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ADVANCED PREPREG BALLISTIC COMPOSITES FOR MILITARY HELMETS

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Abstract: *With the advancement of ballistic materials and technologies, the ballistic prepregs are becoming an essential construction technique for getting the maximum performance out of the high performance fibers. The ballistic prepregs help to maximize the engagement between fibers and high speed projectiles penetrating the ballistic material, thus reducing the amount of ballistic material required to defeat the projectiles. The backbone of lightweight ballistic materials is high performance ballistic fiber. However, the ballistic fibers alone cannot engage a high speed projectile because the projectile can push fibers aside without breaking a single filament in the fiber bundle. To overcome this limitation, the fibers are converted into either a woven fabric or a non-woven material such as a cross-plied unidirectional material. These ballistic materials have fibers in at least two directions which forces the projectile to engage with the fibers by keeping them in place with either thermosetting or thermoplastic polymeric matrix. However, for rigid armor, these prepregs are molded into helmets by utilizing proper molds and molding conditions. In the current paper we highlight the important factors that affect the combat helmet performance such as: fabrication methods, mechanism of ballistic energy absorption, ergonomic aspects of ballistic helmet design and materials systems. Special emphasis is given to thermoset and thermoplastic ballistic composites. Wherever appropriate, in the context of the topic, we refer to our experience in working on the development and serial production of the first ballistic helmet for former JNA (Yugoslav People's Army)*

Keywords: *prepreg, fibers, helmets, ballistic composites.*

1. INTRODUCTION

In the past two decades, ubiquitous armed conflicts have spurred tremendous growth in armour materials and designs. Those who watch the armour market expect demand to continue. For example, a 2009 study by the military armour research specialists predicts that $6 billion (USD) in military body armour will be procured by the U.S. military between 2009 and 2015 [1].

Composites now play a huge role in this market, having steadily displaced traditional materials since the early 1980s. For military helmets, in particular, lightweight composite designs reinforced with aramid, ultrahigh molecular weight polyethylene (UHMWPE) and other fiber types, often in hybrid combinations, have long since replaced the steel “pot” helmets of World War II and the post-war era. The current trend is toward thermoplastic helmets, and such designs are presently under evaluation by the leading armies of the world for the development of advanced combat helmet [1]. Because the future helmet is envisioned as a sophisticated piece of equipment that will integrate more electronics and sensing systems, there will be a need of a helmet that is lighter than existing thermoset models offering more protection.

2. PREPREGS

Composite ballistic helmets and other ballistic items are mainly, now days, produced from prepregs. Prepregs are composite materials in which a reinforcement fiber is pre-impregnated (“prepreg” is short from PRE-impregnated) with a thermoplastic or thermoset resin matrix in a certain ratio. Prepregs have unique properties as they are cured under high temperatures and pressures.

Generally, the resin matrix in prepregs is partially cured for ease of handling and is stored in a cool place to prevent complete cross linking. This B-stage prepreg will need to be heated in an autoclave, hot press or oven during manufacture of composite materials to achieve full cross linking.

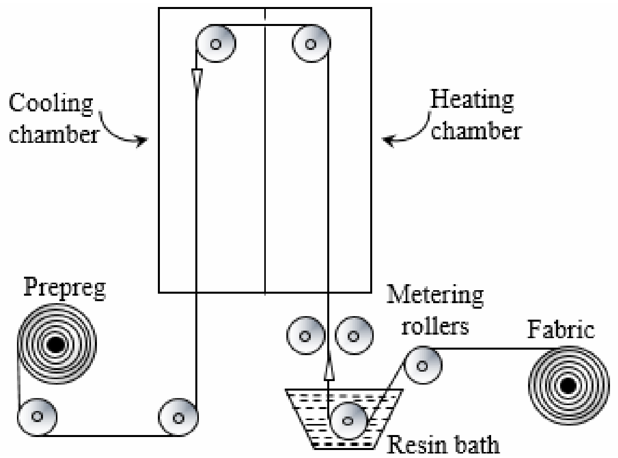
Prepregs for ballistic applications come in two basic forms: *unidirectional tape* is a band of fibers impregnated with resin with all the fibers oriented in one direction, *and fabric prepregs* which are woven fabrics that are impregnated with resin by either a hot melt or solution coating process. Depending on the fiber and the application, prepreg resin content varies but typically, for ballistic application, is kept under 20 % by weight.

