# 7.0 Structural Materials (Integration of Materials and Structure)

Structural, including engine, materials have been largely responsible for the major performance improvements in Air Force systems by optimizing certain physical and mechanical properties, such as density, strength, and stiffness. Future structures are likely to require multifunctional capabilities in single components. The use of structural materials such as composite materials will enable this capability.

Composite materials are themselves "structures." Because of their functionality, composite materials have helped narrow the chasm between the disciplines of design and materials. Structural design and materials science must become even more integrated in the future as materials' properties are graded and locally altered to meet multifunctional requirements in structures. Furthermore, the structures must meet the mission requirements for the full life cycle or must be designed for easy or even self-identification of developing flaws and simple repair. Such structures must also be economically manufactured in terms of the total life-cycle costs.

## 7.1 Materials Payoffs in the Future

The selection of a material is determined by its combination of properties, ease of manufacture, useful lifetime, and total cost. For aircraft structural materials, most airframe materials traditionally have operated near ambient temperature. However, aeropropulsion and hypersonic airframe components must operate at high temperatures, some for several thousands of hours, others only for minutes. Space structural materials must survive excursions to both low and high temperatures. There are frequently other requirements, such as electrical conductivity, optimized thermal management, or dimensional stability (low thermal expansion), which might be combined with the structural requirements. The questions are: What are the trends in materials properties, and what are their payoffs?...What materials might or already provide improved properties?...What is the physical basis for these properties?...What new directions might materials development take to achieve these properties?...Can we fabricate, repair and dispose of them economically?...What enhanced or new systems capabilities will these new materials provide?

### Lower Weight

For a given modulus and strength, the material with the lower density will give a lower weight structure, all other factors assumed equal. Density always provides a first power weight saving: half the density, half the structural weight. This truth accounts for the use of aluminum, and the trend from aluminum to composites. Aluminum is about 50 percent more dense than a carbon fiber / epoxy matrix composite. Polymeric materials, with their very low density, are even more attractive. If polymers were available with suitable mechanical properties, an additional weight savings over present composites could be realized, plus the simplicity of polymeric fabrication. Addition of light-weight elements in metallic alloys usually decrease density. Additions of lithium to aluminum decrease density more than proportionately and even increase stiffness. Performance improvements equal to approximately one-half of those attainable with present composites are possible, yet with the normal advantages of metals. Processing of this reactive material has been costly, and corrosion has been a problem. Addition of aluminum to titanium, nickel, or niobium in larger quantities to form low-density intermetallic compounds offers weight savings of up to 50 percent, often with even potentially better mechanical properties. These trends will probably continue with weight savings of up to 50 percent.

## Stiffer, Stronger Structures

High strength and stiffness require strong chemical bonds, with each atom having as many covalent bonds as possible. The moduli of metals increases linearly with density, such that the specific modulus—stiffness/density—is constant to two significant figures. Beryllium is an important exception, as it has a modulus one-third higher than steel, but with one-fifth the density. Covalently bonded materials have the potential of providing up to 15 times the specific modulus of the common engineering metals. High specific modulus elements are bunched around carbon in the periodic table and include boron, compounds of beryllium, boron, carbon, nitrogen, oxygen, aluminum, silicon, yttrium, and titanium.

Most of these elements are among the most plentiful available, although boron and beryllium are rare. Graphite has the highest specific modulus in the directions of the chicken-wire structure basal planes with about five times the modulus, at less than one-third the density of the common engineering. However, the specific modulus normal to the planes has only one-third the value of the common engineering materials. Carbon fibers having sufficient strengths for structural applications have only achieved about one-third of the theoretical modulus, while carbon fibers with nearly theoretical modulus, but substantially reduced strengths, have been made for other applications. Carbon fibers with 100 percent higher modulus should be developed, with balanced tensile and compressive strengths, to fully exploit the increased modulus. Cost issues surrounding these fibers would have to be monitored to keep them financially attractive.

