ADVANCED MATERIALS

Aerospace Materials Research Opportunities**

Engineered Microstructures
Intermetallics
Advanced Composites
Materials Processing

By Michael Salkind*

As we approach the second century of aerospace, increased emphasis is being placed on endurance, reliability, ease of manufacture, and lower cost, in addition to weight saving. This change in emphasis will have a major effect on not only the selection of materials, but on how materials are integrated into the total system design process. Subsonic aircraft will continue to play a major role in our future with emphasis on increased durability and lower cost. Non-metals that do not corrode are attractive; however, the issues of reliable fracture resistance to ensure safety and durability as well as ease of manufacture and inspection will be key. Higher performance engines and hypersonic aircraft will require higher temperature materials (including a substantial amount of non-metals) along with reliable toughness and ease of manufacture. In space, weight will continue to be a major driving force along with the need for long term vacuum and radiation stability. Ease of assembly and multifunctional use (e.g. electrically or thermally conducting structure) will be additional needs for spacecraft materials. We have reached a point in the evolution of structural materials where we are moving away from processing naturally occurring materials toward synthesizing designed microstructures to perform specific functions. The mathematical modeling of microstructure–property relationships and new chemical and biotechnical synthesis techniques appear to be critical technologies for the future. In addition, the future materials developer will need a broader understanding of the total structural life cycle so that the impact of utilization, maintenance, and training requirements in the design of new materials can be considered.

1. Introduction

For more than 40 years, mankind has not had a major war nor used a nuclear weapon in anger. The USA and USSR are experiencing a decided recent warming in relations and western economic hegemony seems to be yielding to the Pacific miracle. We are seeing more and more transnational companies which challenge some of our assumptions about national economic competitiveness and indeed the definition of a company or a nation. In 1964, General *Schriever* said "The traditional geographical barriers are really meaningless in today's world ... (which) emphasizes ... the inseparability of political, military, economic, and psychological factors."[1] We are coming to grips with the facts that our environment is delicate and that our natural resources are finite. Against this background, we can conclude that the 21st century, the second century for aerospace, will surely bring great change.

The first century of aerospace was clearly dominated by performance considerations. In the future we will still be pushing back the weight and temperature barriers but within the context of limited mineral, financial, and human resources. We will need to provide improved performance for more capable military vehicles, more economical transport vehicles, and new hypersonic vehicles and spacecraft. However, these new capabilities must be more affordable, more reliable, easier to maintain, and less demanding of our environment, including our mineral and energy resources. An historical summary of tactical aircraft costs showing the inexorable climb in unit cost, Figure 1, led *Norman Augustine* to postulate that:

> "In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy three and a half days each per week, except for leap year, when it will be made available to the Marines for the extra day."
>
> *Augustine's First Law*[2]

Augustine's "first law" may be amusing hyperbole, but the underlying data are real and, taken together with the global economic realities, indicate that cost must be a far more significant consideration in future aerospace systems.

Maintenance costs of tactical aircraft also indicate the inexorable upward trend.[2] *Augustine* concluded:

> "Aircraft flight in the 21st century will always be in a westerly direction, preferably supersonic, to provide the additional hours needed each day to maintain all the broken parts..."
>
> *Augustine's Second Law*[2]

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[**] The author would like to thank his colleagues at AFOSR, *J. Dimmock, G. Haritos, A. Rosenstein, L. Schioler,* and *D. Ulrich,* for their assistance in preparing and reviewing the manuscript.