Prepregs provide better mechanical performance over a wide temperature range than wet lay-ups, that is, dry fabric with manually-applied resin. Because the resin is applied to the reinforcements in exact precise quantities in a uniform way, an optimum fiber/resin ration is attained. Prepreg offers consistent mechanical properties in the composite, and lessens the health and safety risks associated with handling liquid resin.

The most common reinforcements used for ballistic prepreg are glass, aramid, UHMWPE and nylon fibers. Resins used in prepregs vary from low-temperature cure thermosets to high-temperature cure thermoplastics. The most common thermoset resins in ballistic composites are modified phenolics, epoxies and polyesters, while the most common thermoplastic resins are polypropylene (PP), polyphenylene sulfide (PPS), bis-maleimids (BMI) and polyurethanes. Both types of resins offer good impact resistance and vibration damping characteristics.

Prepregs are produced using two main processes: hot melt process and solvent dip process.

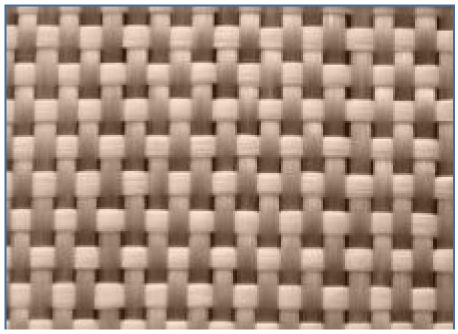
Solvent dip process was the first form of prepregging. In this process, the fiber is threaded over metal bars for controlled tension, and run through a solvated resin bath. Solvated means that alcohol, acetone or some other solvent has been added to the resin to lower its viscosity and assure good fiber wet out. The impregnated fabric continues through a metered set of rollers to remove excess resin. From there, it is conveyed through a horizontal or, more commonly, vertical heating chamber, referred as tower, which has bars at top and bottom to loop the fabric, as shown in Picture 1.



Picture 1. Schematic of solvent dip process

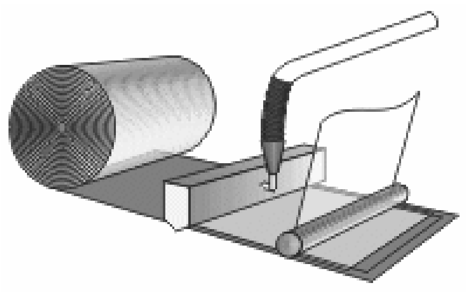
Temperature and roller speed control how quickly the solvents are driven off in the heating chamber, and care is taken to assure that complete curing of the resin does not occur. Once the prepreg is free of most solvent (for military applications less than 1 %) it is cooled and rolled into a core. Thermoset prepreg at this B-stage point is pliable with good tack.

By the way, this process was used in the development of the ballistic prepreg/composites for T-72 tank body protection. Also, such process was used for the development of glass fabric/epoxy prepreg for the production of front and rear (container) pipes for the lightweight, hand-held, 64 mm, rocket launcher "Zolja" (both joint projects of "11 Oktomvri", Prilep and MTI – Military Technical Institute from Belgrade). Picture 2 shows a sheet of woven glass roving/modified phenolic resin used in T-72.



Picture 2. Woven glass roving/modified phenolic resin prepreg

Hot melt process is a newer process and tends to replace solvent dip process because of the environmental issues related to the later. At the hot melt machine the fabric or unidirectional fibers are laid on a carrier silicon paper or polyethylene (PE) film containing a controlled amount of resin. Another roll of carrier paper or PE film is positioned above the fibers. The fibers, sandwiched between the papers, are pulled along the tape line with pull rolls as pressure is applied from sets of heated compaction rolls metered to the prepreg thickness. The compaction ensures that the fibers are evenly spread apart and wet out. Again, as with the solvent dip process, care is taken not to cure the material. A very simplified schematic of this process is shown in Picture 3.



