8.0 Engine Materials

Research and development of materials suitable for advanced engines, including turbine engines and other propulsion systems such as ramjets and scramjets, has over the past 50 years proceeded at a prolific rate. The overall aims of these R&D efforts have been directed into thrust increases coupled with weight reductions, leading to increased engine performance as well as improved specific fuel consumption. The origin of these various efforts has been based largely in the programs undertaken by the engine producers, coupled with programs run by DoD laboratories and ARPA. Universities and national laboratories have been involved in much of the basic research areas (i.e. 6.1 programs) and to a lesser degree in exploratory development (6.2 programs). Much of the progress has been initiated by visionaries in the industrial sector, where the business of engine materials development is well known and a key issue, but often as a result of creative synergistic interactions with scientists and engineers at government and academic institutions. An important issue, to which reference is made in other sections of this report, is that future advances in engine materials will be severely hampered by the fact that investment by the engine producing industries and risk-oriented agencies in these innovative, visionary programs has decreased precipitously. Decreased funding means that there are fewer technologists, with the essential experience, working in or with these industries, and the danger is that we will fall below a critical mass required to permit creative synergism between industry and government to occur.

In this report, materials research and development over two time scales is addressed, one being 10-15 years and the second being 20 years and beyond. In terms of the first, these types of research projects are those involved in 6.2 programs, whereas for the longer time scale, these projects are best described as being of the 6.1 variety. For turbine engine components, the Integrated High Performance Turbine Engine Technology (IHPTET) Materials Program initiated in 1988 includes much of the relevant projects for engine materials. Materials for other propulsion systems have been researched in programs such as the National Aerospace Plane (NASP), and Hypersonics Technology (HYTECH). IHPTET is a three-phase program scheduled for completion within the 10 to 15 year timeframe. Carried into Phase III this is an extremely ambitious program which has precipitated remarkable creativity within the materials sector which is far from being realized. A number of materials being developed in this effort, both in Phase II and projected for Phase III, will require significant further optimization in the future. A number of Phase II technologies are in serious danger of not being developed to the level of production readiness, while some projected Phase III materials technologies will simply not be suitably developed to meet the Phase III demonstration milestones. Stated differently, even the materials technologies demonstrated via the IHPTET program will require 10 to 15 years to reach field deployment. Within the context of this study, some have suggested that even the technology revolution sought in IHPTET Phase III is merely “near term,” thus an even more distant perspective must be developed. For this, there are some exciting possibilities which are described below. However, it should be remembered that step-function progress, in contrast to continuing evolutionary improvements, in materials technology requires that a significant cadre of technologists be focused in these new areas. Hence, attaining progress requires new and effective teaming arrangements between universities, government, and industries.

8.1 New Engine Materials: Why are They Important to the Air Force?

The importance of new engine materials to the Air Force involves increased improvements in engine performance with the added advantages of affordability and environmental friendliness. Clearly, some of these factors are of a strategic nature, some impinge on environmental issues, and others clearly address the issue of cost. In the first of these performance, a goal of the IHPTET program is to reduce engine weight by 50 percent and increase thrust to weight by 100 percent. To illustrate the kinds of weight savings that can be achieved with new and improved materials and processes, and the implication of such weight savings, we refer to the estimates made for the lifetime of the F-22 fighter, where each pound of weight saved in an engine results in a saving of 8.7 million gallons (73 million liters per kilogram saved) of jet fuel. At today's prices, that saves $4.8M in fuel. Estimates of the weight of a compressor bladed ring made from existing superalloy materials is about 25 kg (55 pounds), whereas the same component fabricated from titanium metal matrix composites (Ti-MMCs) would weigh 4.5 kg (10 pounds), a significant savings. For these same materials, the combined weight of the third and fourth rotors, with attendant spacer, is reduced from 69 kg (150 pounds) to 15.5 kg (34 pounds). General Electric's substitution of g-TiAl as the material for the low-pressure turbine (LPT) rotor in a CF6-80C engine results in a reduction of approximately 136 kg (300 pounds). Multiplying these weight savings by the saving in jet fuel used, and even structure redesign, implies a very marked reduction in operational cost to the Air Force. To the warfighter, these gains in engine performance can also be translated into capabilities: For fighters—sustained supersonic operation, 45 percent reduction in take-off gross weight (TOGW), smaller turning radius and increases in range and payload; For transports—increased range and payload, with longer life and reduced maintenance; For expendable engines/missiles—150 percent range increase for strategic subsonic propfan and 75 percent range increase for supersonic tactical turbojets. Over the long term—20 years or so—these benefits will multiply as new materials and designs enable propulsion systems with revolutionary improvements in cost, reliability, performance, and environmental considerations.