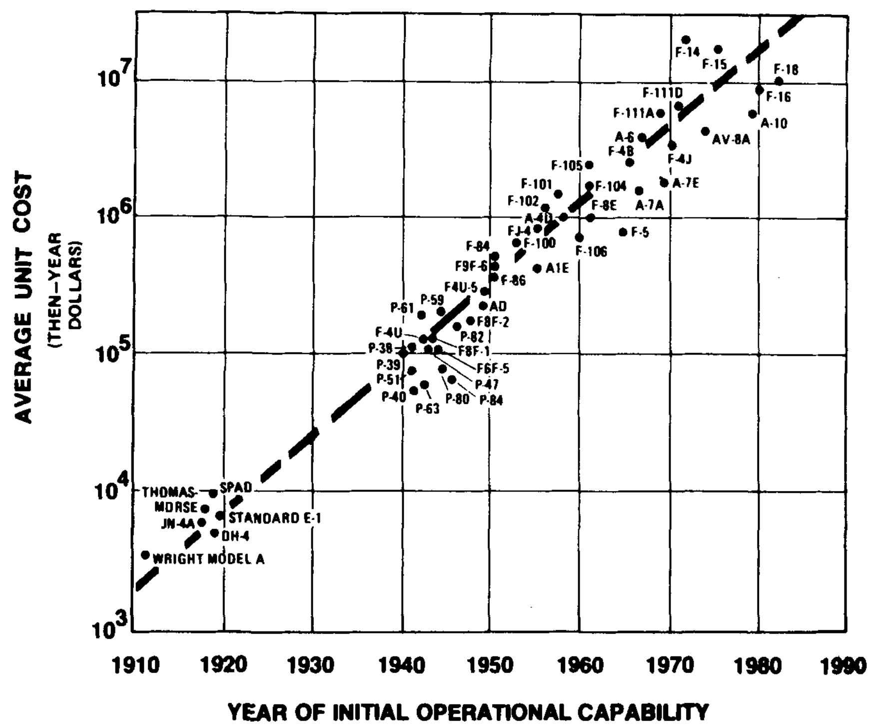


Fig. 1. The unit cost of tactical aircraft has increased consistently by a factor of four every ten years since the beginning of the aviation age. After *Augustine* [2].

Human resource support requirements are rising logarithmically while the capabilities are not. Thus we must conclude that in the 21st century, we will need to produce aerospace systems with more performance, but which, at the same time, are more affordable and supportable.

2. A New Age

"What Age is next?" asks an Alcoa advertisement.[3] *Forney* points out that we have, in rapid succession, entered the Atomic Age, the Space Age, the Information Age, and now the Age of Composites.[4] General *Schriever* called the advent of composites a new age in materials, comparable to the advent of the Iron Age.[1] *Inomori* has said we are entering Shin Sekki Jiddai (the New Stone Age).[5] The Alcoa advertisement goes on to say that we are entering the Engineered Materials Age. Clearly, composites, advanced ceramics, and metal alloys are all subsets of engineered materials or what *Drucker* describes as "... design of the microstructure to give any combination of macroscopic properties."[6] A recent study by the U.S. Congressional Office of Technology Assessment entitled "Advanced Materials By Design" captures this perspective.[7]

We are therefore experiencing a rapid change in materials technology simultaneously with rapid changes in the performance and economic demands on new materials. It is imperative that we see our role as *designers* of materials within the broader context of a systems design. The contrast between design with composites and design with metals is presented in Figure 2. Although the figure relates to fiber composites, it is a microcosm of the newer approach of designing the microstructure (whether metal, ceramic and/or polymer) for the requirement, compared with the former approach of separate materials development. The materials designer must be part of a design team that considers not only the function, but also the manufacture and life-cycle support of the system. This changing perspective implies changes in how we define ourselves, our organizational roles, our educational goals, and the context of future materials research. Materials research and development is no longer just the purview of the Materials Department.

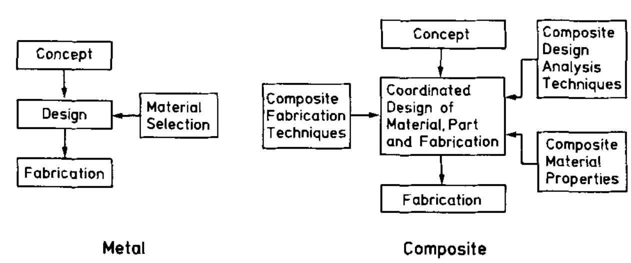


Fig. 2. The advent of materials with engineered microstructures, such as composites, is changing the way materials design is integrated into the total systems design. After *Salkind* [8].

