

# POLYMERIC REINFORCING FIBERS —

## KEVLAR<sup>®</sup>, SPECTRA<sup>®</sup>, AND OTHERS

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### **Why has fiberglass become the dominant fiber reinforcement?**

Fiberglass is dominant as a reinforcement fiber simply because it has high strength and high stiffness at a low price. A comparison of fiberglass with carbon fibers, the stiffest reinforcement material, and with the other principal reinforcement fibers shows just how good fiberglass is when cost is considered. (See Table 1.) Fiberglass has over ten times the strength value (tensile strength per unit cost) and nearly 5 times the stiffness value (modulus per unit cost) as the other major composite reinforcement fibers. Hence, when cost is a major driving force in the selection of a reinforcing material, fiberglass usually is preferred.

In view of these obvious cost benefits for fiberglass, you might ask “What are the reasons that someone would ever choose any other fiber?” In the case of carbon fibers, that reason is usually stiffness for a very high-valued application. For instance, some estimates of the cost to lift one pound of payload into orbit range to over \$100,000. Under these conditions the criteria for selecting a reinforcement material is the specific strength (strength divided by the specific gravity) or, more often, the specific stiffness (stiffness divided by the specific gravity). Carbon fibers have substantially better specific strength and specific stiffness values than fiberglass. Hence, when the weight of the fiber is a strong driving force, carbon fibers can be easily justified.

The performance of aramid fibers (Kevlar<sup>®</sup>, a DuPont fiber, is the most common brand) and especially UHMWPE fibers (Spectra<sup>®</sup>, an AlliedSignal fiber, is the most common brand) are also appealing when weight is a major consideration. Aramid and UHMWPE fibers are substantially different from the other fibers and are less well known. They have unique properties that lead to special applications. These applications are not those usually associated with fiberglass composites, but are, nevertheless, very important and interesting. This paper will explore aramid and UHMWPE fibers and their applications in some detail. Perhaps their properties in a current application of these fibers will suggest a new use or application for you.

### **Aramid fibers**

The DuPont company invented aramid fibers in the 1960's as part of their continuing research into all types of nylon (polyamide) fibers. DuPont found that by making the polymer highly aromatic (that is, using materials containing many benzene rings) a very stiff and strong fiber could be formed. The chemical structure of Kevlar shows the benzene rings along the polymeric backbone. (See Figure 1.) These materials were called "aramids" from a contraction of their chemical description — aromatic polyamides. Aramids are now sold by several companies besides DuPont including: Akzo (Twaron), Teijin (Technora), Monsanto (X-500), and from Russia (Vnilon).

The initial market for aramid fibers was as a reinforcement in tires. Although the tires made with aramid reinforcements performed quite well, they were not able to displace steel reinforcements and have now largely disappeared from the tire market. Not long afterward, however, aramids were used successfully as reinforcements in traditional composite materials. They were high priced, so they rarely competed with fiberglass, but they were found to impart

some very beneficial properties to aerospace composites which could not be obtained using any other reinforcement material. These composite properties stem from a unique combination of physical properties, as shown in Table 2. The most important of these properties for aerospace was toughness. This toughness has been associated with the unique failure mechanism of aramids which is illustrated in Figure 2. This figure shows that when aramid fibers break, they do not fail by brittle cracking, as do fiberglass and carbon fibers. Instead, the aramid fibers fail by a series of small fibril failures, where the fibrils are molecular strands that make up each aramid fiber and are oriented in the same direction as the fiber itself. These many small failures absorb much energy and, therefore, result in very high toughness. For instance, impact damage measurements on pressure bottles made from aramid and carbon fibers and a standard epoxy resin, show that the aramid bottles are able to withstand from 2 to 4 times the impact and still maintain the same bursting pressure.

Many aerospace uses today for aramids involve toughness and impact resistance. Aramid fibers are, for instance, used on the leading edges and undersides of wings and control surfaces of airplanes to help protect against damage that might occur from rocks and other debris kicked up during takeoffs and landings. Aramids are also used for making missile launch cases where damage from handling or transport might damage a carbon fiber case. In some of these applications, the aramid is used only as a surface layer, with the bulk of the part being made from carbon fibers or fiberglass. These hybrid fiber composites give the protection of aramids but the high specific strength and specific stiffness of carbon fibers.

Some aerospace applications for aramids rely upon their excellent fire retardant characteristics, usually combined with their toughness or weight savings properties. Of course,

the resin chosen for these applications is extremely important to their meeting the flammability requirements, but aramids have been shown to meet most aircraft interior flammability standards if used with an appropriate resin matrix.

Other significant applications, both in aerospace and elsewhere, involve the improvement of abrasion resistance when aramids are added to the resin and the very high fatigue resistance of aramid-containing composites when compared to fiberglass or carbon fiber analogues.

By far the most important application for aramid fibers is in armor. This application is discussed in detail in the box accompanying this article.