8.2 Basis for Improvements in Materials for Engines

The most significant factor upon which improvements in engine materials are based involves the thermodynamics of the combustion process. Figure 8.1 is a schematic diagram of a gas turbine engine, from which it can be seen that propulsion is derived from the combustion of a mixture of jet fuel and compressed air. In general, thermodynamics are optimized by increasing the pressure of the air and the temperature of the combustion process. Hence, as the compressor increases the pressure of the air such that the compressor discharge temperature (T_3) is increased, the temperature of combustion increases so that the high pressure turbine inlet temperature (T_{41}) is also increased, and the overall efficiency of the engine improves. The desire to increase these temperatures leads to the first requirement in terms of improved materials, which is for materials exhibiting enhanced elevated temperature properties, not only in terms of mechanical response but also in terms of resistance to corrosion and oxidation. Of course, a second requirement immediately follows, which is that these enhanced properties should be achieved without weight penalties. In fact, increased temperature capabilities and lower materials densities are often played off against one another in application in given components. An example of how these temperatures, nd T_{41}, have increased and are expected to increase with time is shown in Table 8.1.

*Table 8.1. Engine operating parameters over the period 1970-1994, and projected to the year 2010. OPR is the overall pressure ratio, and T_3 and T_{41} have been defined in the text (see Figure 8.1). * data for advanced subsonic flight; § data for the high speed civil transport (HSCT). Data provided by Dr. Lyman Johnson, GE-AE.*

Year	OPR	T_3 (°C)	T_{41} (°C)
1970	15:1	590	1345
1994	38:1	695	1425
2006§	25:1	620-705	1540-1650
2010*	75:1	815	1760

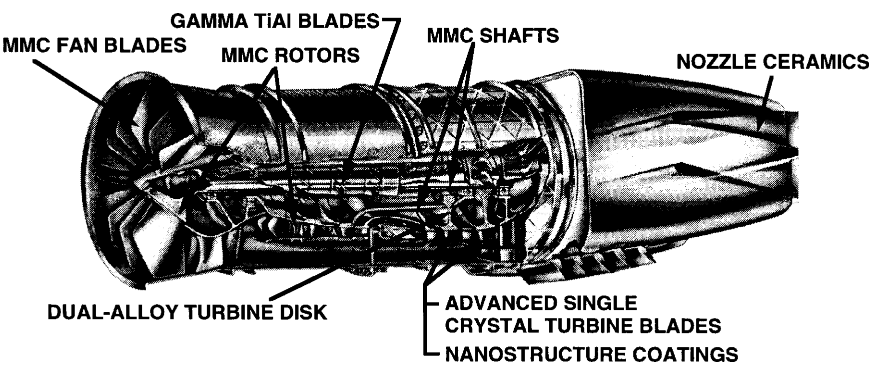

Figure 8.1 Schematic Cut-Away of a High Performance Gas Turbine Engine

In addition to the requirements of higher temperature capabilities to enhance the thermodynamic efficiency of the system, and lower densities to improve specific properties, other characteristics of engine materials need to be enhanced. For example, the durability of components must be improved, particularly as the temperature capability is increased. Also, resistance to environmental degradation is extremely important and the improved materials must be sufficiently damage-tolerant to meet design criteria. The specific stiffness must be enhanced; this is particularly an issue for fan blades and other large structures. The costs involved in processing and production must be minimized so that components made from advanced materials are affordable. For example, component affordability may be improved by increasing yields through the use of process modeling, improved reliability through process controls, and improved cleanliness and near net shape processing.