3. Aerospace Needs

Types of aerospace systems and their range of operating temperatures, together with the capabilities of structural materials are summarized in Figure 3.[9] Materials are the limit-

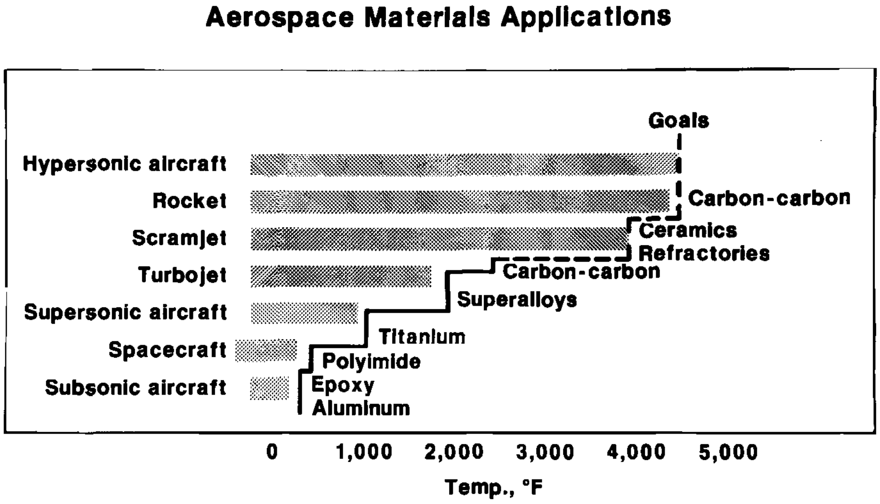
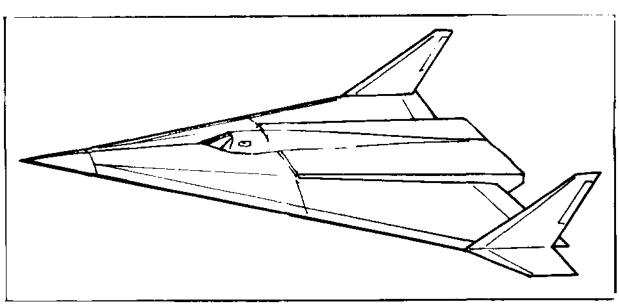


Fig. 3. Summary of Aerospace Materials Requirements and Materials Capabilities. After [9]. x °F = $\frac{5}{9}$(x − 32) °C.

ing technology at the higher temperatures. Over the entire range of temperatures, both materials performance and cost are critical to the mission or commercial success of the system.

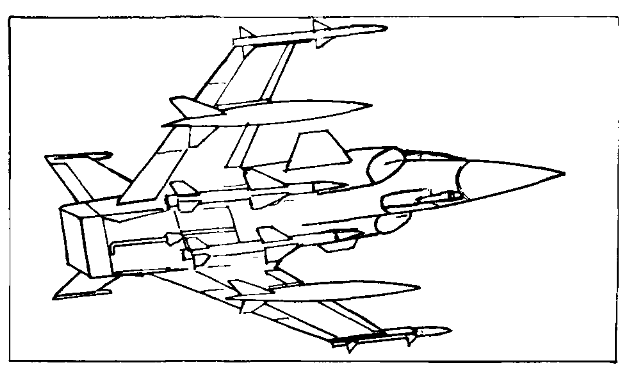
The National Aero-Space Plane (NASP) embodies both significant weight and temperature challenges. Such a hypersonic (Mach 5+) aircraft would take off and land on conventional runways and have both military and commercial applicability. A technology demonstrator, designated the X-30,[10] is planned to be flown in the 1990's to explore the complex aerodynamic, propulsion, structures and materials challenges for the next generation of operational aircraft. *Hadcock*[11] has projected the probable airframe materials and design criteria for such aircraft, as shown in Figure 4. The likely propulsion system, a supersonic ramjet or SCRAMJET, is basically an integral part of the airframe. Multi-phase materials with engineered microstructures will be dominant in such aircraft.