Picture 3. Simplified schematic of hot melt process

Once through the heated compaction area, the sandwich typically passes through cooling rolls before the carrier paper is removed. Trimming both sides of the prepreg to exact width is done just before rewinding.

3. BALLISTIC COMBAT HELMET

The basic function of a combat helmet is to provide protection against fragments (shrapnel) of explosive devices and bullets. The ballistic performance of a helmet can be measured using the ballistic limit velocity, V50. The ballistic limit velocity is defined in NATO standard STANAG 2920. It presents 50% probability of penetration i.e. of non-penetration of the projectile into the test specimen (helmet) and is a statistical measure developed by the US military.

When a bullet strikes a helmet a cone is formed on the back face of the helmet [2]. The depth of this back-face signature (a conical bulge) is required not to exceed a critical value (~ 43 mm). If the depth exceeds this value, the helmet shell can strike the scull, resulting in behind armor blunt trauma.

How severe the back face signature can be is shown on Picture 4, taken during the development of the JNA ballistic helmet (the test is done on a flat panel).

Picture 4. Back face signature of a ballistic composite

There are several major properties to measure the performance of ballistic helmets [3].

- *Weight*

An infantry soldier carries all his equipment. The duties of such a soldier are physically demanding, and any addition to the weight carried generates considerable impairment to his endurance. Therefore, the weight is one of the primary considerations in designing any new helmet system.

- *Ballistic performance*

The ballistic performance of a composite helmet depends on the material used, helmet thickness i.e. the area weight of the composite, and fabrication method. A compromise often has to be made between weight allowed and the ballistic protection requirements.

- *Location of center of mass*

The ideal location of any weight on the head is on the straight line connecting the center of mass (CM) of the head and the CM of the body. Any shift in the weight balance on the head from the natural CM of the head will result in straining and fatigue of neck muscles. It will also hinder the body balance during other movements like running, crouching, jogging, or walking, because of muscles accommodation required.

- *Maintenance of head movement*

An infantry soldier must be able to scan his surroundings for any sign of threats or targets. This implies that there should be not impairment of the head/neck movement. In addition, vision and hearing should be maintained. Particular care should be taken of any attachments on the helmet. Any new attachments should enhance the vision and hearing of a soldier rather than impairing it. It is necessary to test the new helmet in field settings before implementing it. There is possibility that loose hanging wires or cables may entangle with other items/equipment pieces like guns, surrounding vegetation, field telephones or gas masks.

- *Cost and user acceptance*

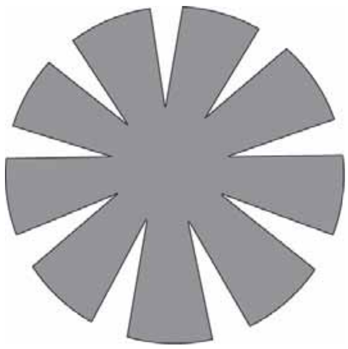
Any helmet that is far too costly to implement will not be fielded. Other factors to consider are availability and cost of materials and ease of fabrication. A helmet that can be produced in large volumes at a reasonable cost has a better chance of being accepted. Acceptance of the user depends on the actual fit of the helmet, comfort level and benefits in actual combats. Engagement of the end users in the development process as frequently as possible will increase acceptance possibility.

- *Helmet size and fit*

Advanced helmets are designed to provide much more than just ballistic protection. If the fit of the helmet were not comfortable, the helmet user would be reluctant to wear it. The fit of the protective head gear thus affects the performance of the soldier. It is found that the optimal standoff distance (gap between the head and the helmet) to be 12.5 mm. Proper helmet size, fit and stability are critical to personnel safety. If the helmet sits low on the head, it interferes with the line of vision. If the helmet sits too high, the risk of injures increases. If it is too tight or too loose, the helmet can be constant bother.