Improvements in engines may be effected by use of materials which are enhanced as described in general terms above. However, often it is not an optimum situation when a new or improved material is substituted for an existing one in a given component. Rather, the design of the component should be re-examined in light of the improved properties of the material. Conversely, new designs are not appropriate if there are no materials which exhibit properties required of the given component. Hence, it is extremely important that an integrated approach evolves in which designers, materials engineers and production engineers develop new systems solutions. A combination of innovative design and materials enhancements represents a very powerful tool for optimization of turbine engines and all other types of propulsion systems. In terms of the materials limitations of today and the near future, it is also important to recognize that the same materials come in several forms, which leads to multiple service limitations. For example, nickel-based superalloy technology falls into several broad classes, such as single-crystal alloys for first-stage turbine blades and powder metallurgy wrought alloys which are used for turbine disks. The disks cannot be made today from single crystals, while the disk alloys would not serve in the first-stage turbine of modern engines. Temperature, stress and lifetime must be considered together in defining materials performance. For these reasons, one must speak not only in terms of alloys or materials, but also in terms of processes and components together with the alloys. Only then are technologies defined.

If R&D resources continue to be invested, dramatic improvements in propulsion materials will be achieved over the next 10 to 15 years. Materials for hypersonic propulsion systems will be developed under programs such as HYTECH and will include nickel-based superalloys, advanced refractory alloys, intermetallics, and coatings for thermal control and environmental resistance. These materials will be for non-manrated systems in early development but will eventually be ready for manrated applications as the reliability of the materials is increased.

Significant improvement in turbine engine performance will be realized over the next 10 to 15 years if materials issues in the following critical technology areas are addressed. These areas may be viewed as seven core technology areas for turbine engine structural materials. The materials capability in several of these areas pace all performance measures of engines. Revolutionary advances are being sought in some of these under the IHPTET Materials Program. The critical components are:

- Light weight fan blades
- T_3 compressor disks
- Compressor blades
- High-pressure turbine (HPT) disks
- HPT airfoils
- Static components (cases, ducts, etc.)
- Combustor and exhaust nozzles

There are a number of candidate materials systems which are currently under development, and, if successful, may be applied in engine applications over the next 10 to 15 years. These are described briefly below.

Light Weight Fan Blades

Of the components listed above, fan blades are operated at the lowest temperatures. However, these items are large, and hence considerable weight savings may be realized by use of low-density materials which exhibit appropriate mechanical properties, for example, a tensile strength of 560-630 MPa (80-90 ksi), which precludes many light weight materials. Considerable interchange between designers and materials engineers has taken place regarding this component, and innovative designs including hollow blades has resulted. For these components, a high specific stiffness is required, and so materials of choice have centered around the exploitation of organic matrix composites (OMC), such as graphite-reinforced resins, and titanium alloys.

In the first of these, OMCs, there are major advantages in terms of weight and durability. For example, the specific strength and stiffness are better than twice those of metallic structures, and the fatigue limits are equally superior. Although these types of materials find application as fan blades at present, there is a need for improvement in capability. For example, for advanced turbine applications there is a need to increase fan temperatures up to 482°C (900°F). This requirement is far beyond OMCs at present, and an ambitious goal which would still offer considerable advantage would be 427°C (800°F). Manufacturing methods under development include improved woven preforms, resin transfer molding, and automated tow/fiber placement. Emerging systems include efforts aimed at development of toughened epoxies, thermoplastics and high temperature matrix resins. Finally, repair of these types of materials is a potential problem, and effort has been placed in this area, such that efficient repair methods are emerging. In general, OMCs are not considered to be suitable for large high-speed fans.

In terms of the upper temperature range for fan blade applications, namely 482°C (900°F), the material of choice is titanium, and in order to reduce weight, a design involving a hollow blade is used. The aim is to develop materials for large high-speed solid fan blades, since the hollow blade design involves a substantial increase in cost. In terms of the optimum design—a solid blade—materials are required which not only meet the strength requirement of 560-630 MPa (80-90 ksi) but also have a maximum density of 3.3 gm/cm^3 (0.12 lb/in^3). This is a very difficult set of requirements. This area of component development involves materials research over a period of time greater than that considered here, investigating materials concepts well beyond all those conceived today.