Theoretically, a high modulus material with high bond strength should also have high tensile strength. Since the most attractive materials from a specific modulus/strength view exhibit brittle failure, the challenge is to develop a material with very small flaws. There are two microstructures that might allow ultrahigh strength: single crystals, or nanocrystalline to amorphous materials. The nanocrystalline approach has been most attractive for near-ambient temperatures because of relatively rapid processing speeds and quick achievement of adequate tensile strengths. The fiber or film form allows more rapid processing with finer microstructures, but more importantly has a small volume and surface area which gives high strength because of the smaller probability of finding a major flaw. Fibers usually increase in strength with decreasing diameter. However, there is a lower limit to diameter: 1) health, (i.e., carcinogenic behavior of small diameter fibers), and 2) manufacturability (i.e., fiber breakage due to aerodynamic drag during spinning). There is also an upper limit due to processing and handling. Practically, fibers can be made in the range of 3 micrometers to 200 micrometers, which also depends somewhat on the process. Fine diameter carbon fibers have been made commercially with a 7 GPa (1 Msi) tensile strength or two times more than commonly used fibers. Hence, twice the stiffness and strength, in both tension and compression, should be attainable, but some novel effort is required. Once again, costs must be contained to make these fibers attractive.

Films provide stiffness and strength in two dimensions. While they are attractive for providing stiffness, a crack can propagate across a whole film, whereas a layer of fibers requires fracture of each fiber. Lamellar structures would provide in-plane isotropy with an increase of approximately 80 percent in stiffness, given the same materials used in fiber form. However, a more reasonable increase is 25 percent, in order to retain a desirable fracture behavior. Very thin lamellar structures in metals have shown experimentally very high strengths and surprisingly up to 30 percent higher modulus. For different reasons, thin ceramic lamellar are predicted to have significantly higher strengths and improved toughness. Both these latter areas are at the research stage. Film or lamellar structures will first appear where a planar, albeit curved, geometry can be exploited. First applications will probably be in aeropropulsion, but skin structures are also likely uses.

## Longer Lifetime

Airframes are being used substantially longer than their original design lifetimes. Furthermore, structural loads are increased due to new mission profiles, armament, and electronics. Deleterious effects on durability and lifetimes can be expected. New systems must be designed for much longer lifetimes, and present systems must be monitored and repaired.

Mechanical failures can occur from simple overload of the structure. Increasing the strength of the material, if possible, alleviates this problem. However, a very strong material may be sensitive to initial flaws introduced during fabrication or service. A major improvement in the strength of materials has arisen from our ability to reduce the size and number of flaws. An important factor has been the development of techniques that can identify very small flaws in complex structures, but improvements will be required in resolution for effective application of high strength ceramic materials. Although intertwined, mechanical failures often occur from the inability of the material to withstand multiple loadings well below the initial failure load, which is frequently exacerbated by corrosion.

Composite materials can have extremely high strength, and modest damage tolerance. For two-dimensional structures such as skins, delamination between composite plies in resin matrix composites is the limiting design parameter. To improve resistance to out-of-plane loads, a variety of techniques have been examined. Stitching has been used, but has adversely affected in-plane properties, such as compressive strength. A more uniform strengthening, which might be more generally applicable, is desirable. Several techniques have shown promise, such as whiskerizing, but have not been implemented. Development of these methods should be pursued. However, improving interlaminar strengths may cause the failure mode to change to in-plane, a potentially more catastrophic failure.

Composite materials have also been touted for their excellent fatigue resistance. That is true if the loads are predominantly carried by the fibers, but not if carried by the fiber/matrix interface or by the matrix. Hence, a composite structure may have little likelihood of a fatigue failure in most of its structure because fibers are carrying the load, but may be very sensitive to fatigue in certain other regions. Careful design is required, and a change in concept from black aluminum to visualizing a composite as an ensemble of ropes loosely coupled together must occur. Free edges and cutouts must be minimized because they are sources of delamination and fracture. Assuming proper design, resin matrix composites generally provide run-out (no failures after more than $10^8$ cycles) at 60 percent (2-D isotropic) to 90 percent (uniaxial) of the tensile strength. This is typically about a two-fold or better improvement in stress over structural metals. Composites do not perform as well in compression or torsional fatigue as the matrices and interfaces must carry major loads. Run-out loads may be limited to as low as 20-25 percent of the single load strength, which is poorer than structural metals. Fatigue in metal and ceramic matrix composites is also observed to be excellent when properly designed, even though extensive microcracking occurs. This may require replacement of the part for loss of stiffness, even though the retained strength may be adequate for the mission.

