly becomes the limiting factor. To preserve the ballistic benefits of thermoplastic matrix aramid systems and minimize the potential for such skull trauma, it will very likely be necessary to combine them with other materials that exhibit greater stiffness against static and dynamic loading. The notion of composite hybrids is hardly new; the challenge becomes delivering the desired level of protection and performance in the overall shell without adding significant weight.

Thermoplastic matrix aramid systems have excellent, mass-efficient ballistic properties. However, the thermoplastic matrix is typically 30% to 60% less rigid than even toughened thermoset (e.g., phenolic) matrix. This has significant implications for the overall static structural stability and resilience of the thermoplastic aramid shell, as well as the dynamic deflections associated with a ballistic event. To illustrate this phenomenon, consider figure 5. A Phantom v.7 high speed digital camera was used to capture the effects of a simulated ballistic fragment impact on the back side of a flat thermoplastic-aramid panel. This panel had an areal density that was nearly 50% of that recommended for producing a helmet shell. As can be seen in the sequence of images, the fragment is effectively contained and stopped but not before it induced significant deformation to the overall panel. A thermoplastic-Kevlar shell at this low areal density may be well suited for certain applications, but given that the deformation was well over 1 inch, it could cause severe skull fracture (and possibly death).

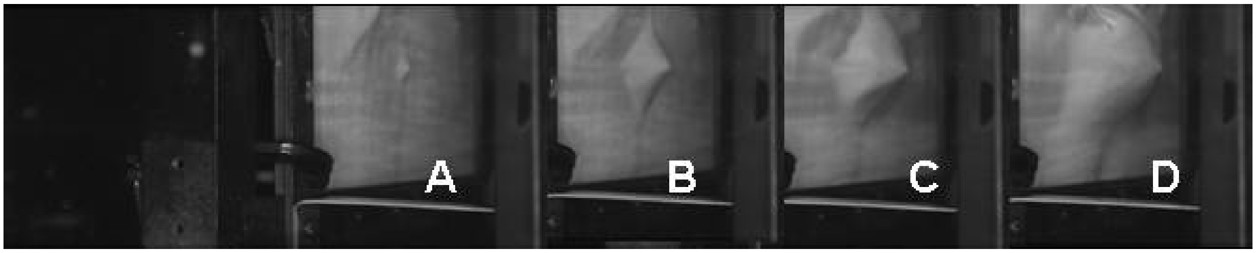

Figure 6. Still photographs from high speed digital imaging of thermoplastic-aramid panel.

4.2 Specimen Preparation and Fabrication

The design goal was to obtain an areal density of 1.75 pounds per square foot (psf) for all Kevlar-thermoplastic panels. Therefore, based on material and construction (i.e., unidirectional, plain weave, etc.), a ply orientation scheme was determined from which we obtained a preliminary weight for the skins. From there, the number of plies of Kevlar-thermoplastic was determined to obtain the 1.75-psf areal density.

The plies were cut into 15-inch square dimensions with the use of rotary shears made by Eastman Machine Co. The plies were then carefully stacked individually to assure proper alignment and to avoid ply sliding in the press (150-ton heat press, model MTP-24 made by Tetrahedron Associates, Inc.) with the thermoplastic side facing up. The last Kevlar-thermoplastic ply was reversed to provide better adhesive properties. The thermoset skin(s) were placed on the last ply. Teflon[8] textured release film was placed between the top and bottom plies and the call plates, which contacted the heated platens. The press cycle used was 300 °F at 500 psi for 60 min and then cooled under pressure to approximately 80 °F. Differential scanning calorimetry (DSC) showed that the 250 °F thermoset "prepregs" were fully cured, and dwell times could be reduced from 60 minutes to 10 minutes, if preferred.

4.3 Mechanical Characterization

These candidate materials not only need to perform well ballistically but must also possess certain mechanical capacities. The American Society for Testing and Materials D790 (*7*), was chosen for mechanical characterization of the specimens. This approach provided a quantifiable means of comparing each recipe by determining the modulus of elasticity from the load-deflection curves for each sample. These baseline data, in conjunction with the ballistic data, provided a reasonable first-level recipe selection process.