The Advanced Tactical Fighter (ATF) will be the Air Force's major tactical weapons system in the early 21st century.[12] It will combine high maneuverability with supersonic cruise, and employ low-observable technologies. In addition to superior performance, it must have double the maintenance interval of current fighters, be more readily supportable, and meet stringent cost requirements. *Hadcock* has summarized the probable material usage and design drivers for future fighters, Figure 5.[11] As with the NASP,



	Airframe Materials	Airframe Design Criteria
Wing/Fins	Oxidation-Stable Carbon/Carbon	Fail Safe
Fuselage	Superplastic Formed/Diffusion Bonded Refractory Alloys	Damage Tolerant
Internal Structure	Organic Matrix Composites	Extended Life
Inlets/Ducts	Ceramic Matrix Composites Rador Absorbing Structure	Maintainability
Nozzles	Ceramic Matrix Composites	High Reliability
Fittings	Titanium	Chemical, Biological, Nuclear and Laser Resistent
Landing Gear	Metal Matrix Composites.	

Fig. 4. Materials applications for 21st century hypersonic aircraft. After *Hadcock* [11].



	Airframe Materials	Airframe Design Criteria
Wing/Fins	Intermediate Modulus Graphite/Bismaleimide	Low Vulnerability
Fuselage	Superplastic Formed/Diffusion Bonded Ti & Al	Damage Tolerant
Inlets/Ducts	Organic Matrix Composites Radar Absorbing Structure	Crashworthy Extended Life
Nozzles	Carbon/Carbon	High Reliability
Fairings	Self-Reinforcing Polymers	Maintainability
Fittings	Al Powder Metallurgy	Chemical, Biological, Nuclear Resistent
Landing Gear	Metal Matrix Composites	

Fig. 5. Materials applications for 21st century tactical aircraft. After *Hadcock* [11].

Table 1. Integrated High Performance Turbine Engine Technology (IHPTET) Goals Require Revolutionary Materials [14].

Engine Component	State-Of-The-Art Materials [a]	IHPTET Material Requirements [a]	Candidate Materials [a]
Cold Section (Fan/Compressor)	Titanium (to 800 °F) Nickel (to 1200 °F)	2–3 × Specific Strength 1200 °F–1800 °F	Ti Aluminide Composites Ti Composites Glass Composites High Temperature Al
Hot Section (Combustor/Turbine Augmentor/Nozzle)	Nickel (to 1900 °F) Cobalt	3–5 × Specific Strength 2800 °F with Cooling 3–4000 °F Uncooled	Ceramic/C–C Composites Adv. Aluminide Composites Refractory Metals
Nonstructural (Bearing/Lubes)	Liquid Lube (to 350 °F) Metal Bearings	up to 1500 °F	Solid Lubes to 1500 °F Liquid Lubes to 800 °F Ceramic Bearings

[a] $x\,°F = \frac{5}{9}(x-32)\,°C$.

the requirements are primarily multi-phase materials requiring engineered microstructures. The requirement for low-observable technology, including radar and infrared signatures, strongly drives the choice of the structural configuration as well as the material selection, particularly for stealth technology aircraft such as the B-2.[13] The materials for such aircraft must be designed to meet not only structural but also electromagnetic requirements. Such multiple purpose designs require the materials engineer (and ultimately the materials researcher) to define his or her role within the broader systems design concept as described earlier.