T_3 Compressor Disks and Compressor Blades

The need is for materials with elevated temperature capabilities which will permit the compressor discharge temperature (T_3) to increase by up to 204°C (400°F), a goal of phase III of the IHPTET program. This will require increases in the performance of compressor disk materials by 66°C (150°F), i.e. up to operating temperatures between 871°C (1600°F). Materials currently under development with reasonable chances for successful application as disks are titanium-based MMCs and for blades alloys based on the intermetallic compound gamma titanium aluminide (γ-TiAl). The most structurally efficient approach being researched is a combined blade and disk, either in the form of a bling or an integrally bladed rotor (IBR). The first of these involve a series of titanium alloys as the matrix, including Ti-64, Ti-1100, Ti-6242S, alloy C, and the intermetallic compound known as orthorhombic Ti (Ti_2AlNb); these are generally reinforced by fibers of SiC. An example of properties obtained for such systems would be for Ti-6242S reinforced with SiC fibers (150μm diameter): room temperature ultimate tensile strength (longitudinal) of 1.9 GPa (276 ksi) and a Young's modulus of 229.6 GPa (32.8 msi). The best promise is afforded by orthorhombic Ti-MMC, where strength levels are sustained to higher temperatures than with conventional titanium alloy matrices. These Ti-MMCs, if used in compressor rotor applications, will require significant additional development.

In terms of alloys based on the intermetallic γ-TiAl for blade and rotor applications, while there has been considerable development to date, not even static components are in service to date, nor will they be for at least three years, even in the commercial sector. Introduction of these alloys will be followed by at least 10 more years wherein today's gamma-alloy technology is fully transitioned from the laboratory to full-scale production in many components. The attractive features of these gamma alloys include a relatively low density (about half the density of nickel), a fairly flat modulus curve over a wide temperature range, outstanding specific stiffness, and useful mechanical properties up to approximately 750°C (1380°F). In the near term these attributes are being sought for static components, such as ducts and nozzles. However, none of these planned introductions is likely to be for compressor disks, or even blades until the latest stages of this period. Risks are quite high for such components, hence the inertia to overcome is great. For the longer-term, higher-risk components such as rotors and cases, there is still a need for R&D over the next 10 to 15 years to advance gamma-alloy technology. In this sense, the turbine-engine business is at the dawn of the next 15 years. During this period dramatic reductions in engine weight will be realized as designers have opportunities and learn how to introduce gamma alloys in engines.

HPT Disks

In principle, as the temperature of the engine is increased, the temperature that HPTs experience also increases. There are schemes which may be employed to meet that requirement, and some of these are discussed in the section dealing with the long-range plans. One solution is to employ materials with improved elevated-temperature capabilities. For example, HPT disks (816°C, 1500°F) are required to exhibit good creep resistance at the rim of the disk and optimum resistance to fatigue in the vicinity of the bore. A potential solution to this problem is to employ a dual-alloy concept, as adopted by the IHPTET program, in which different alloys are used for the rim and the bore, where these have been optimized for the two types of physical requirements and are joined metallurgically. In this way, it has been possible to provide a dual-property disk. Such dual-alloy technologies have been in exploration since the early 1980s, but may become a reality through IHPTET and programs which transition IHPTET technologies to flying aircraft.

HPT Airfoils

Single-crystal nickel-based superalloy HPT blades are the crowning achievement of more than 70 years of superalloy development in the gas turbine era. For component application at the present, there is no competition for a coated high-performance, single-crystal, nickel-based superalloy HPT blade, and advanced processing methods will continue to improve the properties of these materials. An additional increment in improved performance with nickel-based superalloys will be achieved through the use of thin-wall airfoils produced by deposition techniques.

As part of the ongoing search for new turbine materials, there has been a considerable amount of development on the production and property enhancement of single crystals of the intermetallic compound NiAl. This material has a number of intrinsic advantages over superalloys. First, it is 30 percent less dense, giving a reduction in rotor weight of 30 percent. A 200 percent higher thermal conductivity implies a reduction in airfoil temperature of 38°C (100°F). Both of these factors will lead to an increased thrust/weight ratio and lower specific fuel consumption. A potential problem with these materials involves very reduced tensile ductilities; for NiAl alloyed for high strength, the ductile-to-brittle transition temperature rises from approximately 320°C for the binary compound to greater than 760°C for alloyed versions. Issues to be resolved with this type of material are alloying studies for higher levels of fracture toughness, process development for reduced sizes of defects, establishment of damage-tolerance/life-prediction methodologies, and the development of innovative design concepts to compensate for low tensile ductilities.

Static Components

Two classes of materials are envisaged for these applications, namely, for low-temperature environments the use of OMCs, and for elevated temperature applications orthorhombic Ti and g-TiAl. In the first of these, graphite-reinforced epoxies and high-temperature resin matrices are being developed for the following applications:

- Fan case: 150°C - 260°C (300°F - 500°F)
- Fan duct: 300°C (550°F)
- Intermediate case frames: 300°C (550°F)
- Inlet case frames: 150°C (300°F)

The potential benefit from the use of OMCs in these applications involves a weight savings of approximately 30 percent.