In summary, composite materials can offer dramatic performance improvements due to characteristics such as longer fatigue lifetimes. Substantial improvements in composite materials, such as improved fibers, are possible, with a resultant improvement in the performance of system components. Attention needs to be paid to improved composite-specific design practices and to the prevention of service-induced damage.

## Higher Temperature

The higher operating temperature for airframes in sustained supersonic flight makes aluminum and epoxy-based carbon fiber composites marginal, except for lower Mach numbers. Higher temperature metals such as titanium and higher temperature carbon-fiber composites based on imides are currently acceptable for higher Mach numbers. New resin systems with carbon fibers, metal matrix composites, and intermetallic alloys appear satisfactory up to temperatures of approximately 500°C. They are in different stages of development and maturity, but are all likely to find application in aerospace systems.

Materials in the temperature range from 500°C to 1500°C are covered in the section on gas turbines. Even apparently small increases in operating temperatures of a gas turbine have a major impact on specific fuel consumption and thrust to weight ratio. However, increases in operating temperatures are limited by the melting points of the presently-used alloy systems. Future improvements must come from the application of ceramic materials.

Materials for applications above 1500°C are limited. Graphite has a sublimation temperature of about 3700°C and the best mechanical properties at high temperature. Graphite begins to creep at 2200°C, but can be used in lightly loaded structures up to 2800°C or even higher. A problem is that an appreciable vapor pressure exists at temperatures above 3000°C, and this may give rise to an appreciable loss of mass. The major problem with graphite is oxidation in oxidizing atmospheres, which begins at temperatures as low as 350°C and at 700°C for pure and highly perfect single crystal graphite respectively. Much effort has been expended on oxidation protection schemes for graphite, but the fact remains that it does oxidize, and the vastly different coefficients of thermal expansion cause cracking in oxidation resistant coatings and infiltrants.

Substantial progress has been made towards solving these problems, and some parts have withstood 500 hours of cyclic oxidation, but other similar parts have survived for only 50 hours. Oxidation performance depends on the exact temperature cycle, as lower temperature oxidation is often more severe than at higher temperatures. Silicon-based protective systems are limited by the loss of the protective silica film at temperatures above 1740°C and 1 atmosphere. Oxidation protection systems for higher temperatures are based on alumina or hafnia formers. Both are not as good at lower temperatures, but French results with alumina formers have been remarkably good up to 2000 C. Hafnia forming systems are limited to about 2400°C, because the volatility becomes appreciable for long term applications approaching 1000 hours. However, hafnium diboride, with a 3250°C melting point, has been found to provide improved short term, very high temperature oxidation resistance with better low temperature resistance. All these coatings have significantly higher thermal expansion coefficients than graphite, and cracks can occur upon cool-down. Passing an inert or possibly even a fuel gas through a coated carbon/carbon composite may allow active protection.

Oxide materials appear to be attractive for oxidative conditions. However, the most creep-resistant oxide—yttrium aluminum oxide—starts creeping at 1500°C. Hence oxides could only be used in nonload-bearing applications at high temperatures. Melting points and volatility also become a problem. Oxides generally have high thermal expansion coefficients, and relatively high moduli, which makes them susceptible to thermal shock. For relatively short times (hours) and for temperatures above 2500°C, careful design of stabilized hafnia liners may be attractive. The yttria stabilizer, which prevents a phase transformation, evaporates relatively rapidly by 2500°C and its use probably would be limited to a single mission.

Oxide materials are attractive for thermal barrier coatings and reinforcing fibers. For example, multilayered coatings of alumina and zirconia are very effective in decreasing the temperature of parts. The physical understanding of this performance is not understood, and improvements can be expected in the future. Oxide fibers can be used for lower temperature applications. Oxide fibers have suitable thermal expansion coefficients for potential matrix materials. Thermochemical compatibility of the matrix and fiber has been a problem, however.

Non-oxide ceramics fill an important niche between superalloys and graphite. They offer higher operating temperature and good oxidation resistance. Silicon carbide has the potential of adequate creep resistance to 1550°C and to 1800°C in single crystals. The fracture toughness of monolithic silicon carbide is low and formation of a composite is probably required for extensive application. Silicon nitride is much tougher and stronger than silicon carbide, but is probably limited to 1400°C because of creep. Both are limited by active oxidation above 1740°C and more practically to about 1650°C. The development of silicon carbide composites for jet engines would provide large increases in combustor and turbine temperatures compared with the incremental improvements with superalloys. However, the choice of superalloys (or their replacements) with thermal barrier coatings, or ceramic matrix composites is not obvious.