The 0.25-inch-thick panels were machined to 1-inch x 10-inch (WxL) flexural specimens with a Flow International Corporation waterjet system. Cutting such a flexible material proved to be a challenge. The material was machinable, but the edges tended to curl or bevel from the cutting process. Various cutting techniques and a stiffening material added during the cutting process were evaluated. The waterjet cutter, with particle board on the bottom surface of the sample, showed the best results. This method worked well but did not totally eliminate the problem. Therefore, all samples were re-pressed after machining at room temperature (~70 °F) and 500 psi for 0.5 hour. This added pressing step was performed after samples were dried at room temperature for about a week.

Four-point bend tests were performed on an Instron Electromechanical Testing System (Model 4405) with Series IX Material Testing Software. Samples were conditioned according to the standard before testing. A minimum of five samples was tested for each candidate recipe. Samples with thermoset prepregs on one side were tested with the thermoset side facing down, in tension. This would be a true representation of how the helmet would be molded with the stiff material on the outside to accommodate the flexural stresses induced during attempts to collapse the shell in compression.

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[8] Teflon is a registered trademark of E. I. DuPont de Nemours & Co., Inc.

5. Helmet Manufacturing Considerations

Fully realizing the material and performance benefits of thermoplastic-aramids and hybridized solutions will require rethinking of the manufacturing processes currently in use by most of the U.S. helmet manufacturers. Current processes are configured for mass production of thermoset-based, monolithic Kevlar helmets. These manufacturing systems typically use expensive, matched steel tools to consolidate the materials. Cold helmet pre-forms are placed in a hot mold and held under pressure until fully cured. The tools are heated at 325 °F to promote the cross-linking of the phenolic resin. “Bump” and “burp” cycles are used to draw off undesirable gases that evolve during the cure. By contrast, thermoplastic manufacturing cycles have a number of attractive features. Secondary innovations could be introduced in the optimization of a pre-form design and cutting with the use of software and near-net patterns. Table 1 summarizes the essential difference of the two material and process-based approaches.

Table 1. Comparison of current and proposed helmet manufacturing methods.

	Current Approach	**Future Approach**
Tool type	Matched metal (costly)	Female with silicone plug
Heat source	Conduction (heated tool)	Infrared
Pressure	Hydraulic press	Hydraulic press
Resin type	Thermoset	Thermoplastic
Fiber type	Monolithic	Hybrid
Cycle time	15 minutes	5 minutes
Pre-form scrap	15 to 20%	5 to 10%

Ideally, a new process should be conceived that would simultaneously address the materials and fabrication deficiencies of current manufacturing methods and fully exploit the inherent benefits of thermoplastic-based processes. Figure 7 is a conceptual schematic of such a process. Material waste could be reduced or eliminated if neat pre-forms are developed and the reinforcement is hybridized. Infrared heating would rapidly heat the thermoplastic matrix and a silicone plug could be used to improve the hydrostatic pressure distribution used to consolidate the final shell.

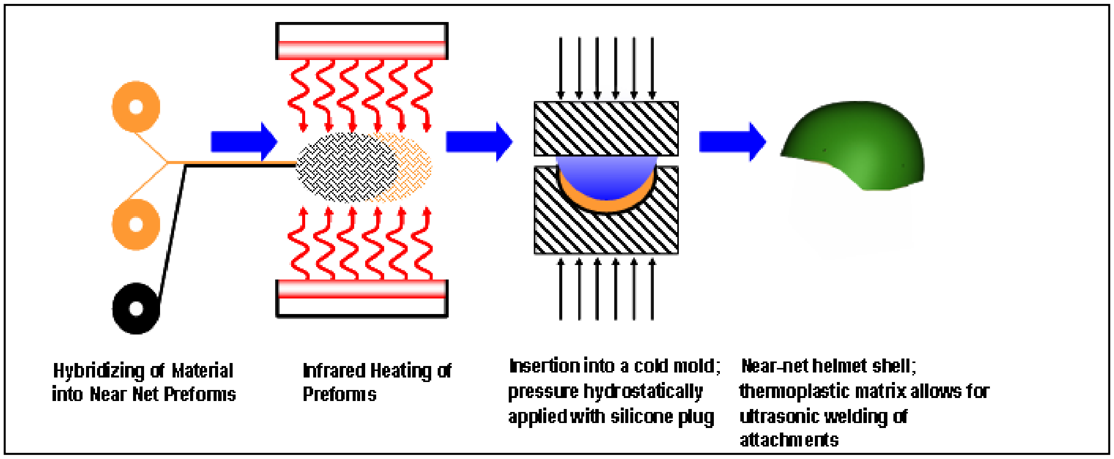

Figure 7. An integrated, low scrap and low cost semi-automated hybrid helmet process.

