The Influence of Aerospace-Performance Requirements on Development of Advanced Structural Materials [and Discussion]

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The influence of aerospace-performance requirements on development of advanced structural materials

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Historically the use of new materials in aircraft construction has accounted for the major amount of mass reduction by new technology. The continuation of this role for new materials in aerospace vehicles in the 1990s is reviewed. The materials scientists' vastly increased ability to synthesize new materials and tailor mechanical and physical properties has created the need for an interdisciplinary approach among aircraft designers and materials scientists in the development of new materials. A system to assess and quantify potential benefits from aims for property improvement is described. Application of this mass-savings methodology to a typical aircraft is presented with the results associated with varying percentage property improvements in strength, stiffness, durability, damage tolerance and density. The need to obtain vastly improved corrosion resistance in magnesium alloys and higher fracture toughness in metal matrix composites is briefly discussed. Trends in high-temperature aluminium-alloy development and property comparisons with titanium are given.

Carbon-fibre reinforced resin matrix composites are discussed in terms of failure modes and design allowable strain for thermoset and thermoplastic systems. Cost of current composite structure is compared with that of aluminium and approaches to reduce manufacturing cost of composites are given. General requirements are presented for high-temperature materials for hypersonic and re-usable orbital vehicles. A basic structural integrity plan for emerging materials is outlined that identifies specific technology transition needs and the related tasks that must be accomplished before new materials can be incorporated into aircraft structures.

INTRODUCTION

It is worthwhile to approach the topic of new materials technology for the 1990s with some historical perspective, because forecasting technology has experienced some dramatic failures of foresight and imagination. For example, Charles H. Duell, Commissioner of the U.S. Patent Office, advised President William McKinley of 1899 to close down his agency 'Because everything that can be invented has been invented'; one year before the Wright Brothers' flight at Kitty Hawk, Professor Simon Newcomb, a distinguished astronomer, said that flying without a gas bag was impossible or at least would require the discovery of new law of nature, and years later in 1948, Thomas J. Watson of IBM wrote that, although a single computer could solve all the important scientific problems in the world, he did not believe it had any commercial possibilities. These examples suggest that if we wish to avoid gross underestimation in our projections we need to be aggressive and optimistic in our considerations of what will be accomplished in future materials technology. The complex relation of scientific research and technological innovation is often viewed as a linear model where basic research leads to applied research and then new product development. This paper addresses new approaches to the communication of aerospace materials technology needs that then can shape and stimulate the required scientific research.

The aerospace industry has been a leader in development and application of new technology. The designer is constantly striving for increased efficiencies in aerodynamics, propulsion systems, and structures to obtain improved performance capability. The continuing evolution of advanced materials has been a source of major improvements in aerospace hardware and this trend is expected to continue in the future.

The trend to achieve the desired improvements in advanced materials has evolved into a close relation between the basic researcher and the applications engineer. We are in fact well into the age of 'engineered materials'. The materials scientist's vastly increased ability to synthesize new materials and tailor mechanical and physical properties has created the need for an interdisciplinary approach among aircraft designers and material scientists in the development of new materials. The U.S. Department of Defense (DoD) has recently reinforced this idea by funding a new University Research Initiative Program that is designed to increase investment in higher risk scientific research and provide more opportunities for joint effort among Universities, Industry and DoD Laboratories to maximize benefits to be derived from defence research.

METHODOLOGY FOR EVALUATION OF MASS SAVINGS

In the past it had been customary for material producers to conduct internal research on new materials, complete the development of a resulting proprietary material and then offer it to industry. Frequently, whereas one or more properties may have been substantially improved, the combination of properties of the new material were not optimum and the product did not succeed commercially. The Al–Li alloy 2020 is such an example. The alloy was introduced in the late 1950s and subsequently withdrawn from the market place in the 1960s because of lack of demand owing to low fracture toughness. Today's approach of engineered materials puts emphasis on obtaining the desired property improvements but also addresses knowing 'what else we get' in the way of total property characteristics.