Other fibers that have thermochemical and thermomechanical compatibility with potential matrices, such as titanium diboride, would provide lower density with higher operating temperature than the nonreinforced matrix.

Hypersonic vehicles using air breathing engines will surely be an important part of the offensive and defensive weaponry of the future. They will use ramjet/scramjet engines and be capable of speeds up to the Mach 25 to achieve access to space. In the near term—the next ten years—non-man-rated vehicles will be built to serve as precision scalpels to expediently neutralize ground targets and air and spaceborne targets. These vehicles would be powered with scramjet engines that use conventional hydrocarbon fuels, making them capable of being incorporated easily into the Air Force warfighting infrastructure, and both the airframe and the engines would be fabricated from materials that are currently being researched.

In the further term—within 25 years—man-rated vehicles operating in the same speed regime would require the same types of materials, but the reliability would be significantly improved as production experience is gained with building the non-man-rated systems. These vehicles could have a variety of roles, ranging from high-speed battlefield fighter aircraft to long-range, global-reach bomber transport aircraft. Ultimately, they could eliminate the need for overseas bases, in the sense that they could reach any part of the world in a few hours.

In the far term, routine access to space will be accomplished using single-stage-to-orbit (SSTO) vehicles. Present trends indicate that these vehicles would be powered by air-breathing engines for most of the flight, with a rocket being used for the space portion. It may well be the case that some new generation of thrust production becomes available, but a clear requirement will continue to be a low airframe structural weight and an efficient, lightweight air-breathing propulsion system. The types of materials used for the near- and middle-term applications will probably include nickel-based superalloys, advanced refractory alloys, intermetallics, metal matrix composites, intermetallic matrix composites reinforced with ceramic fibers, ceramic and carbon-carbon composites, and lightweight thermal insulation materials. In addition, for both the engines and airframe, high thermal conductivity materials such as copper-based alloys, beryllium-based alloys and carbon-carbon composites will be needed. Almost all of these materials will require coatings to provide protection against oxidation and the other environmental conditions associated with high speed flight through the atmosphere. Advanced processing methods will be used to produce the necessary lightweight structures that in some cases will contain arrays of coolant passages through which fuel will flow to serve as the temperature control of the structure.

For the far-term applications, advanced versions of current materials will be needed. These may include super-lightweight materials such as beryllium composites or very high temperature-resistant materials such as fiber-reinforced ceramics, nanostructures, functionally graded materials, multilayer coatings, high-temperature electronic materials, high thermal conductivity materials, high-temperature transparencies, etc. It is clear that materials will be an enabling technology for hypersonic vehicles of the future.

To realize the extraordinary benefits of significantly increased temperatures, superalloys, refractory alloys, intermetallics; ceramic, carbon and intermetallic matrix composites, creep-resistant fibers; environmentally stable, crack-stopping interfaces; and high strain-to-failure matrices must be developed. These are not trivial, cheaply solved problems.

## Thermally Conductive/Thermally Dimensionally Stable Structures

Heat dissipation from electronics modules and space structures is a major problem. Dimensional stability of platforms and antennae when subjected to temperature fluctuations is often required. An increasing demand is also being placed on heat exchangers in aircraft. Future heat exchangers need to have increased efficiency and reduced weight.

High thermal conductivity is often associated with electrical conductivity, but the best thermal conductors near room temperature are phonon (lattice vibration) conductors. The best thermal conductors will be pure elements with strong bonding in a highly perfect single crystal. Isotropically pure diamond has the highest theoretical and experimental thermal conductivity with a conductivity/density ratio over a magnitude better than copper. Diamond films offer much improved thermal conduction for semiconductor heat sinks, such as tungsten/copper laminates, or substrates such as beryllium oxide, aluminum nitride, or alumina. Diamond-film fabrication improvements can be expected to allow large areas to be coated, at higher deposition rates, and at lower temperatures, but possibly not all simultaneously. Chemical vapor infiltration of diamond powder preforms would allow more massive and complex parts to be fabricated. Diamond fibers have the potential of providing high stiffness and strength as well as high thermal conductivity. Diamond fibers would probably have the best compressive properties of any fiber for use in composites if a suitable interface was achieved.