Aramid fibers are readily available in a variety of woven cloth, knits, braids, and stitched fabrics for armor and composite applications. Most commercial matrix resins can be used with aramid fibers, although fiber wet-out is more difficult than with fiberglass or carbon fibers.

The toughness of aramid fibers makes composites of these materials extremely difficult to cut. Therefore, special cutting bits, drills, and mills that both stretch and cut the fibers are recommended. Cutting of composite materials containing aramid fibers with water jets or lasers can be done without difficulty.

### **UHMWPE fibers**

UHMWPE stands for Ultra High Molecular Weight Polyethylene. Fibers are made from this material by AlliedSignal (Spectra<sup>®</sup>), DSM (Dyneema<sup>®</sup>), Tenfor (Snia<sup>®</sup>), and Mitsui (Tekmilon<sup>®</sup>). The molecular formula for this polymer is the same as common polyethylene (see Figure 1), but is significantly different because of the very high molecular weight, from 10 to 100 times higher than commercial polyethylene molding resin. The high molecular weight results in

physical properties that are, in many aspects, competitive with fiberglass, carbon fibers, and aramids, as shown in Table 1.

UHMWPE fibers can be used with most commercial matrix resins such as vinylesters, epoxies, and polyesters. However, the chemical properties of UHMWPE fibers are such that few resins bond well to the fiber surfaces and so the structural properties expected from the fiber properties are often not fully realized in a composite. Several surface treatment methods have been tried to improve the adhesion between UHMWPE fibers and the most common resin matrices, but these treatments have met with only limited commercial success. However, the fibers continue to be used in many non-structural applications.

Another problem that has limited the use of UHMWPE fibers as structural reinforcements is their tendency to creep and to lose strength at high temperatures. UHMWPE fibers should not be used above 200°F or in applications where a load will be applied for an extended period of time, even at room temperature. (Creep can be as high as 10% in 90 hours when a 30% load is applied at room temperature.)

Even with these restrictions for structural applications, the uses of UHMWPE are numerous. For instance, sails for world class competition boats now routinely are made from UHMWPE fibers. The resistance to water, light weight, high strength and toughness, and the good resistance to distortion make the use of this material in sails a natural. Many of the same physical and mechanical properties are advantageous in marine ropes. The light weight, ability to float on water, abrasion resistance, and cyclic fatigue resistance of UHMWPE fibers give added value to rope applications.

Both UHMWPE fibers and aramid fibers are difficult to cut. This property complicates their use in some composite applications, but gives added value to some fabric applications. For instance, these fibers are used in making cut-resistant gloves, arm guards, chaps and aprons in industries such as meat packing, commercial fishing, poultry processing, sheet metal work, glass cutting, and power tool use.

The excellent electrical properties of UHMWPE fibers has led to their use in a variety of radomes. Their impact resistance has been a contributing factor to enhance their value in this application, often in combination with glass or quartz fibers.

As with aramid fibers, the major market for UHMWPE fibers is armor. This application is discussed in detail in the accompanying box. In addition to armor applications, the toughness of the UHMWPE fibers is evident in their use as a cladding material for airplane surfaces subject to impacts and as helmets for motorcyclists and soldiers.

## **Summary**

As the use of composite structures becomes ever more demanding and widespread, the use of fibers other than fiberglass is likely to increase. For some of these applications, the high performance fibers may not be used exclusively, but, rather, in combination with fiberglass or with some other fibers. These hybrid structures may be especially important in sports and recreation applications, aerospace, uses of composites in the infrastructure (highways, etc.), and in oil and pipeline applications, especially for off-shore oil platforms.

## **Acknowledgments**

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Table 1 — Comparison of Physical Properties for Common Reinforcement Fibers

Fiber	Tensile Strength (10 <sup>3</sup> psi)	Tensile Modulus (10 <sup>6</sup> psi)	Elongation (%)	Cost (\$/lb)	Strength Value (T.Str/Cost)	Stiffness Value (T.Mod/Cost)	Specific Gravity	Specific Strength	Specific Stiffness
Fiberglass <sup>1</sup>	500	12	4.9	1	500	12	2.6	192	4.6
Carbon Fiber <sup>2</sup>	600	35	1.6	12	50	3	1.8	333	19
Aramid <sup>3</sup>	575	19	2.8	19	30	1	1.4	410	14
UHMWPE <sup>4</sup>	422	16	2.9	20	21	.8	.97	435	16