The current development of second-generation Al–Li alloys has been accomplished by close cooperation between the researchers and users. Coordination and information exchange then continued throughout the development cycle. The scope of mutual interest extended to fabrication considerations where weldability and superplastic forming capability added important new dimensions to the potential usefulness of these advanced Al–Li materials. Discussions were held early in the development cycle and agreement was reached on the definition of achievable sets of property improvement goals. This effort stands as an excellent example of a team work approach to advance Al–Li alloy technology.

Now that the second generation Al–Li alloys are successfully emerging as production materials ready for current applications, attention has turned to longer range possibilities. Work is underway to develop substantially lower-density Al–Li alloys that could be available in the mid to late 1990s. Aluminium alloys with densities reduced by 15–20% appear achievable (Simenz 1983).

The advent of rapid solidification processing (RSP) gave alloy design such wide dimensions that it soon became apparent that a system was needed to assess and quantify potential benefits to be derived from potential property improvements. This situation led to the development of a mass-saving evaluation methodology that has found wide use in establishing sets of property improvement goals (Ekvall *et al.* 1980). In this procedure the structural mass of the component to be evaluated is distributed according to the primary failure modes that size the structure for a particular type of aircraft. In this procedure, the structural mass of the component to be evaluated is distributed to prevent failure in the critical (primary) failure modes. These primary failure modes, then, determine the local thickness and stiffness of the structure, and are said to size the structure for a particular type of aircraft. Equations relating to basic material properties are shown for each failure mode in table 1. The durability and damage tolerance allowable is determined by analysis of fatigue, crack growth, fracture toughness and stress corrosion data for each material. The relation of benefit against improvement in strength, stiffness, durability and damage tolerance (DADT), and density are given in figure 1 for the S-3 twin-engine, carrier-based patrol aircraft. The mass savings shown in figure 1 were derived from the equations in table 1 for a series of four candidate alloys each having a different combination of assumed property increases over a baseline 7075-T76 aluminium alloy material. As shown in figure 1 the effects of improvement in tensile strength or modulus are about equal and reduce structural mass by about 2.5–3.5% per 10% property improvement. The DADT property improvements have the least impact on over all structural mass savings because of the low percentage of structure in this category as indicated in the design-requirements pie chart in figure 1. Because density affects all failure modes, the structural mass saving is directly proportional to the improvement in density. Such information can be of great benefit to the alloy researcher in design of alloys. Because the relative potential benefits can readily be seen, the alloy researcher can establish priorities for property improvements during his analyses of achievable property combinations.

Table 1. Mass ratio against failure mode

(Percentage of mass savings: 100 $(1-M_2/M_1)$.)

category	failure mode	mass ratio M_2/M_1
1	tensile strength	$\dfrac{\rho_2}{\rho_1}\dfrac{F_{\mathrm{tu}_1}}{F_{\mathrm{tu}_2}}$
2	compressive strength	$\dfrac{\rho_2}{\rho_1}\dfrac{F_{\mathrm{cy}_1}}{F_{\mathrm{cy}_2}}$
3	crippling	$\dfrac{\rho_2}{\rho_1}\left[\dfrac{E_{\mathrm{s}_1}}{E_{\mathrm{s}_2}}\right]^{0.25}\left[\dfrac{F_{\mathrm{cy}_1}}{F_{\mathrm{cy}_2}}\right]^{0.26}$
4	compression surface column and crippling	$\dfrac{\rho_2}{\rho_1}\left[\dfrac{E_1}{E_2}\right]^{0.4}\left[\dfrac{F_{\mathrm{cy}_1}}{F_{\mathrm{cy}_2}}\right]^{0.2}$
5	buckling compression or shear	$\dfrac{\rho_2}{\rho_1}\left[\dfrac{E_1}{E_2}\right]^{0.33}$
6	aeroelastic stiffness	$\dfrac{\rho_2}{\rho_1}\dfrac{E_1}{E_2}$
7	durability and damage tolerance cutoff (DADT)	$\dfrac{\rho_2}{\rho_1}\dfrac{F_1}{F_2}$
8	general instability compression or shear	$\dfrac{\rho_2}{\rho_1}\left[\dfrac{E_1}{E_2}\right]^{0.5}$
9	minimum gauge	$\dfrac{\rho_2}{\rho_1}\dfrac{t_2}{t_1}$

F, allowable stress; E, modulus of elasticity; E_{s}, secant modulus; F_{cy}, compressive yield stength; F_{tu}, ultimate tensile stress; ρ, density t, material thickness. Subscripts: 1, material 1; 2, material 2.