5.1 Series Fabrication

A logical approach in fabricating a structure made of two or more materials is to assign a processing step for each material system. For example, the thermoplastic matrix-based aramid could be placed in the helmet mold and processed under a minimum of 3500 kPa and a temperature of at least 120° Celsius. Once the helmet is formed, cooled, and stabilized, a secondary process step could be employed, which would apply a layer of graphite to the aramid-thermoplastic "core." This could be done with a vacuum curable prepreg, provided the cured and finished laminate demonstrates the required stiffening effects for the overall helmet system. This process approach can be considered a series-type manufacturing method insofar as the material systems are separately and sequentially fabricated. A schematic of a basic series process cycle is shown in figure 8a. The advantage of this method is that, given two distinct resin types (thermoplastic and thermoset), having two separate process steps ensures an optimal process cycle for each material. The disadvantage is that this process method inherently introduces a secondary process step, and as such could increase process cycle time, touch labor, and secondary process infrastructure.

5.2 Parallel Fabrication

A possible remedy for minimizing or eliminating additional process steps in the manufacture of hybridized material systems is to combine the material assembly as much as possible and co-process the materials together. Generally, the aramid fibers are tolerant to relatively mild variances in process temperatures. The matrix materials, however, are not; indeed, thermoplastic matrices typically process at temperatures below thermosets. However, it is possible to select thermoset resin systems that are curable at or near the temperatures required to melt and consolidate the thermoplastic matrix material. Prudently selecting the matrix material provides the opportunity to effectively co-process the materials. Figure 8b schematically depicts this parallel process approach. The advantages of this manufacturing method are the ability to reduce the number of overall processing steps and to minimize the labor and cycle time required to effectively produce a hybridized helmet material system (*8*). The disadvantage is the possible limitation of certain thermoset resin systems if the cure temperature far exceeds the process cycle temperature for melting and consolidating the thermoplastic. The time required for curing the thermoset skin will influence the total process cycle time.