<sup>1</sup> E-glass

<sup>2</sup> Magnamite AS-4D

<sup>3</sup> Kevlar 49

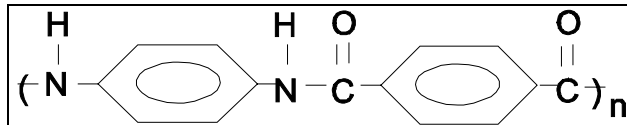
<sup>4</sup> Spectra 1000

Table 2 — Properties of Aramid Fibers

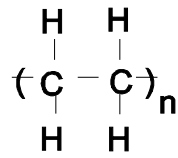
<u>Property</u>	<u>Comments</u>
Toughness	2 to 4 times better than carbon composites
Thermal stability	Unchanged properties from -40°F to 266°F
Flammability	Can meet aircraft interior flammability standards
Solvent resistance	Unaffected by organic solvents and bases, attacked by strong acids.
Water resistance	Absorbs about 2% water
Abrasion resistance	Extremely good
Cyclic stress performance	Excellent
Fiber wet out	Difficult — use low viscosity resins
Machining/cutting	Difficult — use special tools

Figure 3 — Properties of UHMWPE fibers

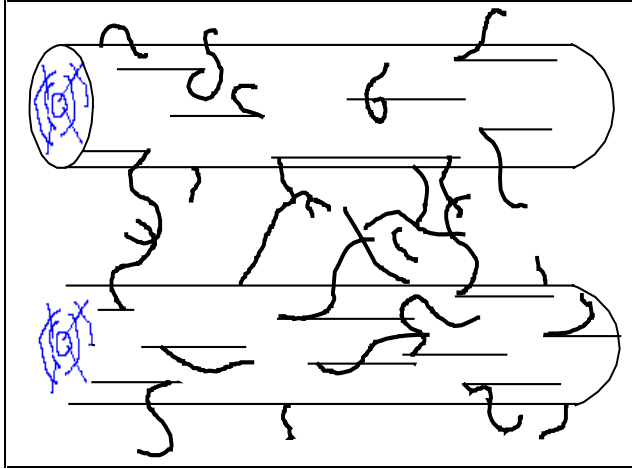
<u>Property</u>	<u>Comments</u>
Toughness	Very good, especially on a weight basis
Thermal stability	Do not use above 200°F
Flammability	Burns readily
Solvent resistance	Virtually unaffected by organic solvents, acids and bases
Water resistance	No appreciable water absorption
Abrasion resistance	Excellent
Cyclic stress performance	Excellent
Fiber wet out	Similar to fiberglass
Machining/cutting	Difficult — use special tools
Electrical	Low dielectric constant (2.2) over a wide range of frequencies



a) Aramid



b) UHMWPE



## ARMOR APPLICATIONS FOR ARAMIDS AND UHMWPE FIBERS

of weapons, man has sought ways to protect himself from injury in war. The first armor was made from boiled and hardened animal hides. As weaponry grew more effective, developing armor capable of protecting against the new, increased threats became an ever greater challenge. Then, when armor became effective against a particular threat, the challenge of warfare was to increase the effectiveness of the threat, thus creating a cycle of ever increasing threats and armor improvements.

History has seen some sophisticated uses of body armor. In ancient Rome, centurions wore a thick leather garment called a “cuirass” to protect themselves. In the middle ages soldiers wore chain mail (a flexible covering made from interlocking small metal rings). When the crossbow made this armor ineffective, solid metal armor was developed. The weight and rigidity were, of course, a serious limitation. This problem was overcome in part by the development of metal plate armor with chain mail joints for increased flexibility.

Advanced firearms came along in the twentieth century and shortly thereafter came the development of synthetic-based body armor. Ballistic nylon vests were credited with the first law enforcement “saves” from both knife thrusts and bullets in the 1960's.

Shortly thereafter Kevlar<sup>®</sup> (DuPont Trademark) was developed and almost immediately it became the standard material for modern body armor. After several years, Spectra<sup>®</sup> (AlliedSignal Trademark) was developed and it, too, has become a standard material.



## Making the body armor

Usually the materials are not laid up as loose fibers. Prepregs of the fibers are made in normal prepregging operations. For body armor, the prepreg matrix is flexible. For instance, in the case of Spectra, the matrix is a thermoplastic elastomer. This holds the fibers in place and yet gives high flexibility to each sheet. Normally, two layers of the prepreg material, one oriented at 0° orientation and the other oriented at 90°, are bonded together and covered top and bottom with thin sheets of polyethylene to create a single unit that is sold as the basic building material for body armor. The polyethylene sheets allow each unit to slide against adjoining units and thereby give a more flexible armor material. Several layers of these basic units are stacked and placed into a pouch which is then sewn closed. The vest or jacket has numerous pouches with these stacked reinforcement units, thus creating the armor material.

The National Institute of Justice has established a standard for assessing the ballistic resistance of body armor. This standard (NIJ Standard 0101.03) sets specific procedures for testing body armor and establishes levels of threats. The number of layers of basic reinforcement materials needed to meet various threats are illustrated in the accompanying table.

Level	Ammunition Stopped	Number of Layers of Spectra
2A	9 mm	22
2	44 mag & 357 mag & 9 mm	32
3A	wad cutter, 240 grain bullet	40