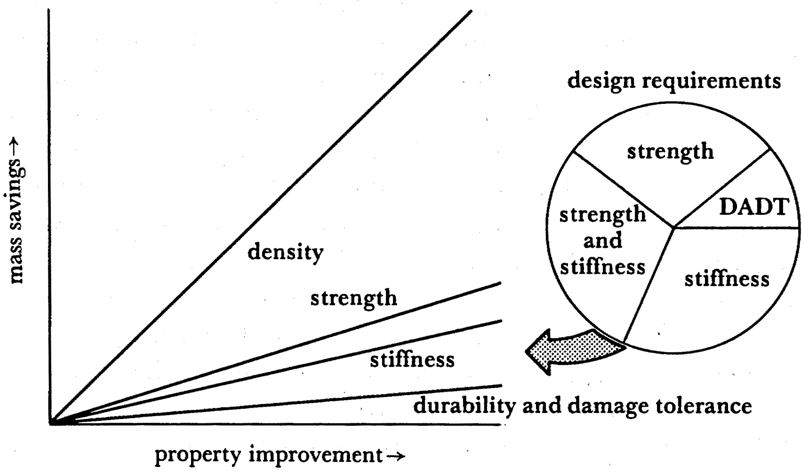

FIGURE 1. Relation of property improvement to aircraft mass savings.

RSP MAGNESIUM ALLOYS

Research efforts to improve the properties of magnesium alloys through the use of RSP are an excellent example of how aerospace requirements drive result in research and development goals. In spite of inherent low density, magnesium alloys are not widely used in aerospace. Many military and commercial customers restrict or prohibit the use of magnesium alloys.

The high chemical reactivity and resultant poor corrosion-resistance are the main reason for the poor acceptance of magnesium alloys for use in long-life structures. RSP offers many opportunities to obtain enhanced strength and stiffness in magnesium alloys, however, such improvement must be accompanied by vastly improved corrosion resistance or such materials are not likely to find significantly increased acceptance in aircraft applications.

There are indications that RSP may indeed offer alloy approaches that beneficially alter magnesium oxide to obtain an enhanced passive surface film for increased resistance to atmospheric corrosion as well as resistance to galvanic attack (Das & Chang 1987). There is a real potential to develop new magnesium alloys by RSP methods that offer acceptable corrosion resistance combined with strength and stiffness improvements that will make them very competitive with carbon-fibre reinforced plastics and other advanced structural material candidates.

METAL MATRIX COMPOSITES

It is not unusual to see tensile strengths greater than 758 MPa in aluminium–silicon-carbide whisker material with modulus of elasticity values of 124 GPa or higher. However, these property levels are accompanied by low elongation and poor fracture toughness that limits the material usefulness in practical structure. These very high-strength versions of Al–SiC_w materials have shown undesirable fabrication characteristics such as shattering during simple forming operations and poor resistance to fracture from low-energy, low-velocity impact as might be experienced by dropping a small hand tool, etc. Consequently work has concentrated on raising fracture toughness and elongation through changes in alloy composition, improvements in reinforcements, compaction and thermal mechanical processing. Progress in raising fracture toughness and elongation is indicated in figure 2. This illustrates another example of the impact of aerospace requirements on material development trends.

When the options of alternate alloy matrices, continuous and discontinuous reinforcements and processing are considered it appears likely that metal matrix composites will emerge as an important class of structural materials for design and application in the 1990s for a wide range of applications including those with very high-temperature demands.