Graphite provides almost the same specific thermal conductivity as diamond but only in the two dimensions of the planar structure. When combined with a carbon matrix, the resultant composite has the highest thermal conductivity of any composite material. Carbon-fiber/aluminum provides more than twice the conductivity of aluminum with 15 percent less density. Reliability of electronics and weight savings could be achieved by direct replacement of present thermal conductors with these materials. While life-cycle costs may be reduced, the initial cost of high conductivity carbon fibers—$2000 per pound—limits their application. Part of the high cost is caused by the small production volume associated with high-temperature processing. Certainly, a great reduction in costs is possible with changes in precursors and increase in production volume. Decreasing the cost nearly two orders of magnitude is conceptually possible, but would require improved chemistry to be developed. This also may allow the thermal conductivity to double, approaching the theoretical value.

Thermal conduction in composites for space structures could be enhanced if diamond fibers were available. Thermal conductivity, stiffness, and compression would be the major considerations and all are well satisfied by diamond. An alternate is a lamellar structure using diamond films, which may be cheaper and provide two-dimensional conductivity. Carbon fibers might be developed that would meet all the requirements. However, high thermal conductivity fibers and structural carbon fibers are a more likely optimum.

Strong bonding and an open structure, typical of covalent bonding, tend to produce low thermal expansion coefficients. Negative thermal expansion coefficients are frequently observed in rod layer and other anisotropic structures. Negative coefficient materials can be combined with a positive coefficient material to provide a zero expansion coefficient, at least over a limited temperature range. Often this can be done with one material, since the different expansion coefficients can be in two directions within the crystal. Graphite and magnetostrictive materials, including some alloys and titanates, are examples. High-modulus carbon fibers have a small negative coefficient at room temperature that can be used to produce structures with near-zero thermal expansion and high stiffness. The problem again is poor compressive strengths. A different fiber architecture is required, but it has not been proved that a better balance of properties can be achieved. Stiff rod-like polymers also have a negative thermal expansion coefficient along the rod. However, the transverse thermal expansion and the moduli have not allowed near-zero expansion for angle-ply composites. Large changes in properties are not required to achieve zero thermal expansion. The problem is that these aligned rods buckle under very low loads in compression. Most designs require balanced tensile and compressive properties. While the problem appears to be inherent to the material, the payoff is sufficiently high for both polymeric and carbon fibers that any innovative but sound idea should be funded.

## Future Materials Chemical Compositions

Considerations of density, stiffness, strength, thermal conductivity and thermal expansion all lead to more emphasis on the lighter elements in the center of the periodic table. Aluminum, magnesium, carbon, beryllium, silicon, titanium, yttrium, and their compounds with oxygen, fluorine, and nitrogen provide the highest potential improvements. Additions of light elements to form intermetallic compounds of titanium, the iron group, niobium, and perhaps several others offer lower densities, higher operating temperatures, and sometimes improved oxidation resistance, but usually with a loss of ductility. Progress in achieving a modicum of ductility in some of these systems can be expected.

### Desirable Microstructural Architectures

A material's properties are partially determined by its composition and crystal structure, and also by its microstructure. The size, shape, and orientation of the crystals in a solid have a primary effect on a material's properties. The improvement of materials will continue by finding new materials compositions and optimization and control of the microstructure. The ability to control microstructure on a finer scale will undoubtedly lead to unexpected changes in properties. However, finer control of properties by placement of materials, as in fiber-reinforced composites, leads to a higher level of architecture. Designers in the future will dictate this top level of architecture, by specifying the orientation and number of plies in a composite, for example, as well as by integrating sensors to measure stresses or failure. In addition, this design flexibility allows anisotropic elastic properties which provide bend/twist and tension/torsion couplings. While well-known, the only application has been to increase the stability of the forward swept X-29 wing. The perception that anisotropic composites must warp with temperature or humidity is incorrect. Finally, variation in the orientation of fibers need not be limited to twist between the plies. Curvature and splay within a ply allows the stresses to be kept within the fibers, minimizing the loads carried by interfaces and the matrix to increase the safety of the structure.