The joint Department of Defense/NASA/Industry Integrated High Performance Turbine Engine Technology (IHPTET) program[14] has the goal of doubling the performance (thrust-to-weight-ratio) of turbine engines by the beginning of the next century. The materials challenge, Table 1, involves major usage of non-metallic materials which have traditionally been avoided because of their low toughness.[14]

Although first cost, and total cost of ownership, are becoming far more important for military aircraft, such considerations have always been dominant for commercial aircraft. There currently exists an economic dilemma in terms of new materials usage in commercial planes.[15] Whereas the soaring fuel prices of the 1970's accelerated the need for fuel efficient technologies, including composites and aluminum–lithium alloys for weight reduction, the oil glut of the 1980's slowed down the introduction of new aircraft and consequently new technologies. According to *Swihart* the price premium that the market would bear for a 10% fuel saving dropped from 16% in the 1970's to 2.5% in 1985.[15] The cost of ownership has replaced the fuel cost as the largest part of the commercial transport direct operating cost.[16] The next generation of transport aircraft will likely consist of derivatives of current models. As a result, the opportunities for introduction of new materials will be very much dependent upon economic considerations. For composites, which could be as much as 65% of the structural weight of new transports,[16] the cost of fabrication is a major factor. The emphasis on cost further reinforces the theme that the materials design must be more fully integrated into the systems design.

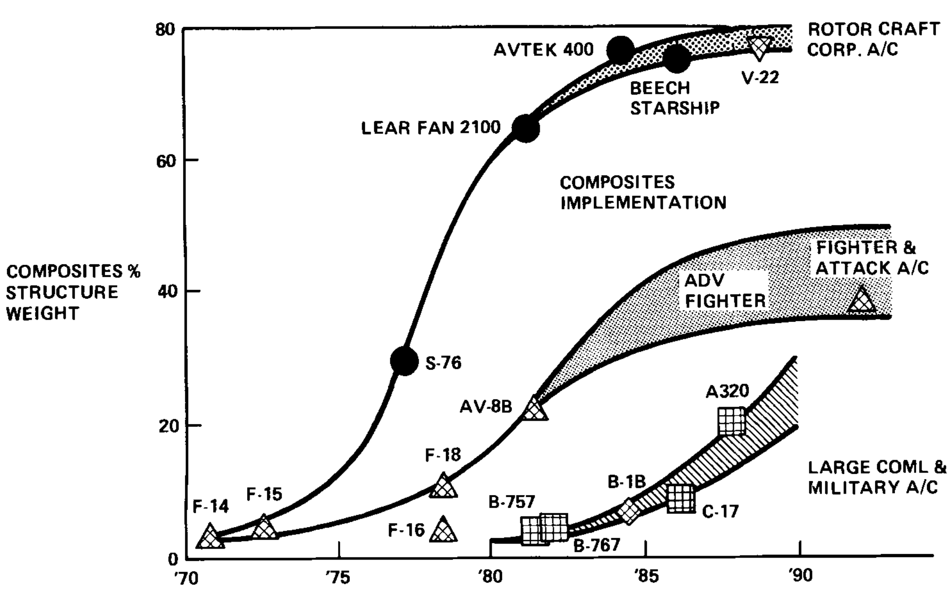


Fig. 6. Increased Usage of Composites in Aircraft. After *Hadcock* [11].

The introduction of new materials, such as composites, has been more rapid in helicopters and light aircraft than in tactical or transport aircraft, Figure 6.[11] Prototype all-composite helicopters have been built[17–19] and have demonstrated the potential for significant (30%) cost reduction. The cost reduction accrues primarily from an order of magnitude reduction in the number of parts and the attendant assembly labor reduction, which more than overshadows the higher materials costs.