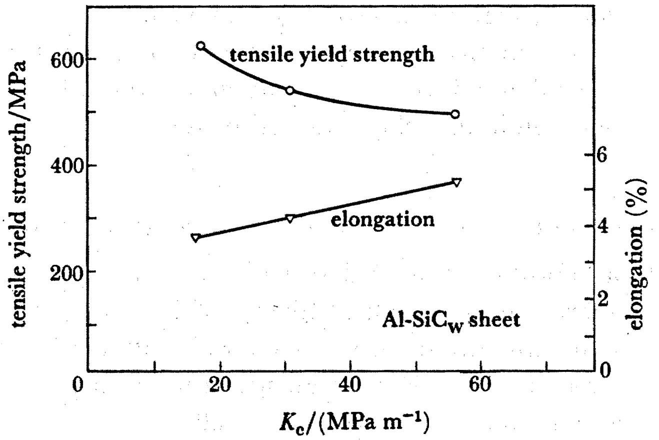

Figure 2. Strength–toughness relation for aluminium metal matrix composite.

High-temperature aluminium alloys

Powder metallurgy aluminium alloys have been developed that extend the useful temperature of aluminium up to approximately 158 °C. Studies of the properties of these alloys indicates potential benefits of up to 27 % mass savings and 69 % cost savings when the alloys are used to replace titanium (Sakata & Langenbeck 1983). Material property comparison for a PM Al–Fe–Ce alloy is given in figure 3. Work is well under way to fabricate and test components made from these elevated temperature aluminium alloys and the USAF is planning a large-

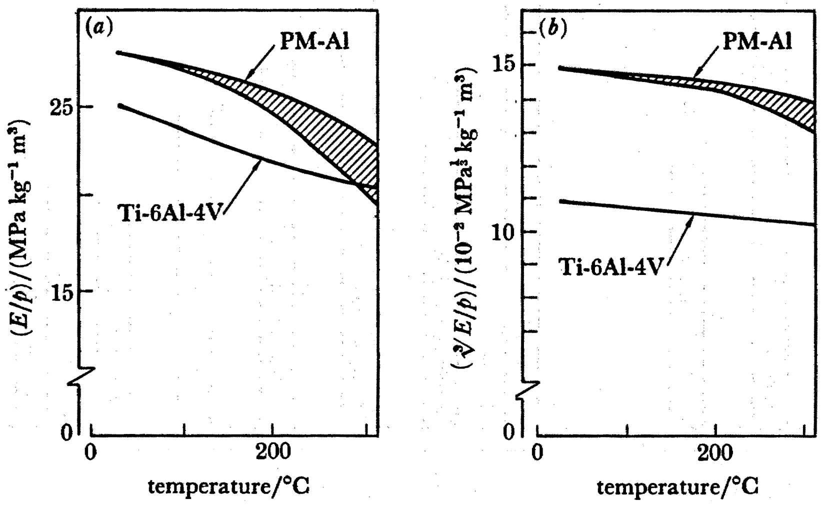

Figure 3. Comparison of $E/\rho(a)$ and $\sqrt[3]{E}/\rho(b)$ for Ti–6Al–4V and PM Al–8Fe–4Ce (mass percentage composition).

scale elevated temperature structural component programme to validate the technology for use in aircraft in the 1990s.

Encouraged by this successful development of aluminium alloys useful to 316 °C, the Air Force (USAF) has solicited proposals to conduct research on Al and Ti alloys to extend their useful temperatures to 482 and 926 °C, respectively. The development plan could mature this new technology by the mid- to late 1990s.

The results of airframe applications, and analysis of benefit will be communicated early in the research effort to guide the high-temperature Al and Ti alloy development regarding the relative importance of particular material properties and characteristics. For example, low thermal expansion to reduce thermal stresses is highly important in hot structure and will be given appropriate consideration in the alloy synthesis phase.