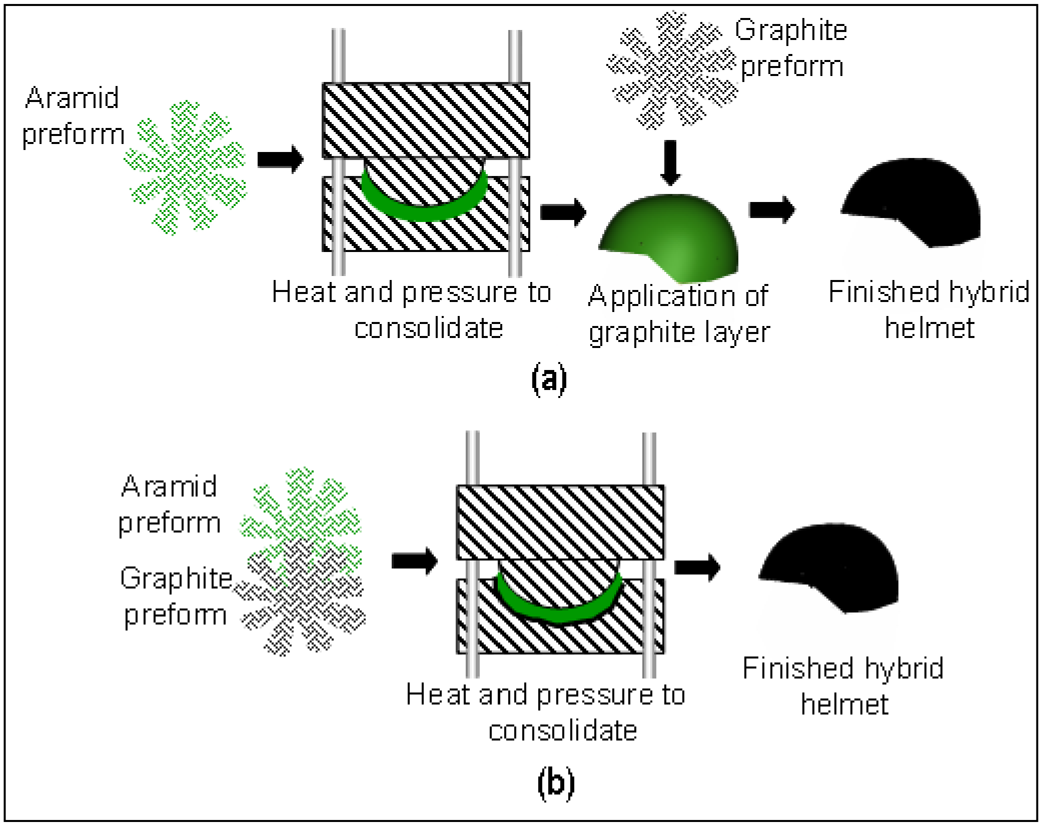

Figure 8. A comparison of series and parallel fabrication cycles for hybrid helmet manufacture.

6. Results and Discussion

ARL has explored a variety of thermoplastic-based systems, including hybridized derivatives. The flexural data for both thermoplastic Kevlar KM2 and IM7-epoxy thermoplastic KM2 hybrid are shown in figure 9. Table 2 provides a summary of flexural modulus data for some of the ballistic recipes that were explored. The preliminary conclusions based on ballistic and mechanical data are that it is possible to reduce the overall areal density of a typical PASGT shell (Kevlar 29-phenolic) by 25% with the use of hybridized, thermoplastic based aramids. It appears that the dominating design factors at reduced weight are static and dynamic structural rigidity and integrity. Simply preventing penetration of a bullet or high speed fragment is not a sufficient condition for Solider-borne head protection. The deformations witnessed with monolithic thermoplastic aramid systems rapidly increase, raising serious concerns about localized and blunt force trauma such as fracturing of the skull. Still, through hybridization and prudent design trade-offs, it is possible to construct a thermoplastic based helmet with superior mass-efficient ballistic properties as compared to current thermoset helmet shell systems.

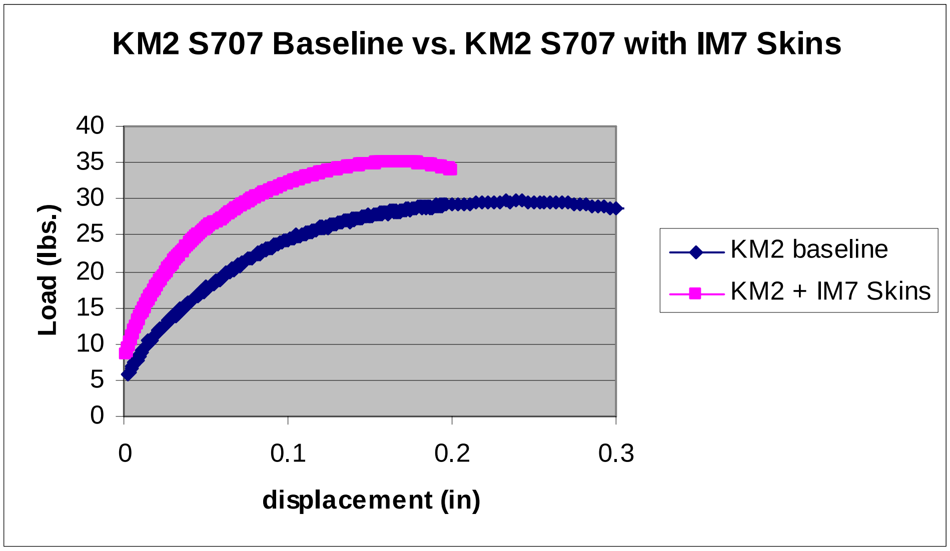

Figure 9. A comparison of monolithic and hybrid (IM7 graphite) thermoplastic KM2.