## 7.2 Processing and Fabrication Technology

Processing and fabrication of materials into structures is of importance here, because of the cost and performance requirements of the final structure. Processing of a material generally includes synthesis or reduction of a compound to a metal, refining, and forming to an intermediate product such as powder, pellets, or billets. Processing also includes such things as rolling, injection molding, and sintering. Fabrication usually involves machining and the building-up of a structure, frequently from mill forms, such as bar, sheet, or forging. The dividing line between processing and fabrication is ill-defined, and has become more diffuse with the introduction of composites. Processing and fabrication costs are varied, depending on the part. For example, the cost for a large number of injected molded parts can be largely for materials. By contrast, the materials cost when fabricating a small number of complex parts is usually a small fraction of the total cost. Even with a composite, carbon fiber prepreg is made to structure at three to six times the material cost. Airframes fit the second case quite well, as serial numbers are small and complexity is high. Obviously, any process that can take a raw material and directly produce a final shape that requires a minimum of machining is desirable.

### Bulk Materials

Parts may be short and squat, or thin, such as skins. The processing and fabrication techniques may be quite different for the different categories. For short and squat parts, direct casting to shape is very cost-effective. Traditionally, cast properties have not been as good as wrought products. However, computational programs for the design of the casting process and new compositions, which can produce desired microstructures, have reduced (and even eliminated, in some cases) the difference in the properties. Powder processes also allow near-net shape processing and allow high-strength, rapidly solidified compositions and structures to be retained. The process can be economical, even with the added cost of the powder. However, for reactive metals and some ceramics, powder costs and handling are very high.

Direct spray-up of molten metal droplets into the final shape including skin structures eliminates intermediate steps, and maintains the benefits of rapid solidification. This general trend of building up materials, rather than machining away, will continue, as subelements can be easily added throughout the process. Sensors, actuators, electrical conductors, or insulators can be directly placed within the structure. Sensors could measure stresses and temperatures during service, which can be directly input to deterministic lifetime prediction models. Spray-up, electron-beam (e-beam) evaporation, and other techniques would also be directly applicable to lamellar composite and functionally graded structures. The one-dimensional gradings usually implied by functional gradients will become generalized to three dimensions in the future. Stress concentrations caused by discontinuous changes in the material properties will be eliminated or at least moved to a much finer scale.

Composite fabrication costs have been relatively high. A major part of the problem is that the design makes for expensive processing. For example, redesign of a carbon/carbon part for manufacturing would include the incorporation of channels in the preform to enable rapid mass transport and high deposition rates. The extremely long deposition times could be reduced by a magnitude, while retaining the economies of scale inherent in using large furnaces.

## Prototype Fabrication

Prototype parts have traditionally taken many months for fabrication and are extremely expensive. The major cost driver in this environment is tooling. Designs often had to be modified after the first prototype, and a second or several more variants had to be fabricated. Today's computer design of parts can check fits and clearances easily, but a prototype must still be fabricated, if only to serve as a model for mold manufacture. Free-form fabrication enables direct mock-up or real fabrication of a prototype part from computer input. Several techniques exist at present, but stereolithography will be described.

In this case, a platform is placed just below the surface of a photo-polymerizable polymer, and a computer-controlled laser beam cures the liquid polymer on the platform, but just in the regions where material is desired. The structure is built-up layer by layer. The plastic part can be used as a nonworking model or as a model for mold fabrication. The total time can be hours to 1-2 days, depending on the size and complexity of the part. Replacement of out-of-stock parts is also facilitated. Hip joints are tomographically scanned into a computer, worn regions redrawn to original shape, and a stereolithographic part is made in plastic. A titanium hip replacement is then cast in a mold made from the model. The part fit to the patient is much improved. The Air Force should make use of this technology to help maintain aging hardware.

Today's properties obtainable with directly used free-form parts do not match those from other processes. However, tomorrow's properties may allow direct fabrication of the final part, without using an intermediate model.

## Production Fabrication and Minimum Touch Labor

Airframes still require "touch" labor. The low production numbers and complexity of structures has made automation difficult to justify, due to high nonrecurring capital expenses. However, the decision also results in a large, highly skilled work-force. The difficulty in hiring highly skilled, highly paid employees in the future, given our lack of apprentice schooling, will cause accelerating use of automation. The ease of implementing these complex tasks will ease with time because of continued development of computational software.

Composite fabrication of complex parts has been manual labor-intensive, and the cost of quality has been relatively high. Given the costs of composite parts, few get scrapped, and rework and reinspection are cost penalties. Numerous processes exist that have not been fully exploited to minimize touch labor, to rapidly process material, and therefore to reduce fabrication costs.

