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Basics of Aerospace Materials: Aluminum and Composites

Machine Design

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Aluminum will likely be in airframes for another century, while composites represent the new material on the block.

Two materials play major roles in modern aerospace: aluminum alloys for airframes and skin, and composites for structures. Here's a look at both.

Aluminum

There are some aviation observers who predict composites and titanium will rule the roost when it comes to aerospace airframes and structures. But that seems rather unlikely. Aluminum is still lightweight, technically advanced in terms of forming and alloying, and it relatively low cost, especially when compared to titanium and composites.

Alcoa, for example, predicts 6% more aluminum will be used in planes in 2013 compared to 2011. The company, a major producer of aluminum, also points out that the current fleet of airliners and military jets are heavy users of aluminum, and newer designs continue to specify lots of aluminum. The Airbus A380, one of the largest passenger airliner in the world, contains 10 times the amount of aluminum used in the Airbus A320. And Boeing's 787 Dreamliner, which is often described as a composite aircraft, contains 20% aluminum (by weight) which includes aluminum 7085, a relatively new aluminum alloy.

Other segments of the aircraft industry are also continuing to use aluminum instead of composites. A regional jet being developed at Mitsubishi, for example, was initially going to be equipped with composite wings. Eventually, the company admitted it would go with aluminum wings and they would be "a better overall solution." And Mitsubishi supplies composites to commercial aircraft manufacturers.

Even on high-performance military jets, aluminum continues to have a significant role. For example, aluminum is used extensively in the J-35 Joint Strike Fighter. It makes up six forged bulkheads that form the aircraft's major weight-bearing portion of the airframe.

Aluminum characteristics: Though lightweight, commercially pure aluminum has a tensile strength of about 13,000 psi. Cold working the metal approximately doubles its strength. Aluminum is usually alloyed with elements such as manganese, silicon, copper, magnesium, or zinc to further increase strength. The alloys can be made stronger by cold working. Some alloys are further strengthened and hardened by heat treatments. At subzero temperatures, aluminum is stronger than at room temperature and is no less ductile. Most aluminum alloys lose strength at elevated temperatures, although some retain significant strength to 500°F.

Besides a high strength-to-weight ratio and good formability, aluminum also has its own anticorrosion mechanism. When exposed to air, aluminum forms a hard, microscopic oxide coating which seals the metal from the environment. The tight chemical oxide bond is the reason aluminum is not found in nature; it exists only as a compound.

Aluminum and its alloys, numbering in the hundreds, are available in all common commercial forms. Aluminum-alloy sheet can be formed, drawn, stamped, or spun. Many wrought or cast aluminum alloys can be welded, brazed, or soldered, and aluminum surfaces readily accept a wide variety of finishes, both mechanical and chemical. Because of their high electrical conductivity, aluminum alloys are used as electrical conductors. Aluminum reflects radiant energy throughout the entire spectrum, and is nonsparking and nonmagnetic.

The most common aluminum alloy used in aerospace is 7075, which has zinc as the primary alloying element. It is strong, with strength comparable to many steels, and has good fatigue strength and average machinability, but has less resistance to corrosion than many other aluminum alloys. Its chemical composition roughly includes 5.6-6.1% zinc, 2.1-2.5% magnesium, 1.2-1.6% copper, and less than half a percent of silicon, iron, manganese, titanium, chromium, and other metals. It is commonly produced in several heat temper grades.

Aluminum matrix composites: Metal matrix composites (MMCs) consist of metal alloys reinforced with fibers, whiskers, particulates, or wires. Alloys of numerous metals (aluminum, titanium, magnesium and copper) have been used as matrices to date. In the NASA Space Shuttle, for example, 240 struts are made of aluminum reinforced with boron fibers.

Superplastic aluminum: Superplastic metal forming, a process similar to vacuum forming plastic sheets, has been used to form low-strength aluminum into nonstructural parts such as cash-register housings, luggage compartments for passenger trains, and nonload-bearing aircraft components. But superplastic-formable high-strength aluminum alloy, a relatively recent development, is available for structural applications and designated 7475-02. Strength of alloy 7475 is in the range of aerospace alloy 7075, which requires conventional forming operations. Although initial cost of 7475 is higher, finished part cost is usually lower than that of 7075 because of the savings involved in the simplified design and assembly.

Composites

In the early days of composites, glass fibers were used to strengthen a matrix of epoxy resin. This glass reinforced plastic (GRP) was used for radomes and helicopter blades but found limited use in airplanes because of its low stiffness. In the 1960s, new fiber reinforcements were introduced, including Kevlar, an aramid with the strength of glass fibers but stiffer. Today, carbon fibers are the reinforcement of choice for aerospace composites.

Carbon fibers in aerospace composites can be long and continuous, or short and fragmented, and they can be directionally or randomly oriented. In general, short fibers cost the least and fabrication costs are lowest. But, as with glass, properties of resulting composites are lower than those made with longer or continuous fibers.