Table 2. Mechanical data for monolithic and hybrid recipes.

TP0721G	30 plies S707 + 2 plies S2/M36	Comp	0.2574	0.0009	2,808,121
TP077C	40 plies S707 + 2 plies S2 FgBT250E	Tens	0.2602	0.0015	2,334,024
TP077C	40 plies S707 + 2 plies S2 FgBT250E	Comp	0.2615	0.0004	2,587,133
TP05c1	32 plies 705/SP	N/A	0.2693	0.0006	2,403,230
TP0710D	41 plies S707 + 2 plies K49 Bt250E	Tens	0.2668	0.001	2,414,482
TP0710D	41 plies S707 + 2 plies K49 Bt250E	Comp	0.2672	0.0004	2,782,257
TP0733K	41 plies S707 + 1 ply Twintex EG/PP	Tens	0.276	0.001	1,778,301
TP0733K	41 plies S707 + 1 ply Twintex EG/PP	Comp	0.2747	0.0016	1,906,098
TP05b3	31 plies 705/PU	N/A	0.2836	0.0009	193,221
TP0730J	42 plies S707 + 1 ply Twintex C/N	Tens	0.2826	0.0011	1,245,251
TP0730J	42 plies S707 + 1 ply Twintex C/N	Comp	0.2836	0.0012	1,217,542
TP075A	42 plies S707 + 2 plies Cytec 381/IM7	Tens	0.2673	0.0004	2,741,839
TP075A	42 plies S707 + 2 plies Cytec 381/IM7	Comp	0.2674	0.0011	3,126,790
TEPNY	TEP/NYLON	N/A	0.2831		903,264
TP0740A	Double-Sided S707/TP	N/A	0.2644		4,111,269
TP0741N	S707/TP/Kevlar/Phenolic/PVB	Tens	0.2662		1,784,187
TP0741N	S707/TP/Kevlar/Phenolic/PVB	Comp	0.2661		1,751,947

The development of the materials and processes in this research is pertinent not only to next-generation helmet systems but to currently fielded systems as well. For example, as shown in figure 10, as each new and improved thermoplastic recipe is developed, it is possible to consider one of two uses for this technology. The first is a lighter helmet shell that delivers essentially the same ballistic, static, and dynamic characteristics as a current helmet (e.g., the PASGT). This is the current intention of the FFW. However, a second option is to consider providing an improved level of protection at the same weight. For example, this could entail replacing the Kevlar 29-phenolic with KM2-thermoplastic hybridized with a stiffening material (e.g., glass or graphite). This helmet could exhibit less deformation and improved ballistics at the same weight of the current PASGT system.