Discontinuous fibers have been largely neglected in high-performance composite structures, because of the possibility of compromising mechanical properties. While these materials do not display significant decreases in in-place static tensile properties, effects of compression loading, temperature, combined temperature and stress, and time dependence have not been thoroughly characterized for complex structures. These materials allow for easy molding of sheet materials to form relatively complex shapes with either thermoplastic or thermoset resins. Simple application of the technique is difficult, as the fiber movement during forming must be controlled. The understanding of the deformation and the development of simply used software for design of dies and processing control will speed the application of this technique. Short discontinuous fibers can be aligned into preformed sheets by paper-making technology with only a 10 percent to 15 percent decrease in composite tensile properties parallel to the fiber axis. More importantly, the slight misalignment of fibers increases the often limiting transverse properties by 50 percent. Reaction injection molding of the preforms in a mold produces a net-shape part. Obviously, simpler shapes could be reaction injection molded with continuous fiber preforms as well. Textile technology could be applied to minimize cut edges on preforms, and directly weave "2 1/2 dimensional" structures. These materials are not made rapidly now, but would allow integration of sensor fibers into the structure.

Tape lay-up and broadgoods will continue to be developed. However, the use of high-throughput, limited-geometry technology such as pultrusion, braiding, and filament winding will increase. Versatility of these processes will be expanded by such techniques as fast-winding of a simple shape and subsequent deformation to a more complex geometry. Again, application will depend on the development of simple software that automatically handles the "inverse" deformation of the final geometry back to an easily wound shape.

Autoclave curing is a relatively inexpensive, but time-consuming process. Principal recurring cost factors are vacuum bagging and loading labor costs. The autoclave provides heat for curing the resin and pressure for consolidating the composite to minimize internal voids, to eliminate gaps between pieces, and to provide a good outer surface. It does not maintain tight tolerance on thickness. It does not provide a uniform heating cycle for uniform curing of thick parts. Given these deficiencies and expense, non-autoclave processes are highly desirable. Molds can provide pressure and tight dimensional tolerances, but are expensive and limited in size. As fabrication experience increases, tolerances of prepregs and tows can be expected to improve, and the necessity of using high pressures for curing will be reduced. Elimination of vacuum bagging is desirable, and will be eliminated or at least simplified as defects in materials and manufacturing are reduced. More novel pressurizing systems, such as foam in-place and structural foams, which pressurize skins against molds, will probably be used more commonly. Better foam materials, such as high modulus, low density carbon foams, will provide higher structural efficiencies with either closed or open cell structures. Heat is generally required to cure high performance resins, but UV or e-beam curable resins are available. UV may not penetrate the part sufficiently for cure, but e-beam can, and both are used in commercial applications for electronics. The use of low-energy curing resin systems offers the potential for dramatically reducing costs, because they allow much cheaper tooling materials to be used.

High-temperature composites usually require quite different processing. One approach is to apply resin matrix technology by using polymeric precursors to carbon or ceramic matrices. The major problem, if low-porosity and high-strength matrices are required, is that multiple reimpregnations are required, because of the shrinkage and cracking that occur with the density increase from polymer to ceramic. Conceptually, the fibers and matrix could be processed together to better match processing shrinkages. Up to the present, coprocessing has not produced good mechanical properties. If innovative concepts for overcoming the problems emerge, they should be funded.

Chemical vapor infiltration of composite matrices has often given the best mechanical properties. Little has been done to determine fiber and filler architectures that would produce a more pore-free structure, and simultaneously allow rapid and complete infiltration. Many schemes for more rapid deposition have been proposed and investigated, such as forced flow and temperature gradient. However, processes that can be used with complex arbitrary shapes should also be developed, such as liquid and supercritical precursors.

Molten liquid impregnation is one of the few really low-cost techniques for high-temperature composite fabrication. The major limitation is the lack of really desirable systems that can be processed this way.

Finally, processing and fabrication costs could be reduced if structures were designed for manufacturability as well as for performance. Similarly, life-cycle costs could be reduced if structures were designed for inspection, repair, and disposal.