Milled fibers are the shortest carbon fibers used for reinforcement. They range in length from 30 to 3,000 microns, averaging approximately 300 microns. Mean L/D ratio (length to diameter) is 30. Short chopped fibers with an L/D ratio of about 800 increase strength and modulus of composites more than milled fibers do. Cost of a molding compound reinforced with short fibers is about twice that of one containing milled carbon fibers.

Long chopped fibers (up to two inches long) are often added to a thermosetting glass/polyester sheet-molding compound to increase the stiffness of compression-molded parts. Continuous carbon fibers provide the ultimate in performance and weight reduction. Continuous fibers are available in a number of forms including yarns or tows containing 400 to 160,000 individual filaments; unidirectional, impregnated tapes up to 60 in. wide; multiple layers of tape with individual layers, or plies, at selected fiber orientation; and fabrics of various weights and weaves.

The important design properties of carbon composites are their high strength-to-weight and stiffness-to-weight ratios. With proper selection and placement of fibers, composites can be stronger and stiffer than steel parts with similar thicknesses but 40 to 70% less weight. Fatigue resistance of continuous-fiber composites is excellent, and chemical resistance is better than that of glass-reinforced composites, particularly in alkaline environments. Like most rigid materials, however, carbon composites are relatively brittle. They have no yield behavior and resistance to impact is low.

Thermal characteristics of carbon fibers differ from those of almost all other materials. Linear expansion coefficients range from slightly negative for 30 million-psi modulus fibers to approximately -1.3×10^6 in./(in.- °F) for ultrahigh-modulus fibers. This property makes possible the design of structures with zero or very low linear and planar thermal expansion — a valuable quality for components in precision instruments. Transverse coefficients of expansion are quite different — typically 15×10^6 in./(in.- °F).

Comparing aerospace composites

Material Type	Nomenclature	Tensile strength (ksi)	Modulus (Msi)	Strain (%)
Carbon/Epoxy	T300/934	245	20	1.0-1.2
	IM7/8551-7	400	24	1.62
	P75/934	135	44	0.2-0.5
	AS4/3501-6	100	10	1.0
	IM6/3501-6	330	23	1.5
Glass/Epoxy	E-glass/934	150-170	6-8	2.75
Kevlar/Epoxy	K-49/7934	80-85	4	1.85
Carbon/PEEK	IM7/APC-2	419	24	1.6
Carbon/Phenolic	FM5055	15-20	2.6-2.8	1.0-1.2

Aerospace Composite Glossary

Adhesive: A thermoset resin such as epoxy or phenolic in the form of a film or paste, cured under heat and pressure to bond a wide range of composite, metallic and honeycomb surfaces.

Aramid: A strong, stiff fiber derived from polyaqmide. Kevlar and Nomex are aramids.

Carbon fiber: Fiber produced by carbonizing precursor fibers based on PAN, rayon, or pitch. The term is often used interchangeably with graphite. However, carbon and graphite fibers are made and heat treated at different temperatures and contain different amounts of carbon.

Composite materials: Materials made by combining two or more dissimilar materials such as fibers and resins and having structural properties not present in the original materials.

Engineered core: The forming, shaping, machining, or bonding of sheets or blocks of honeycomb into profiled and complex shapes for use as semi-finished parts of composite assemblies and structures.

Fiberglass: Filaments made by drawing molten glass. Often used as a composite reinforcement.

Filament winding: A process used to make composite-material components such as rocket casings and cylinders. Fiber filaments are impregnated with a resin and wound over a form or mandrel of the component. How the fibers are wound affects strength and stiffness.

Honeycomb: A lightweight structure made from metallic sheets or on-metallic materials such as resin-impregnated paper or woven fabric formed into hexagonal nested cells, similar in appearance to a cross-section of beehive. The structure adds strength to finished panels and parts.

Modulus of elasticity: The measure of a material’s stiffness. The higher the modulus, the stiffer the material.

Polyacrylonitrile (PAN): A polymer which gets spun into fibers used as a precursor material when making certain carbon fibers.

Precursor: The PAN, rayon, or pitch fibers from which carbon or graphite fibers are derived.

Prepreg (pre-impregnated): A composite material made by adding reinforcement fibers or fabrics to a thermoset or thermoplastic resin matrix.

Primary structure: A critical load-bearing structure on an aircraft. If this structure is severely damaged, the aircraft cannot fly.

Reinforcement: A strong material which gets mixed with a resin to form composite materials. Reinforcements are usually continuous fibers, which may be woven. Fiberglass, aramid and carbon fibers are typical reinforcements. Fabrics can also be used as reinforcements, including those made using fiberglass, carbon, or aramid.

Resin matrix: A polymeric substrate such as epoxy or PEEK.

Sandwich panels: A stiff and lightweight panels consisting of thin sheets such as aluminum or cured prepreg laminate bonded to a low-density, rigid-core material such as foam or honeycomb.

Spectra: A high strength polyolefin fiber from Allied Signal. Woven Spectra fabrics are strong and lightweight and are used in composite materials.

Tow: An untwisted bundle of continuous carbon filaments.

Yarn: A twisted bundle of glass filaments, not necessarily continuous.

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