For applications such as cases and ducts, which experience temperatures up to 760°C (1400 F), γ-TiAl is being developed. This intermetallic compound has been described above but in summary it is a high modulus material which has approximately 50 percent the density of nickel and 80 percent the density of titanium. It is castable, and it can be machined and welded, even though it is more brittle than conventional materials. Development programs are in place to provide solutions to the problem areas.

Combustor and Exhaust Nozzles

Ceramic matrix composites (CMCs) are being developed for application in these components. There are three driving forces for their use: 1) increased thrust/weight ratios through elevated temperature combustion, 2) lower emissions from higher temperatures in the combustor, and 3) achievement of reduced signature levels in advanced fighter engines. The ability, in principle, to operate the combustor at significantly higher temperatures through the use of CMCs does offer the advantage of lowering the emission (NOx) levels dramatically, and such environmental concerns are becoming increasingly important. Intrinsically, the use of ceramic materials for these very high temperature applications, typically in the range 1200°C - 1400°C (2200°F - 2600 °F), is attractive because of the well-known properties of such materials. However, SiC-matrix materials reinforced by nicalon fibers are limited to approximately 1100°C (2010°F) and oxide-based systems potentially limited to 1350°C (2460°F), are only in early exploration; as can be seen, they barely make the cutting edge for these applications. Other properties, such as toughness and ductility, also raise obstacles to application, although the use of fibers as the reinforcing medium has tempered the toughness problem. Properties such as thermal fatigue and corrosion resistance are relatively unexplored in the relevant component geometries.

While there are still many development challenges, CMCs are slated for application as compressor shrouds, combustor liners in the high-speed civil transport (HSCT), divergent seals, and spherical convergent flap nozzles (SCFN), and following considerably further development (see below) as airfoils. CMCs will be used extensively in expendable engines, including rotating ports, which will provide invaluable experience for future use.

8.3 Concepts for Improved Materials Beyond the Next 20 Years

In discussing research concepts for materials to be developed over the next 20 years and beyond, two aspects are considered. The first of these involves a discussion of how the various candidate materials topics are developed, noting that recent changes in research infrastructure presents challenges which must be faced. The second aspect considers some examples of exciting, innovative materials technologies and systems.

As has been pointed out above, the period 10 to 15 years ahead in terms of materials development realistically refers to materials which are either transitioning from 6.1 funding to 6.2, or those already under exploratory development. When considering a longer period, such as 20 years and beyond, it is important that research concepts chosen for study are those which are highly creative and most definitely appropriate for 6.1 funding. Traditionally, the engine producers have played a major role in selection of long-term research projects. Thus, with significant investment in their own industrial R&D laboratories, and largely under internal R&D funding, technologists have had the resources to conduct research which, because of their familiarity with the business of producing engines, has been of a nature that would have a high probability of success in terms of return on investment. Typically, the subject of emerging technology studies would be chosen on the basis of interactions between these technologists and the materials community as a whole. These efforts were coupled with government funding, and technology transfer occurred with scientists, for example, in the Air Force. Upon developing directions based on an integration of these research concepts, R&D programs were established by the government in which the various industries competed and participated. In this way, a significant input into federally funded programs of research originated at the engine companies, and hence relevance was assured.

Two very important changes have taken place in the recent past. First, the investment by the engine companies in research has dropped precipitously, and very little funding of what might be termed technology invention now occurs. The result is that work which might lead to new ideas is not being done, but rather the engine companies appear to be pinning their hopes on the concept of continuous evolutionary improvement of existing products.

