Recent carbon fiber advancements

William H. Gardner

Composite materials based on carbon fiber reinforcement are finding uses in aircraft structures, in high-performance rocket motors, and in precisely constructed space structures.

The aerospace industry is in the midst of a significant revolution. High performance requirements, such as reduced fuel consumption and enhanced maneuverability, have led many manufacturers of new aircraft to use a new class of materials known as fiber-reinforced composites. These advanced composites, which are made of high-performance fibers and resins, provide better performance than glass/polyester composites.

Fiber-reinforced composites are used as a metal substitute because they provide lighter-weight structures and can enhance mechanical performance. These composites can also offer advantages in manufacturability and cost.

This article outlines some of the recent developments in carbon-fiber technology and products.

Applications

The use of advanced composites within the aerospace industry has grown rapidly in the last ten years. In most cases, military applications have paved the way for spin-offs in the commercial sectors.

Today's composite materials

The aerospace industry initially used carbon-fiber-reinforced epoxies to fabricate doors and other secondary structures that were not critical to flight safety. Now carbon/epoxy composites are used for primary airframe structures such as aircraft fuselages and wings.

Carbon-fiber-reinforced composites are valued for their high elastic strength (specific Young's modulus). **Table I** shows the relative physical and mechanical properties of some of the composites that are now available.

High-modulus fibers for aircraft structures

Fibers with increased stiffness, such as IM-6, have spawned much interest because they have made it possible to manufacture high-modulus materials without sacrificing tensile strain or compressive strength. Before the introduction of IM-6 fibers, increases in tensile modulus were accompanied by decreases in strength. This material is used to fabricate the structural frames of fighter aircraft, where stiffness is a critical factor.

New methods for the manufacture of carbon fiber were developed to provide materials for these advanced structures. The physical properties of these high-modulus fibers are given in **Table II**.

Continuous filament reinforcements are of little value without a matrix to hold the filaments together. In the aerospace market, this matrix has generally been an epoxy resin system. As we move to the next generation of fighter aircraft, the temperature requirements dictated by the speed of these aircraft will push us beyond the temperature capability of epoxies. There are several possible alternative systems.

Bismaleimides and polyimides or combinations of these with epoxies will be one set of materials. Thermoplastics are another group of candidates. No matter what matrix is employed, the reinforcements will have a combination of high tensile and compressive strength as well as high specific modulus. Airframe structures have become a large segment of the advanced composites application base, and this trend is expected to continue.

High-strength fibers for rocket motor cases

A smaller but not insignificant utilization for these advanced composites is in the area of high-performance pressure vessels, such as the motor cases for solid-fuel rocket motors. This area can be divided into two parts, the relatively small ultra-high-performance strategic missiles and the large booster rockets used for space flights. Both applications can benefit from materials with high specific tensile strength (strength/density).

Solid-fuel rocket motors were made of steel cases in the 1950s, fiberglass in the 1960s, and aramid-fiber-reinforced cases in the 1970s. Carbon-fiber-reinforced motor cases were introduced in the 1980s. Each of these developments can be traced to improvements in the specific strength of the case materials. Today's strategic rocket motors use a carbon fiber with specific tensile strength of 12.4×10^6 in. (3.1×10^5 m).

Designers of some space defense initiative (SDI) rocket propulsion systems would like to see improvements of 10–20% in specific strength. This level of specific strength would require a material with the density of carbon fiber

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I. Physical and mechanical properties* of various composite structures

	0° Tensile strength		0° Tensile modulus		0° Tensile strength, %	0° Compressive strength		Density	
	10^3 lb/in.²	GPa	10^6 lb/in.²	GPa		10^3 lb/in.²	GPa	lb/in.³	g/cm³
S-2 glass	388	2.67	7.8	53.8	5.0	100	0.69	0.1471	2.6
Aramid	325	2.24	11.8	81.4	2.8	100	0.69	0.0924	1.45
AS-4 *(carbon Hercules)*	360	2.48	20	138	1.8	250	1.72	0.0645	1.8
IM-6 *(carbon Hercules)*	390	2.69	24	165	1.6	270	1.86	0.0627	1.74
HMS-4 *(graphite Hercules)*	120	0.83	29	200	0.4	150	1.03	0.0645	1.8

*All data normalized to 62% fiber volume in epoxy resin.

