COMPOSITE ARMOR —

A DIFFICULT BUT HUGE MARKET

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World War II puzzle

During the middle part of WWII the British Royal Air Force faced a very difficult problem. They were simply losing too many bombers during the daily bombing runs over Germany. Something had to be done to protect the airplanes from the near-blanket anti-aircraft coverage that was being put up by the German defenders. However, several constraints made the solution very difficult. A new design was impossible and the fix had to come on the current planes. The planes could not fly higher or faster because of design limitations, nor could the entire plane or even the entire underside be armored because the weight would be excessive. The British decided to abandon daylight raids and began to fly only at night. (The Americans then flew during the day but the American planes could fly higher.) The RAF eventually developed new long-range fighter escorts, but that was not enough. Still too many planes were being shot down.

The RAF called in experts by the busload, but no one seemed to have a solution that would work. Finally, after carefully inspecting dozens of the planes that had returned from numerous flights, one expert (a mathematician/statistician) made an interesting discovery that led to a suggestion with the kind of logic and simplicity that just seemed to be right. The RAF took the suggestion and substantially reduced the number of bombers being lost. **What was the suggested solution?**

Before you read further, take a moment and let your mind run over the problem, the constraints, the possible findings of the expert, and the situation of the times..........

Ready for the answers?

Observation: The expert noted that there were some specific areas on almost all of the planes he inspected (those that had returned safely) in which no bullet or shrapnel holes were present. He then reasoned that this situation was highly unlikely because the bullets and shrapnel were surely random since they nearly blanketed the entire sky. However, thought he, the anti-aircraft fire was random over all the airplanes in the sky, not necessarily random on just one plane. Therefore, since the planes that returned did not have holes in some specific areas, the planes that were missing (those that did not make it back) must have been the planes that were hit in those areas. Hence, the areas without the holes were the areas where the planes were vulnerable.

Suggestion: Put armor only in the areas where there were no holes. The total additional weight from this selected armoring was determined and armored areas were still small enough that the planes could fly, and yet the critical places would be covered.

Lesson learned: Strategically made and placed armor can defeat offensive weapons, at least until a new, more powerful weapon is developed.

The armor market yesterday, today and in the near future

Just as in WWII, the ability to have light weight and effective armor is the key to saving lives. Furthermore, that armor needs to be designed to meet the perceived threat. Too little armor; and little benefit is gained. Too much armor; and other important factors (such as mobility) are sacrificed.

In WWII armor was almost always made from traditional materials such as metal plates, but that concept has evolved. A good example to illustrate the move from traditional materials to polymer composites is the evolution of the military helmet. Thin steel was the helmet material of WWII and remained the principal material until around the 1980's. The advantages of using steel included a simple technology for manufacture of the helmets, low cost, and reasonably good impact protection. However, these helmets were found to provide only marginal protection against fragments.

During the Vietnam War, the U.S. Army experimented with fiber-reinforced inserts in the helmets. These inserts improved ballistic protection but, at the same time, added weight and reduced the air space between the head and the helmet.

By the early part of the 1980's, the U.S. military had developed the first all-composite, 100% fiber-reinforced helmet. This development resulted in even better ballistic protection without altering the weight of the helmet. Other improvements included better head coverage and more space for ventilation.

Other countries such as the united Kingdom and South Korea decided to use a moderate cost, moderate performance nylon composite helmet. These helmets were manufactured by molding with either 100% nylon fabric or a mixture of nylon and aramid and then coating with a phenolic resin and curing. Nylon had a number of qualities that encouraged its use in these helmets. At the time, nylon was locally available and also had excellent insulation capabilities in both hot and cold climates. However, nylon was found to provide only the bare minimum in ballistic protection and, as a result, was discontinued everywhere except in Great Britain.

Another helmet then began to be used in several parts of the world. These helmets were reinforced only with aramid. The basic material was typically a woven prepreg with phenolic as the matrix resin. In the development of these helmets, engineers and designers learned that, to a certain point, a lower resin content performed better in ballistic resistance. Hence, the resin was lowered to approximately 12%.

In the latter part of the 1980's, another helmet began to be used which was based on the lay up of UHMWPE fibers in a 0° and 90° crossply which was then bonded with a thermoset resin. The first to use this technology was the French army. The weight of the helmet was reduced to 1 kg from the previous value of about twice that much. This type of helmet is pictured in Figure 1.

Composite materials have taken a leading position in modern armor, such as helmets but also bullet proof vests. Most of the modern composite material applications center around reinforcements that are very tough and strong fibers, usually aramid (like Kevlar®, a DuPont trademark) or UHMWPE, like Spectra®, an Allied Signal trademark) which are the two most common types of these reinforcements in the United States. But these are not the only materials nor are helmets and bullet proof vests the only applications.