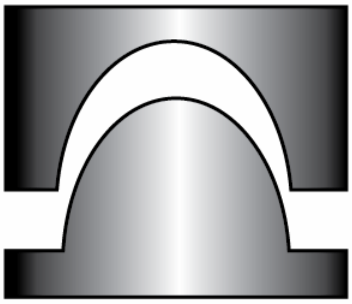
4. FABRICATION METHODS

Generally, helmets are produced by stacking together multiple numbers of prepregsheets which a compression molded in a close matched tool. The number of sheets (the thickness of the helmet) depends of the required level of protection and on the area weight (thickness) of the sheets. Thermosetting prepregs are based on bidirectional woven fabrics which are delivered in rolled form. The first step in helmet fabrication is cutting the blanks from the roll. For the replacement of the steel helmet of former JNA with composite one, in the initial development phase, darted blanks were used. Darted blank is a single ply of precut prepreg with material removed within the part area, as shown in Picture 5.



Picture 5. Darted blank

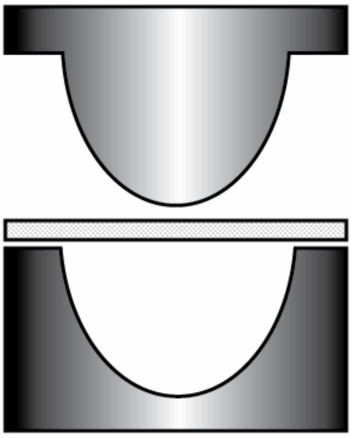
During molding, darts would close up so that their edges nearly join together. To avoid having the darts align with the part, the dart is offset (the blank is rotated) ply to ply within the stack. This prevents wrinkling and folding of the material in the helmet shell. 2D blanks are preformed into a 3D shape before loading on the male part of a close matched die, shown in Picture 6. Retention of the blanks position in relation to each other during preforming is a key process step.



Picture 6. Closed match die

The curing of the thermosetting resin takes place at 140 ^{o}C – 160 ^{o}C under pressure, usually 4 MPa – 8 MPa, within 75 minutes – 90 minutes, into a down-acting press.

Fully thermoplastic composites (both, the resin and the fibers are thermoplastic) use the, so called, “deep draw” process. First, the stack of plies is molded into a flat panel. Prior to molding the panel is preheated into an infra-red oven to make it softer and more flexible; then, the panel is molded in a close matched die mounted into a down-acting press and shaped into a helmet shell, as shown in Picture 7.



Picture 7. Deep-draw process

The next step, for the both processes is trimming of the helmet shell. High-performance fibers (aramids, UHMWPE) are very tough to cut using traditional steel or carbide tools. Therefore, in the development of JNA composite helmet water-jet was used to trim the shell.

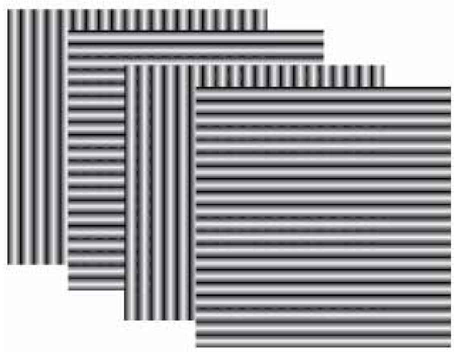
5. THERMOPLASTIC VS. THERMOSET-BASED COMPOSITES FOR HELMETS

Polymer matrix composites (PMCs) consist of a polymer resin reinforced with fibers and are highly anisotropic materials. PMCs respond to ballistic impact in ways that depend on their particular structure and thus are different from other protective materials.