There is significant future potential for both military and civilian usage of space. Whether or not the current world situation slows the development of space weapons, there will be a need for both military and civilian communication, surveillance, and navigational satellites. In addition, there is the potential for exploiting the space environment for materials (including biological materials) processing. The NASA Space Station represents a major thrust in space in the 21st Century. Because of the high launch costs, weight remains a more dominant factor in spacecraft than aircraft; however, long term durability continues to be an increasingly important consideration. The combined effects of vacuum, radiation, and thermal cycling are particularly challenging, especially for non-metals. The use of metal matrix composites for microwave packaging is typical of the emerging need to integrate the materials design with the total system requirement.[20] In this case the material functions simultaneously as a structure and a heat rejection mechanism, and meets stringent electromagnetic and thermal stability requirements. So-called "smart materials", that have embedded sensors and can change characteristics as required, are the obvious extension of the integration of materials design with systems design.

4. Research Opportunities

In examining research opportunities it is clear that we must posture ourselves to design microstructures to meet a broadened range of requirements. The relationship between microstructure and properties is the traditional domain of the materials scientist. The classic work of *Hall*[21] and *Petch*[22] in the 1950's, relating grain size in steel to mechanical properties, established the significance of quantitative microstructure–property relationships. There is a need to establish these relationships in a more precise quantitative form than has been done in the past. Traditional continuum mechanics, based on the assumption of homogeneous continua, cannot handle multi-phase materials nor discontinuities such as damage. Although micromechanics has been developed to handle some simple aspects of fiber composites, a new level of materials mechanics is needed to provide the mathematical basis to truly design a general microstructure.[23] Such an approach requires extensive collaboration between materials and mechanics researchers. There is also a need for a more precise and universal mathematical description of microstructure as the common language of this collaboration. Some metallurgical approaches[24, 25] coupled with the use of fractals[26–28] appear promising. Fractal dimension can be a powerful mathematical description of microstructure. We need a standardized language to describe the shape and size distribution of each phase (including interfaces) and its spatial arrangement. Such a scheme must be able to characterize such complex structural materials as soils (solid particles plus liquid and gas phases), chemically bonded ceramics (including concrete and cement), and deliberately porous materials.

5. Tough Materials

It is clear that in developing a new quantitative mechanics of microstructures, the property we call toughness is probably least understood. Our emergence from the Stone Age, more than five thousand years ago, was prompted by the lack of toughness of ceramics. Because metals exhibit extensive plastic deformation, we have come to equate ductility with toughness and have assumed, erroneously, that uses of materials exhibiting little or no plastic deformation are limited by their brittleness or low toughness. In recent years, experience with multi-phase materials, especially fiber composites, has taught us that there are microstructural alternatives to plastic deformation which can handle stress concentrations and exhibit significant toughness.

Toughness tests normally involve notched or pre-cracked specimens and measure resistance to damage propagation. For inhomogeneous anisotropic materials, it is not always clear how such measured properties relate to actual performance in structures. The following discussion treats such measured resistance to damage propagation as an indicator of toughness. Ceramic and carbon fiber reinforced glass-ceramics have exhibited macroscopic toughness values over 20 MPa $m^{1/2}$ which is comparable to metal alloys.[29–30] *Cook* and *Gordon* described how the fiber matrix interface can open to blunt a crack, which is analogous to plastic deformation blunting the crack tip in metals.[31] The role of the fiber interface in imparting toughness has been the subject of extensive discussion. Fiber surface treatment has been shown to dramatically change the toughness of fiber reinforced polymers,[35] hydrated cement,[36] and ceramic/ceramic composites.[37–39] The research challenge of understanding the microstructure–toughness relationship is also dependent upon the complex state of stress determined by the other microstructural characteristics, such as the relative properties of the phases and their shape, size, and spatial arrangement.[37, 40–44] The exact mechanism of toughening will be dependent upon the interaction of the relative and absolute properties of the phases and the interface. In addition to the composite approach to providing toughness to otherwise brittle materials, there have also been extensive efforts to control[48, 49] and characterize microstructural defects and to provide phase transformation toughening.[50]

The groundwork for the required mathematical mechanics treatment of microstructure–property relationships has begun. *Kunin* has extended the description of elastic media to include microstructure.[51] Major efforts have been made to account for damage,[52, 53] and inelastic behavior.[54] A concerted effort is needed by materials and mechanics researchers to develop a more precise mathematical basis for the design of microstructure.