Carbon-fibre reinforced resin matrix composites

The technology of carbon-fibre reinforced plastic (CFRP) has progressed rapidly in the aerospace industry. Most forecasts today indicate the use of these composite materials will grow to 50% and more of aircraft structural-mass fraction for aircraft developed in the 1990s. CFRP low density (i.e. 45% less than aluminium), high strength and high stiffness provide vastly improved structural efficiency indices. However, not all of the indicated strength can be exploited when realistic design requirements are imposed. Figure 4 compares tension and compression failure strain of composites for a number of conditions that must be considered in design for tension- and compression-type loadings. Unlike the case with metallic structure, cyclic loading in tension is not the critical case. Rather a static notch, as with an ordinary hole is the limiting condition for the tensile case. The short history of carbon-fibre reinforced plastics

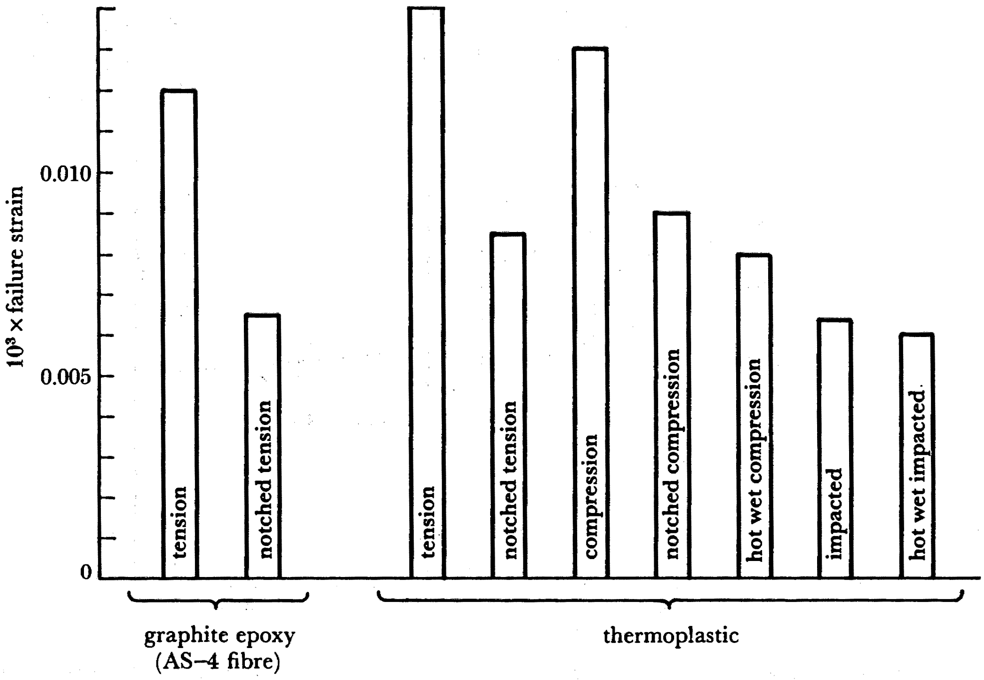

FIGURE 4. Typical strength comparisons for various quasi-isotropic composite laminates.

has uncovered a number of unique design considerations in compression loaded structure. In the mid-1970s the deletereous effects of absorbed moisture on resin glass transition temperature and elevated temperature strength became of concern in epoxy and other thermoset resin matrix materials. Resistance to 'hot wet' conditions became a key parameter for the matrix resin developer.

The brittle nature of first generation epoxy matrix composites was also well recognized and accommodated by drastically limiting maximum design strain to account for undetected impact damage. Continuing structural development is evolving post impact compression, G_{Ic}, G_{IIc} and other test parameters that better characterize the behaviour of candidate CFRP systems and can be used for resin development and evaluation to assess their potential for aircraft applications. Figure 5 compares the benefit of higher strain cut off in terms of calculated weight reduction and figure 6 depicts the substantial property improvements made in development of toughened thermoset and thermoplastic matrix systems.