Some other applications for modern armor are listed in Table 1. No attempt is made to quantify these markets because they are, largely, untapped and still in development. Moreover, some of the applications will require a change in people's minds to be fully developed because the need for armor is not now recognized. However, a major change in that perception and a more ready acceptance can be achieved in some of the cases by a simple word change – from “armor” to “protection”. The protection could be against bullets, shrapnel, knives, explosions, crashes, impacts from falling or flying objects, or even from fires. Current growth in many of these markets suggests that the change in perception is underway. However, to exploit these markets, some of the basic concepts and details of materials and manufacturing used in composite armor should be understood.

Concepts

Almost all armor applications begin with an assessment of the protection level afforded by a particular armor material. For body armor, this assessment considers the ability of the material to protect against two major dangers: 1) penetration from various missiles, and 2) blunt trauma. The leading authority and the entity that has established most of the standards for these two risks is the National Institute of Justice (NIJ). Their literature sets out the procedures for testing and analyzing for penetration and for blunt trauma. Most applications other than body armor focus entirely on penetration unless they are also considering some additional danger such as fire or explosion shock. In general, no agency has taken overall control of the tests and the manufacturers are largely on their own to specify the protection level in these other areas.

By far, the most common method of reporting armor performance is to use the classifications and the testing methods of the NIJ. The standard (NIJ Standard -0101.03) establishes six formal armor classification types plus a seventh special type as listed in Table 2 as they relate to penetration. Each type lists the type of bullet, the size of the bullet, and the velocity of the bullet against which protection is provided. Higher classifications give protection against larger bullets at higher velocities. Therefore, a purchaser of the body armor must evaluate the likely threat and choose the type that will meet that threat. (For instance, Type II provides multiple-hit protection against .357 Magnum JSP 158 grain bullets to a maximum velocity of 1,395 feet per second, and 9mm FMJ 124 grain bullets to a maximum velocity 1,175 feet per second.)

To establish these types and to determine the rating of various body armor materials and configurations, a special test was run in which rounds of each type were fired into the armor under test. The test set-up was established as shown in Figure 2. The result of the test is the velocity at which the probability of penetration is 50%. This value is obtained by firing many shots into the vest and noting the velocity of each round. The number of rounds that penetrate the vest is then plotted for each velocity, as shown in Figure 3. The velocity at which 50% of the rounds penetrate, which is called V_{50}, is found from the graph as shown in Figure 3.

Body armor manufacturers frequently report the V_{50} value for a particular product and, therefore, the tendency among consumers is to compare the materials on this basis alone. Great caution should be exercised in making these comparisons since the test procedures can be legitimately varied somewhat. Moreover, armor penetration is very complicated and simple correlations can be difficult. For example, Figure 4 gives some indications of the changes in V_{50} that might occur with various changes in the armor material or in the test parameters. As shown, V_{50} tends to increase with fiber or yarn strength (tenacity), fabric weight, and the number of layers but will decrease as the number of filaments in the yarn increases. The complication is, of course, that all of these and, perhaps, other factors such as lay up sequence, the type of matrix, whether the fabric is woven or cross-plied unidirectional, and the strength of the bond between the fiber and the matrix (that is, the presence of a sizing or coupling agent) can all make major changes in the values.

Energy dissipation is the key

Underlying all of the factors discussed above is the concept of energy dissipation. Armor materials work because they dissipate the energy of the bullet or other missile that impacts against the surface of the armor material. The dissipation phenomenon is quite complicated but some of the mechanisms are reasonably well understood. Perhaps the most important of these is the ability of the armor material to quickly (nearly immediately) spread the impact energy sideways into a wide area. This capability requires that the fibers must be strong enough that they do not immediately break when impacted and also have some interconnectedness with the surrounding fibers.

If the fiber can also internally absorb energy by some mechanism, such as internal splitting or heating, then additional energy can be absorbed. Therefore, in addition to high strength, the fibers must have sufficient elongation that they move or give slightly and, thereby, transfer some of the load to other neighboring fibers that are connected through the fabric weave or through the matrix. However, if the bond between the fibers and the matrix is too strong, the total energy dissipated is actually reduced because this strong bond eliminates another source of energy dissipation – the sliding of the fiber against the matrix. The manufacturers of armor must, therefore, balance the need to have a matrix-fiber bond that is strong enough to transfer the energy throughout the structure but also allows some slippage to give additional slippage. A recent finding is that energy dissipation can be altered by changes in the directions of the fibers in adjacent layers. Some sequences seem to pass energy more efficiently from one layer to another and then to move the energy laterally in the structure. Another recent finding is that more energy is dissipated when adjacent layers are of different material (such as aramid next to UHMWPE).