6. Biological Models for Designed Microstructures

In a fascinating new book, *Gordon* points out that living organisms provide manifold examples of structural materials, engineered within a total system design including cost (defined as metabolic cost).[55] Bone is a marvelous example of an engineered microstructure. It is a fiber composite containing stiff hydroxyapatite fibers in a collagen matrix. The fibers are oriented to resist the principal loads and, because living bone is constantly dissolving and regenerating its structure, can reorient the microstructure to respond to changes in loading (e.g. a fracture). In addition, bone microstructure simultaneously performs non-structural functions such as conveying blood via built-in tubular cells. Bone is not as structurally efficient as wood (another living engineered fiber composite), because it is optimized to function along with tendons and muscles in a total structural system.

In a remarkable example of man imitating nature, *MacCready* et al. built a flying replica of the extinct reptile *Quetzalcoatl Northropi* (QN).[56] In the course of doing so, he studied the detailed design of engineered materials in birds within the context of complex system design (Fig. 7). A key design factor in the QN replica was an on-board control system (brain analog) to maintain structural and dynamic flight stability under changing loading conditions. The structural materials design could not carry the flight loads in the absence of the control system, which was inadvertently demonstrated when the QN was accidently launched with its control system off. Analogously, the human body cannot stand straight with its control system (brain) off. So-called smart materials, containing sensors and actuators to change structural characteristics, are future materials research opportunities which could mimic the integrated systems of biological materials.

Fig. 7. A man-made *Quetzalcoatl Northropi* incorporating nature's design concepts. The materials design was fully integrated with structural and control design. Photo courtesy of Aerovironment Corp [56].

7. Processing Opportunities

Perhaps one of the most challenging materials research opportunities is processing. Not only will we be challenged to economically produce geometrically precise microstructures, but we will also likely shift away from energy intensive thermal processing toward more low temperature chemical and even biological processing. This will require an additional shift in our perspective and a blurring of the traditional roles of materials supplier, processer, and user.

Sol–Gel processing of ceramics is an example of a new lower temperature chemical technique.[57, 58] It consists of polymerizing a porous ceramic gel from solution and subsequently drying and densifying it. The technique allows processing below 500 °C compared with traditional melt processing at three times that temperature. Recent research has focussed on chemical additives to control the kinetics and therefore the pore size, distribution, and residual stresses.[59] Perhaps more important than low temperature processing, is the opportunity to produce composites by sol–gel processing.[58] By dispersing two or more phases in the sol, precisely controlled multiphase microstructures can be produced at fine scale. The term nanostructure or nanocomposite has been used to describe such structures with nanometer scale phased dimensions. Because the size of each phase is only a few atomic layers, such materials tend to have properties significantly different from bulk properties.[60] This has significant potential for both structural and electronic applications.

Another approach is reaction processing, in which the components react chemically in the solid state with a gas or liquid phase to provide densification.[61] An extreme example of this is self-propagating high temperature synthesis involving a combustion reaction.[62] The LANXIDE process involves forming solid oxide structures by the controlled reaction of a molten metal with an oxidizing vapor. By conducting the reaction in the presence of a solid second phase, composites can be fabricated.[63]

A very intriguing materials research opportunity lies in mimicking the way living organisms process ceramic composite structures such as bone and shell. *Calvert* and *Broad* have used such bio-mimetic processing to produce metal oxide materials.[64] Coupled with our new insights into the structure of DNA and the ability to bioengineer designer organisms, it seems a natural extension to design organisms to produce precisely defined microstructures.