II. Strength properties of high-modulus PAN based carbon fibers

	0° Tensile strength		0° Tensile modulus		0° Tensile strain, %	0° Compressive strength	
	10^3 lb/in.²	GPa	10^6 lb/in.²	GPa		10^3 lb/in.²	GPa
IM-6 (carbon)	390	2.69	24	165	1.6	270	1.86
IM-X (carbon)	365	2.52	27	186	1.4	290	2.00

All data normalized to 62% fiber volume in epoxy resin.

III. Strength properties of ultra-high-modulus fibers

	0° Tensile strength		0° Tensile modulus		0° Tensile strain, %	0° Compressive strength		Short-beam shear strength	
	10^3 lb/in.²	GPa	10^6 lb/in.²	GPa		10^3 lb/in.²	GPa	10^3 lb/in.²	GPa
[a]P-75 (UCC)	110	0.76	40	276	0.3	75	0.52	7	0.048
[b]GY-70 (BASF)	120	0.83	40	276	0.3	75	0.52	7	0.048
[b]XUHMS (Hercules)	300	2.1	40	276	0.8	150	1.03	8	0.055

[a]Pitch based
[b]PAN based

to have strengths of 1,000,000 lb/in² (6.9 GPa). Carbon fibers with strength in this range have been made on a research scale and are being developed for production manufacture.

The key areas in the development of high-strength fibers have been the reduction of filament surface defects and improvements in filament homogeneity. High-strength carbon fibers with strengths in excess of 2,000,000 lb/in² (13.8 GPa) are within the realm of possibility.

Ultra-high-modulus fibers for space structures

Although space applications for advanced composites account for only a small portion of the total amount produced, these applications provide unique manufacturing opportunities for specialty products.

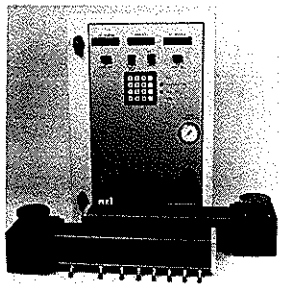
Most of the fiber-reinforced composites are anisotropic. This characteristic, coupled with a fiber that has a negative axial coefficient of thermal expansion, enables the design and construction of structures with an overall near-zero coefficient of thermal expansion. This attribute is extremely beneficial for satellite structures, and fabricators are willing to pay to meet these unusual requirements.

Dimensional stability is also enhanced by significant increases in stiffness. High-modulus reinforcement is needed to make stiff structures. Graphite fibers in excess of 50×10^6 lb/in.² (345 GPa) moduli have been available for some time. Suppliers of graphite fiber made from either pitch precursors or polyacrylonitrile (PAN) have products in the 70×10^6 lb/in.² (483 GPa) region. These ultra-high moduli do not come without penalties. Generally, the tensile strength and, hence, the tensile strain are much lower than those of lower-modulus carbon fibers. Shear strength and compressive strengths are also much

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Thus, there is a clear need for improvements in the tensile strengths of these ultra-high-modulus fibers. Strength development in ultra-high-modulus fibers made from PAN precursors shows promise (**Table III**) when compared with typical high-modulus fibers made from pitch precursors.

Conclusions

Design engineers have defined the need for better, stronger carbon fibers. Producers of carbon fibers are meeting this challenge by preparing carbon fibers with the requisite properties. Specifically, the fibers that are becoming available have (a) very high tensile strength at conventional modulus levels, (b) high tensile strength at high modulus levels, and (c) improved tensile strength at ultra-high modulus levels.

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