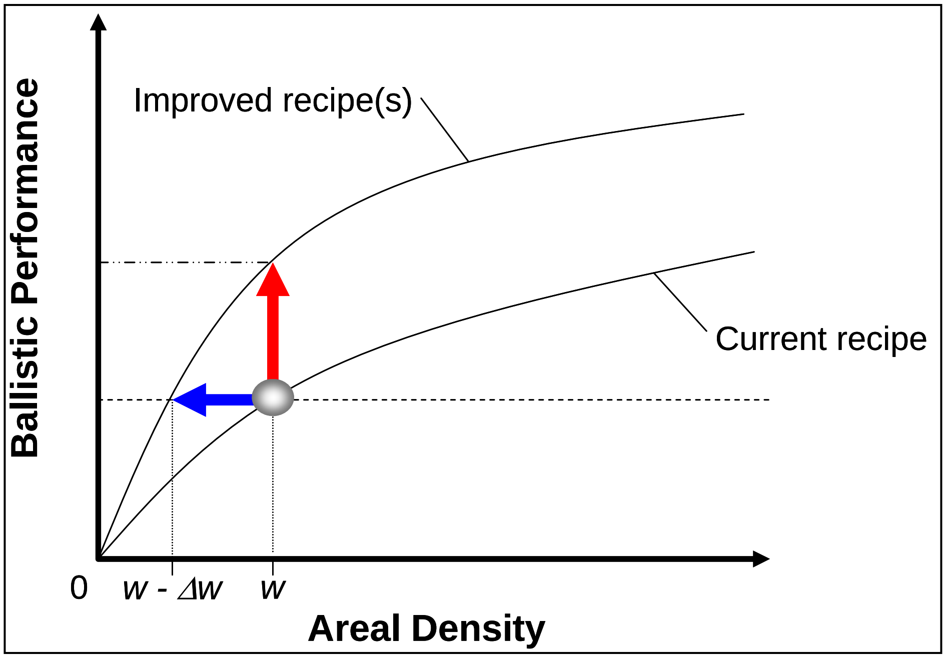

Figure 10. Applicability of new helmet recipes to current and future helmet systems.

6.1 Flat Plate Fabrication and Results

Previous studies had initiated the fabrication of flat plate specimens for structural and ballistic testing (*5*). Each of the flat plate “recipes” represented a potential helmet material solution to meet key performance requirements that included fragmentation, dynamic deflection, and structural integrity. The current research focused on refining the leading candidate recipe, which consists of IM7 graphite-epoxy co-processed with a polyolefin matrix, Kevlar KM2 woven reinforcement (figure 11). It is possible to reduce the weight and increase protection levels simultaneously (table 3).

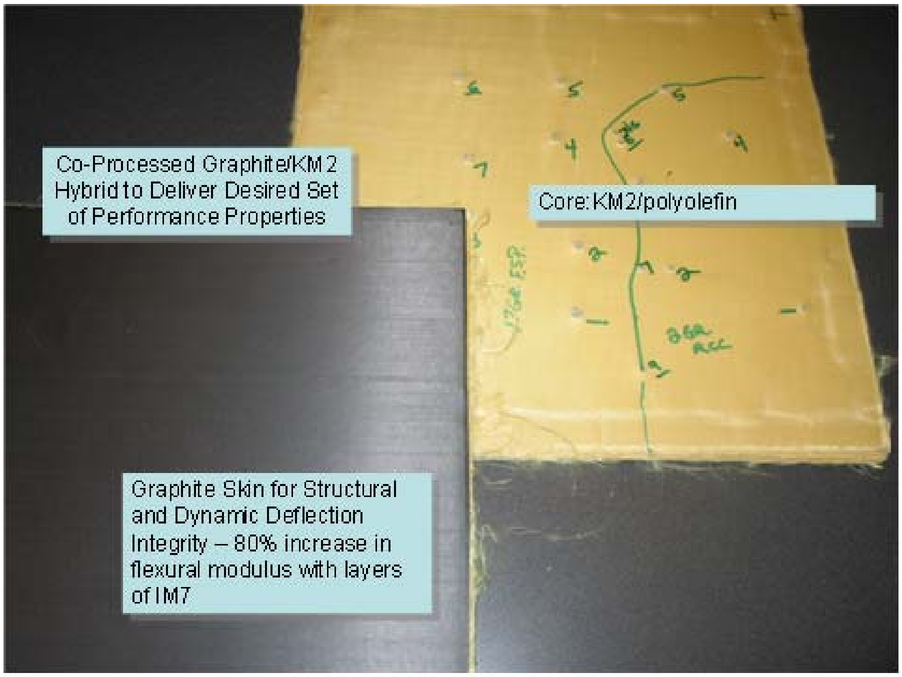

Figure 11. ARL recipe.

Table 3. A comparison of PASGT and hybrid shell materials.

All data normalized using PASGT as baseline	PASGT	KM2-polyolefin Hybrid
Normalized Areal Density	1	0.76
Normalized 2-grain V_{50}	1	1.02
Normalized 17 grain V_{50}	1	1.20

6.2 Helmet Design Variations

Once a viable hybridized material recipe was identified (in this case, a graphite-KM2 polyolefin), it was possible to use the aforementioned processes to begin forming the materials into a helmet shell. The goal was twofold: to characterize the influence of the process cycle on the material and to explore weight-saving methods of selectively stiffening the helmet shell. Helmet fabrication was performed by Diaphorm LLC (Limited Liability Company) in accordance with ARL materials, designs, and process specifications.