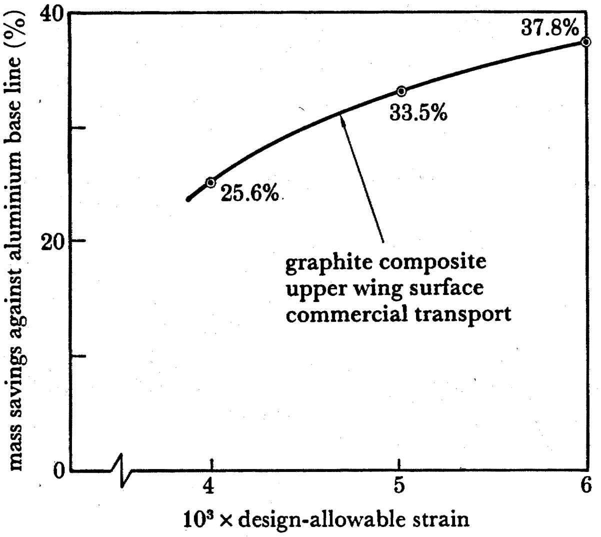

FIGURE 5. Influence of design allowables on mass savings.

Much has been written about cost savings of CFRP compared with metallic structures for given components. Actual production history generally indicates somewhat higher cost for CFRP than for comparable metallic parts. This discrepancy is attributed to lagging innovation and automation of CFRP fabrication. As depicted in figure 7, the premium material cost for CFRP will always exist, therefore, savings in fabrication must be obtained to achieve lower cost of structure. Extensive use of automation is expected to play a key role in lowering the cost of CFRP.

Newly available, tough, solvent-resistant thermoplastic matrix resins offer near term potential for reducing manufacturing, operation and maintenance costs. Their unique characteristics include short fabrication cycles, unlimited shelf life, reformability, weldability and potential for unique mechanical material-placement techniques for fabrication of complex shapes. Available material forms include the usual unidirectional and cloth prepreg (fibre reinforcement coated with resin) as well as comingled tows, fibres coated with matrix resin from powder slurrys or extruded matrix coatings. All of these attributes allow greater design flexibility and manufacturing options.

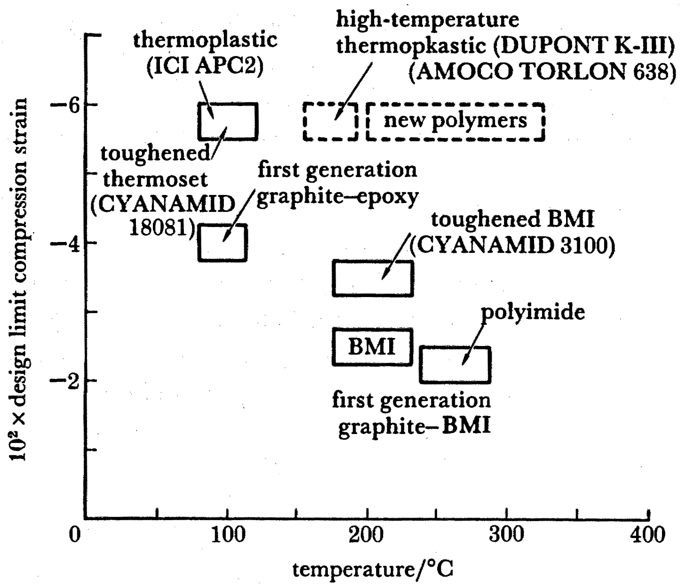

FIGURE 6. Comparison of design-limit compression strain with temperature. BMI, bismaleimide.

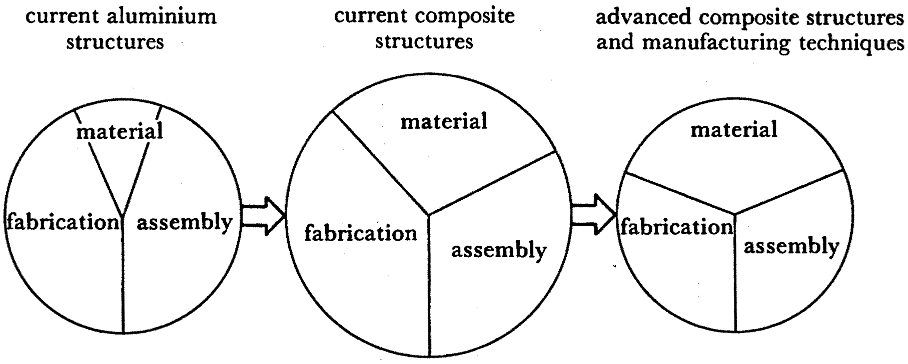

FIGURE 7. Aluminium against composites: cost comparisons.