There are also significant research opportunities in the area of processing metal alloys and metal matrix composites.[65, 66] Castings are attractive because of the low cost and their potential for production of net-shape or near net-shape parts. Processes such as directional solidification to control or eliminate grain boundaries and hot isostatic pressing to eliminate defects have moved castings from the low to the high performance arena. Whisker reinforced cast aluminum exhibits properties approaching polymer matrix composites with the inherent low cost and handling familiarity of metals.[67, 68] The key technological issue is processing to provide a controlled whisker dispersion. Intermetallics have significant potential for higher temperature application, but with significant processing challenges.[69, 70]

The technology of polymers has been traditionally process oriented. The engineering of polymer chains probably represents the most extensive use of engineered microstructures.[71–73] Some of the newer oriented polymer fibers compete with some of the best inorganic fiber reinforcements. An exciting outgrowth of this area is the possibility of simultaneously polymerizing rigid rod fiber polymers in a matrix of a more flexible polymer thus creating a molecular composite.[73] Thermoplastic polymers are attractive because of their lower processing cost and cycle time compared with thermosets.[74, 75] Research challenges include synthesizing new higher performance (including higher temperature) thermoplastics with improved environmental resistance along with improved processability in composites. Polymer blending offers the potential for providing ease of processing with improved performance.[76, 77]

8. Conclusion

There are exciting challenges facing the materials research community. Although the technical needs are well known, and many important new approaches are well defined, it is important for the materials scientist to see himself or herself in a broadly expanded context. The design of materials as a part of the overall systems design will become the norm. As a result, such factors as cost, durability, supportability, and specialized functions will take on added importance in materials science, engineering research and education. Important research opportunities include joint materials–mechanics efforts to provide precise mathematical microstructural design tools, and new chemical and biochemical processing techniques to synthesize the designed microstructures. In particular, the advent of bioengineering offers the possibility of genetically engineering new biological species to produce precisely designed microstructures.

Received: December 19, 1988

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Challenges in Materials for Health Care Applications

Implanted Devices
Tissue Replacements
Biocompatible Polymers

By David F. Williams*

Important issues face the use of advanced materials in medical applications. It is now possible to replace or augment many tissues and parts of the body by implanted devices, but there are still severe limitations to functions they are able to perform and problems associated with their compatibility with the tissues. Biomaterials of the future need to simulate more closely the tissues they are replacing and both the current position and future outlook are reviewed in this light.

1. Introduction

In the fifty years that have now passed since the invention of Nylon by *Wallace Carothers*, we have witnessed many changes in materials science and in the contribution of materials science to the welfare of mankind. This paper will discuss and review the current status of, and future challenges for, the uses of materials in one specific aspect of this contribution, that of implantation within the tissues of the human body.

There are many reasons why it is necessary or desirable to place some of today's advanced materials within the body,[1] but it is not the purpose of this paper to review them in detail. Some of the major reasons, and the current technical advances that have been made, are now well-known (Table 1). The twin diseases of rheumatoid and osteoarthritis are unfortunately very common, but the surgical technique of joint replacement, developed to overcome the pain and disability caused by these diseases is widely practiced, and has become a familiar landmark of late twentieth century surgery. Cataracts in the eye are now effectively treated in some half

Table 1. Some current applications of implanted devices.

Clinical area	Implant	Tissue replaced or augmented
Orthopedic surgery	Total joint replacement	Bone, cartilage
	Fracture fixation	Bone
	Ligament repair	Ligament
Cardiovascular surgery	Mechanical heart valve	Valve leaflet
	Bioprosthetic heart valve	Valve leaflet
	Vascular prosthesis	Blood vessel
	Pacemaker	Nerve
Ophthalmology	Intraocular lens	Lens
	Keratoprosthesis	Cornea
Ear, nose and throat	Ossicular replacement	Bone
	Cochlear stimulation	Cochlea/nerve
Maxillofacial	Dental implant	Teeth
	Fracture fixation	Bone
	Mandibular reconstruction	Bone
Plastic surgery	Breast reconstruction	Soft tissue

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