Yet another factor in energy dissipation is breaking up of the bullet itself which might be caused by shattering against an outside layer of the armor. Ceramics and ceramic composites have proven to be especially useful for this purpose, especially in combination with aramids, UHMWPE, or fiberglass composite as a backing material. A structure of this type is shown in Figure 5.

It is probably obvious that many of these factors must be simultaneously optimized and that several compromises must be made in order to achieve the best performance. Moreover, it seems certain that optimizing for ballistic protection will force some decrease in other properties, such as part mechanical strength or stiffness.

Hardened airplane cargo containers

Whenever an airplane explodes in mid-air from a bomb or some other related difficulty, there is a renewed interest in developing a hardened (meaning blast containing) airline cargo liner. Fortunately, some dedicated individuals and companies have taken the challenge to develop such a container even though the design difficulties are tremendous.

Many of the difficulties are emotional, especially as the public and elected officials become involved. Some other difficulties are technical and, in the current state-of-the-art, are very difficult to solve, including some of the following:

- the container must be light weight

- the container must have an operational and rugged door that opens frequently, perhaps several times each day, and yet must participate in the overall function of the container
- the container, including the door, must contain the large and rapid air expansion associated with an explosion
- the container must contain whatever shrapnel is created by the blast
- the container must contain, at least for a specified period, the fire that is likely to occur as a result of the explosion and the subsequent burning of the luggage
- the container must maintain its protection properties throughout its normal useful life (even considering that it is likely to become damaged by rough handling, forklift impacts, weather, and other normal difficulties)
- the container must be flexible enough to contain the explosion blast but not so flexible that surrounding parts of the airplane are damaged
- the container must satisfy these minimum requirements whether full or mostly empty
- the container must be reasonably priced

The simultaneous accomplishment of all these design constraints is proving to be very difficult. The handful of companies (really they are consortia of manufacturers, airlines, and universities) who are working on the problem have been working closely with the Federal Aviation Administration (FAA) to jointly find the solution and to do the testing. The consortia and governmentare trying to do some predictive work using finite element analysis (FEA) but that is very difficult because of the very short times, high loads, and fully dynamic nature of the problem. Ultimately, testing will require that someone (the government) buy jet airliners (perhaps several) and explode bombs in them. This is very expensive but seems to be worth the cost and effort.

Current concepts include containers that are all fiberglass, hybrid reinforcements (including various combinations of fiberglass, carbon fiber, UHMWPE, and aramid), non-composite (aluminum) and perhaps others. The composite containers are likely to be single-unit construction (with the exception of the door) whereas the aluminum is probably a frame and panel construction. Because of the weight and performance requirements, the manufacturing methods are likely to be similar to those used in aerospace (sophisticated fiber lay down with autoclave cures). The current efforts are directed toward making a LD-3 container which is for wide-body airplanes (planes with two aisles) as these are the type most likely to fly overseas and, therefore, most vulnerable to terrorist attack.

Entering the armor market

At this moment, many aspects of the total armor market are changing. Several fibers, both new and others which have been around for years, are being investigated for armor capability both alone and in combination. These might be treated in special ways or used in unique lay up patterns to optimize for energy dissipation and cost. Several matrix materials, including both thermosets and thermoplastics, are being investigated as well. Some applications eliminate the matrix altogether. The addition of secondary materials, such as ceramics and, perhaps metals, is also being investigated.

In addition to the many investigations of materials, the methods of manufacturing are also being re-examined. What has traditionally been done by hand lay up, may now be done by RTM.

This change may require completely new concepts in weaves and preforms, thus requiring another round of material optimization.

On top of all these material and process investigations, the basic shapes of the products are being changed and shapes of new products are being created.

The armor market is certainly in flux. That is, for some, a time of great opportunity even though the risks are high. It may not be a market for your company, but at least, it might be an interesting one to evaluate.

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Table 1. Actual and potential markets for armor/protective materials

Major Market Category	Specific Product Examples
Military personnel protection	helmets, combat vests, land mine demolition gear, special gear for various duties (pilots, tank operators, medics, special forces, artillery gunners
Military armor systems	vehicle exteriors, vehicle interiors, aircraft vulnerable sites, radomes, naval armor, personnel carriers, body bunkers, land mine containment tubes
Law enforcement	police and security guard vests, riot gear, riot shields, armored boats, police helicopters, bomb blanket
Other products	safety helmets, explosive containment boxes (aircraft cargo), engine fragment containment, fuel cells, pressure bottles, armored bank trucks, armored personal cars, ambulances, butcher aprons and arm guards, bus and taxi driver shields, hunter vests, body armor for at-risk people (public figures, body guards, store operators in high risk areas or stores), fire protection, firearm barrels