Another important effort to reduce manufacturing costs in thermoplastic matrix composites is the current emphasis on developing an integrated approach to material product forms, computer-aided design and critical fabrication issues of geometries, energy-transfer methods, process modelling, process control and tooling. The aim of this effort is to develop a working methodology that has the capability to select material system and starting forms and then optimize the selection of subsequent processing and manufacturing operations to achieve thermoplastic composite structures that have lower acquisition cost than their metal counterparts. Computerized material-property information systems are a vital part of this new approach to design and manufacture.

SUPERSONIC, HYPERSONIC AND RE-USABLE ORBITAL VEHICLES

There is renewed interest in supersonic and hypersonic aircraft and re-usable launch, orbital vehicles such as the United States National Aerospace Plane Program. Studies of various re-useable launch orbital vehicles have discussed the significant challenges facing the materials and structures communities (Eldred 1984; Martin 1985). Generally, systems studies indicate a need for up to 25% reduction in structural mass fraction compared with the current U.S. Space Shuttle Orbiter; a factor of five increase in mission life; higher maximum-use temperatures and heat loads, reduced cost and turn-around time; and flexible launch–landing sites (Dixon *et al.* 1985).

Candidate materials for hot structure include polymer and metal matrix composites, advanced Al and Ti alloys, ordered structure alloys like ductile aluminides, superalloys, carbon–carbon and ceramic composites, see figure 8 (Tenney 1985).

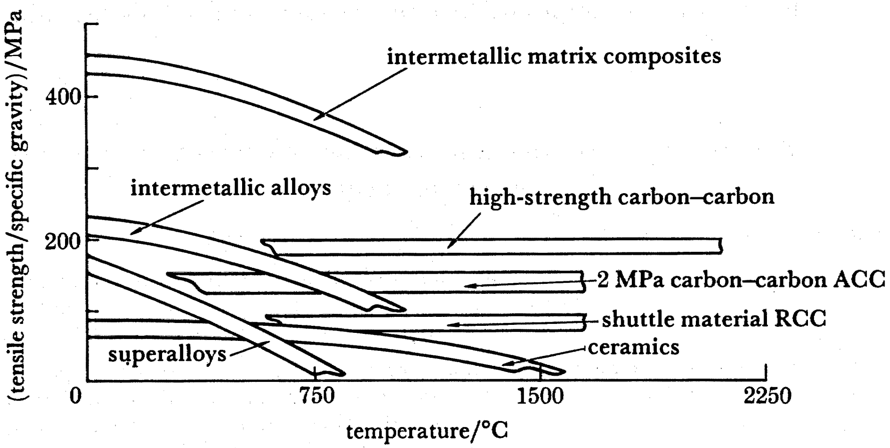

FIGURE 8. Candidate materials for hot structures. (RCC, reinforced carbon composite; ACC, advanced carbon–carbon.)

Carbon-fibre reinforced polyimide resin systems show great promise on the basis of specific strength and stiffness; and fabrication capabilities of large components has been demonstrated for polyimide systems of the polymer from monomeric reactants type such as PMR-15 and LARC-160. Nevertheless, issues of improved processability, oxidative stability, microcrack resistance to thermal cycling in the range −121 to 316 °C, improved toughness and increased strain to failure must be addressed to improve the viability of polyimide systems.

One approach to achieving the required improvements is to develop structural polymer blends. Professor Frank Karasz, of the University of Massachusetts, is conducting molecular mechanics research on high-performance polymers such as polybenzimidazole (PBI) and liquid crystal polymer (LCP) to produce blend systems with great promise for improved processing characteristics and property balances. Figure 6 includes the temperature against compression-strain capability goals for the new blended polymers.