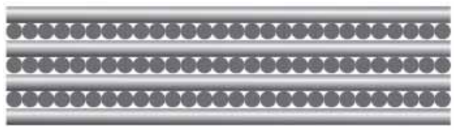
When a woven fabric is impacted by a projectile, transverse and longitudinal waves are generated. These longitudinal and transverse waves travel along the yarn until they encounter an obstacle like a fabric edge or a fiber cross-over point. The waves are reflected at the obstacles and collide with the onward traveling waves. The kinetic energy carried by these stress waves is dissipated through a number of mechanisms, including cone formation on the helmet back face, deformation of secondary yarns, primary yarns breakage, inter-yarn friction and friction between projectile and the fabric [4]. Shear plugging has also been observed as one energy dissipation mechanism. As the strain within a fiber exceeds a critical value the fiber fails. Each successive fabric layer absorbs the un-dissipated energy until the projectile is defeated. Failure of all fabric layers results in complete perforation. If the projectile velocity becomes zero before complete penetration, then the projectile has been successfully defeated.

The main difference between thermoplastic and thermosetting composites for ballistic protection is that thermosetting use fabric as reinforcement while – advanced thermoplastic use unidirectional (UD) fibers cross plied at $0^{o}/90^{o}$, as shown in Picture 8a, Picture 8b shows cross-section of UD prepreg.

Unlike thermoset-based composites, which undergo time-consuming chemical cross-linking during processing, thermoplastic-based composites are typically processed using only heat and pressure.



(a)



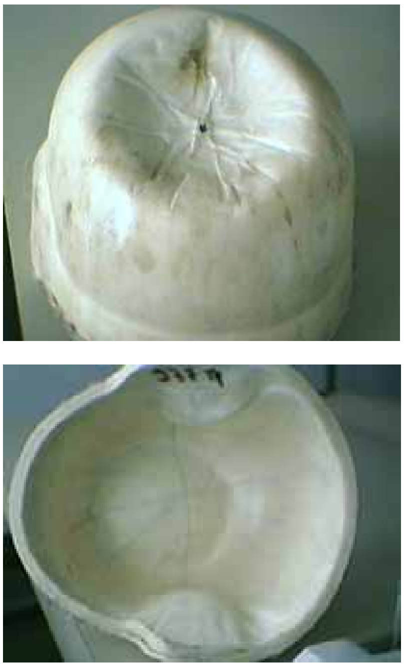
(b)

Picture 8. Construction of unidirectional prepreg, a) alignment of fibers, b) cross-section

Thermoplastic advanced composites also offer potential benefits of reduced cycle time and in-plant air quality for manufacture. The storage of the prepreg can be at room temperature with, practically, no limited shelf-life.

The main draw-back of thermoplastic based composites is the much lower stiffness than those based on thermosetting matrix.

Picture 9 shows thermoplastic based helmet shell, from the early development of JNA helmet, subjected to drop weight impact test. As can be seen, the composite lacks stiffness and deflects tremendously. This problem can be overcome by using hybridized helmet shell. It is achieved by adding several layers of thermosetting resin based prepreg or by incorporating small quantity of stiffer fibers, like carbon, for structural integrity. In the second stage of development of JNA helmet, hybridized shell was developed incorporating ballistic nylon fibers/thermoset resin and UHMWEPE fibers/thermoplastic resin. The latest generation of advanced ballistic helmets e.g. US Army ECH (Enhanced Ballistic Helmet) are fully hybridized with outer shell based on carbon fibers (for stiffness) and inner shell based on aramid (Kevlar) fibers for ballistic protection [5].



Picture 9. Thermoplastic-based helmet shell after drop weight test

For high volume productions thermoplastic composites are beneficial since greater automation in the fabrication process is possible.

Contrary to the thermoplastic, thermoset resins are much stiffer which is of great advantage for ballistic protection. Drawback of thermosetting prepregs is their storage, which must be in freezing condition and their limited shelf-life.

Their fabrication process is not entirely friendly for the environment and that's why, slowly but steadily, thermoplastics are taking ground tending to replace it entirely in the future.

5. CONCLUSIONS

Advanced composites are rapidly growing field of advanced materials. Comprising reinforced fibers in a matrix of thermoplastic resin, these materials offer high specific strength and stiffness, much low density than the traditional (metals, alloys, ceramic) ballistic materials. High performance fibers, aramids and UHMWPE, are the main contributors to the structural and ballistic properties of these materials.

The future development of these materials is based on thermoplastic matrices because of their outstanding properties and environmentally cleaner fabrication.

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