## Bonding, Joining, and Fastening

The potential weight savings to be gained by using composite materials is often halved by the necessity of joints. Better design of the structure may ameliorate these losses, but better ways to connect structural elements can provide large weight savings. Adhesive bonding would make aerodynamically smoother skins, but reliability of adhesively bonded structures and repairs has limited its usage to secondary structure and lightly loaded parts. Cocuring of composite parts is more attractive, because a continuous polymeric phase forms through the interface. This allows a lower part count, particularly of fasteners, for final assembly. The lower fastener count is important for carbon fiber composites, because the structure is weakened by fasteners, but more importantly because of the high cost of titanium fasteners required to prevent galvanic corrosion. Replacement of these costly fasteners by substituting an adhesive bond with the carbon-fiber equivalent of Velcro to aid in assembly and to provide strength between the plies would be desirable. Bonding, joining, and fastening are often neglected areas, as they are not as flashy as other areas. However, the payoffs in initial weight and lifetime of the structure make advancements in this area important.

## 7.3 Repairing Structures

Structures should be designed for inspection and repair. Sensors will be incorporated in the structure to monitor and record the history of the structure, so that a life-prediction model can predict the safety of the present structure. Ready access for inspection of structures that can not be monitored onboard should be designed-in. Similarly, the design of a large integrated structure should allow simple cutout or patching of a failed or weakened region at a minimum cost.

### Active Repair of Cracks

Traditionally, materials have been repaired actively by a person performing the repair. The crack might be welded, diffusion bonded, or glued. An economic impetus will probably develop to try to repair subcritical cracks, and particularly invisible cracks. Techniques that might fill these cracks, such as a smart glue, or gas or vapor transport to a crack-tip with local deposition of the repair material at the stress concentration, could prolong the lifetime of structures.

### Surface Roughness

Slip bands and asperities can initiate fatigue cracks. Surface roughness analysis will be used to identify the initiation of these regions, which then would be smoothed by local polishing using wet or dry chemical and/or mechanical polishing.

### Surface Coatings

Paints and wear- and oxidation-resistant coatings often have to be stripped for depot maintenance and then recoated. The cost for stripping frequently is a multiple of the cost of application. “Paint for Life” is an ideal goal. Initial cost of the material should not be the only consideration. However, localized repairs are desirable, such that the coating only forms on a scratch, for example. Electrical fields or chemical reactions with the bare substrate could be used to cause localization. Very high-temperature materials may need a transient protective coating to be formed during heat-up or cool-down. For example, the oxidation of carbon/carbon composites is poor at relatively low temperatures. Thus, a carbon/carbon composite turbine blade or combustor might provide longer lifetime if a small amount of a boron-containing fuel was used during engine startup and shutdown.

### Passive Self Healing

The recovery of load-bearing capability after failure would be a major step forward in the development of man-made materials. Biological systems show the ability to repair, albeit slowly. In a sense, metals that exhibit plastic deformation exhibit self-healing. Atomic bonds are broken and remade as a dislocation moves through a metal. Very fine-grained nanostructures may also allow deformation to occur, but by a different mechanism. The two required characteristics are the reformation of bonds, and the ability to accommodate large strains to relieve high stresses. Recovery of load-bearing capability has been demonstrated with graphite. The possibility exists for the development of carbon-fiber or other composites that can quickly recover the ability to carry loads.

## 7.4 Summary

- Any significant performance gains in our future systems, such as hypersonic vehicles, will depend on structural materials.
- Computational capability will allow rapid scanning of unstudied, complex systems for discovery of new and desirable chemical compositions. Systems containing low-density elements are likely selections. Understanding from atomic-to-structural scales will result in higher strength and new ductile materials. Improvements in mechanical properties can be expected to double present strengths.
- Multifunctional structures are a trend. Integration of sensors and thermal and electrical conductors with load-bearing structures will make future airframes look more like a giant semiconductor chip. Gradients in materials composition, rather than discontinuous jumps, are more likely to minimize interfacial stresses and failures.
- Free-form manufacturing may become the norm. Replacement of worn parts can be done by tomographic scanning, modification of input for wear, and free-form manufacturing.
- Processing and fabrication processes that minimize “touch” labor will increase in importance. Software for easy application of this technology will speed its introduction and growth. The use of specific materials that simplify processing will also increase in importance.
- Self-healing materials and films will be developed.
- Finally, designers of structures should also consider processing, fabrication, joining and assembly, inspection, repair, and disposal to reduce life-cycle costs.