For extreme temperature environments, high-strength version of carbon–carbon composites combined with new integrated oxidation protection systems show promise for vast improvements over current carbon–carbon structures. Integrated protection systems are under development that use combinations of outer surface coatings, inner layer sealing, inhibited matrices and carbon-fibre coatings to achieve improved cyclic, stressed and pressure driven oxidation resistance in carbon–carbon structure.

Toughened ceramics and fibre-reinforced ceramics offer another alternative to more reliable high strength, low density and oxidation resistant structure for high-temperature usage.

NEW MATERIALS AND AIRCRAFT STRUCTURAL INTEGRITY PROGRAMME REQUIREMENTS

New materials must achieve certain predictable developmental milestones in the orderly progression from the laboratory to use in full-scale production hardware. Knowledge and understanding of the typical requirements are essential to realistic and timely planning of material development cycles.

Dr J. Lincoln of the USAF has characterized these steps in his approach to an aircraft structural integrity programme (ASIP). The pertinent material elements of his plan require the tasks shown in table 2 to be accomplished before the start of any full-scale aircraft-system development.

TABLE 2. REQUIREMENTS FOR THE TRANSITION OF NEW-MATERIAL TECHNOLOGY TO FULL-SCALE DEVELOPMENT

technology transition need	tasks
producibility	material available in appropriate forms and quantities fabricate detail parts and assemblies develop and demonstrate non-destructive inspection (NDI) procedures
characterized manufacture and production	preliminary manufacture and production specifications, acceptance standards and manufacturing instructions identify and evaluate all material behaviour uniquely dependent on features that distinguish the new material from conventional material and that may affect producibility and structural integrity evaluate material performance at extremes of material and process parameters
design mechanical properties	material properties including environment – strength, durability and damage tolerance (DADT), creep, corrosion building-block process: coupon–element–subcomponent tests sufficient data base to preclude potential failure and permit usable mass prediction

Information obtained in these tasks is an input to the requirement of the ability to predict the structural performance of the new material. Typically these tasks may require three to four years to establish technology readiness and achieve acceptable risk to proceed to the next phase of full-scale development.

When the entire process is viewed it is readily apparent why the cycle of new-material development is usually ten years: three to four years on research, three to four years on technology development and two or more years devoted to hardware application during full-scale system development.

SUMMARY REMARKS

These brief comments have covered a broad spectrum of material and structural requirements for application to advanced aerospace vehicles. The key points discussed can be summarized as follows.

1. Advanced materials will play a major role in improving the efficiency of aerospace vehicles in the 1990s.

2. Today's era of 'engineered materials' requires close coordination between the material scientist and the aerospace designer to establish achievable target properties that represent the optimum combination of properties to maximize benefits.

3. A mass-saving methodology has been developed that has proved to be effective in quantifying potential benefits related to property improvements.

4. Reduction in material density offers the most direct benefit thus further reductions in density are desirable in Al-, Mg-, Ti- and Ni-base alloys along with improved specific properties and higher temperatures of use.

5. CFRP materials with higher strain to failure, improved toughness and greater impact resistance are required. Innovative design and manufacturing approach, automated fabrication and assembly combined with the required material improvements will achieve the goals of lower acquisition and life-cycle costs.

6. Hypersonic and re-usable launch, orbital vehicles present significant challenges to the materials scientist and engineer to develop higher structural efficiency, greatly improved temperatures and oxidation resistance, and higher reliability.

7. Requirements of vehicle-structural integrity must be defined and related to material-development plans in the early stages of the material-development cycle.

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Discussion

L. H. SCHWARTZ (*Institute for Materials Science and Engineering, National Bureau of Standards, Gaithersburg, U.S.A.*). In anticipation of the subject to be discussed in the next paper, I would like to ask Mr Simenz if he would address the issue of transfer of materials research and development from defence-related to civilian-related applications. Do barriers associated with security significantly impede the transfer of new materials technology to the private sector in the aerospace industries?

R. F. SIMENZ. There may be exceptions, but in general I do not think that security barriers significantly affect the rate of transfer of materials R & D from the defence-related applications to the private sector.