6.2.1 Monolithic KM2 Shell-Polyolefin Shell

It is important to have a baseline when one is developing a hybridized material system. In this particular application, the base material is polyolefin-KM2 (aramid) composite. Figure 12 shows the results of consolidating this material into a helmet shell. For these studies, the helmet shell "shape" is arbitrary as long as it remains fixed for each of the subsequent material variations. "Petal" shapes are apparent on the aramid fabric in order to limit wrinkling during molding. Since there is no thermoset present, the polyolefin melts, conforms fully to the mold shape, and upon cooling, retains the shape and rigidity associated with the mold and KM2-thermoplastic material.

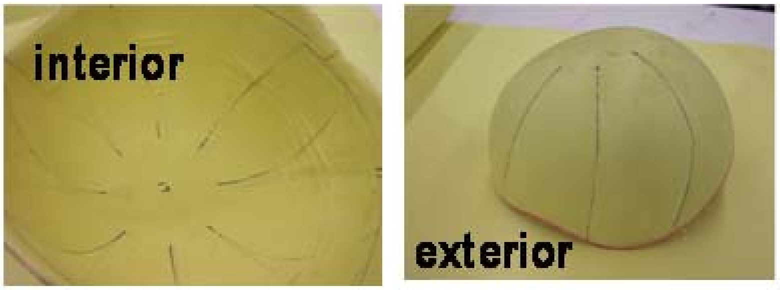

Figure 12. Monolithic shell composed of KM2-polyolefin.

6.2.2 Graphite Skin on Polyolefin-KM2 Shell

The first variation is the application of a graphite-epoxy skin to the outer surface of the KM2-polyolefin, as shown in figure 13. Some of the latter material was removed to keep the areal density of the helmet consistent with the monolithic KM2-polyolefin shell. Like the flat plate work that preceded it, the bond between the graphite-epoxy and the KM2-polyolefin was excellent. Because a silicone plug, instead of the matched compression tooling, was used to consolidate, some wrinkling on the interior of the shell was apparent.

Figure 13. Graphite-epoxy on outer surface of KM2-polyolefin shell.

6.2.3 Polyolefin-KM2 Encapsulated by Thermoplastic Graphite

A second variation was the application of a graphite-nylon layer to the interior and exterior surfaces of the KM2-polyolefin shell, as shown in figure 14. Again, the areal density was kept equivalent to the monolithic KM2-polyolefin shell. This shell was extremely stiff even though the nylon thermoplastic modulus was less than that of the graphite-epoxy material. This variation also demonstrates the total elimination of thermoset matrices in the stiffening or ballistic components of the helmet. Cure kinetics were not an issue in determining the cycle time for this process. Only the ballistic capability of the skin material is yet to be determined. Similarly, additional studies of the lower pressure consolidation influence on ballistics are required.

Figure 14. KM2-polyolefin fully encapsulated by graphite-nylon.

6.2.4 Integrally Stiffened Polyolefin-KM2 Shell

A third variation is the *selective* application of a graphite-epoxy material to the KM2-polyolfin ballistic “core.” Like the first variation, two layers of graphite-epoxy were applied to the exterior surface of the KM2-polyolefin shell as shown in figure 15. However, graphite was applied in a hoop on the lower perimeter of the shell, as well as in a U-shaped piece in the middle interior of the shell. The purpose was to selectively stiffen only those regions that required it, thereby minimizing weight. A limited amount of wrinkling is apparent on the inner surface, which is attributable to low pressure consolidation.

Figure 15. Integrally stiffened KM2-polyolefin shell.

7. Conclusions

A series of thermoplastic-based aramid materials has been hybridized with secondary structural materials. These specimens have been characterized ballistically and structurally. The conclusion is that thermoplastic based systems can yield a 10 to 25% weight reduction over conventional thermoset (PVB phenolic) helmet materials while maintaining equivalent protection levels. The focus of the present work is to begin identifying materials and design opportunities that could be used to engineer a lighter helmet that meets prescribed baseline performance specifications. In addition, practical manufacturing methods for producing these systems have been identified and preliminary prototypes of these new material and system designs have been fabricated through relatively low pressure manufacturing.

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