Second, a decade of experience has been built in the Air Force laboratories which are well postured for exploring and advancing the projected revolutionary technologies and research. At the same time, the gas turbine industry has focused most of its research investment on the evolution of commercial products. The result, if this trend continues, is an emerging mismatch which will adversely affect technology readiness for the Air Force in the long term. Natural barriers will rise between the three origins of advanced technology—universities, government laboratories, and industry—which have traditionally supplied technology superiority through synergy, not independence. A simple solution involves two steps, one being an increased investment by the engine companies in long-term research, perhaps an unlikely eventuality at present, and the other a closer alignment of the defense customer's expectations with the business realities. The recommendation, then, is that the Air Force must continue to provide leadership in long-range research needed for future engine materials if military capabilities are to be advanced, and that such research must be conducted in partnership with all levels of the engine industry. The industry should be given direct support for, as well as incentives to invest in, materials research. Air Force laboratory personnel should continue to realistically couple the research required to meet military needs with the marketplace realities of the engine industry. This includes prime contractors and suppliers, which are performing less of the research every year, but all of the transition. Furthermore, the Air Force materials scientists and engineers must continue to be responsible for establishing effective teaming arrangements between themselves, those in the engine business, and qualified personnel from universities and government laboratories.

Materials Technology and Systems

In considering new research concepts for materials in engines to be developed beyond the 20 year period, it is possible to consider these systems in three different categories:

- Research on existing materials which have remarkable properties in one sense, but other undesirable properties which have limited their application. Research is aimed at applying innovative concepts, including processing, compositional and microstructural modifications, to provide solutions to these limitations.
- Development and synthesis of new materials making use of innovative schemes for materials processing. This represents a very exciting possibility for advances in the engine business, with the possibility of truly revolutionary advances.
- Development of new systems applications, where improved or alternative materials will be used, possibly in conjunction with changes in design, which will lead to marked improvements in performance.

Examples of these three aspects are given below.

Existing but Limited Materials

- *Oxidation-resistant refractory alloys*: Alloys based on high temperature refractory alloys exhibit high strength, good ductility and toughness. Metallurgical techniques can be used to develop reasonable creep resistance. The show-stopper tends to be a poor resistance to environmental degradation, such as oxidation. Attempts to make these alloys more oxidation resistant in the past have generally resulted in marked reductions in ductility; indeed, the alloys are rendered unsuitable for application. Innovative approaches to the oxidation problem have demonstrated that it may be possible to solve this problem, while maintaining an attractive balance of properties. Application of novel processing routes may well not only render these alloys oxidation resistant, but also provide useful creep and fatigue resistance. An example of the improved resistance to environmental degradation is given in Figure 8.2, and the improved stress rupture properties are indicated in Figure 8.3. A successful outcome in this research effort would be a 200°C increase for HPT blades.

- *Exotic materials*: There are a number of so-called exotic metals and alloys which exhibit attractive properties but have not found application because of either expense or other factors such as a tendency for toxicity. An example of this class of materials is beryllium. This metal has a very low density and a high value of stiffness. These properties when combined with attractive mechanical properties cause the metal to be a prime candidate for turbine engine application. However, beryllium has been traditionally moderately expensive, and the oxide, when finely divided and present in relatively large concentrations, can cause berylliosis in susceptible persons. For these reasons, there has been a reluctance to apply this metal in components. However, recent research has resulted in the development of investment casting techniques in which near-net shape processing of components is possible. This processing results in the material processing costs being significantly reduced, and some alloys processed in this manner have exhibited

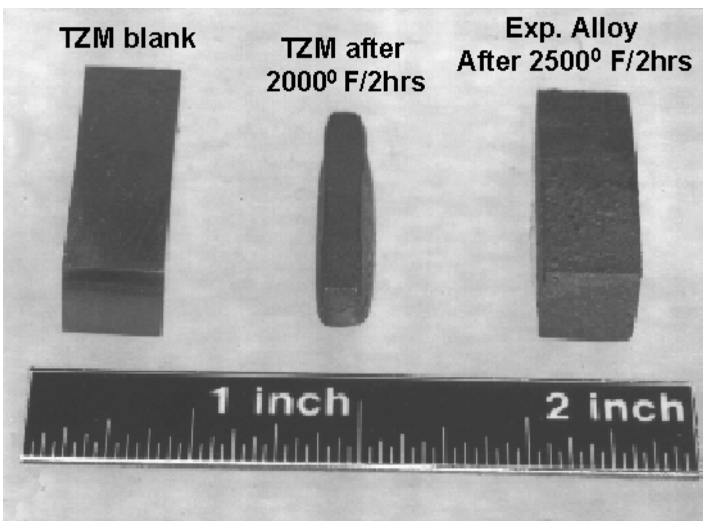

Figure 8.2. Comparison of performance of TZM Molybdenum with a new experimental Mo alloy after the given exposures to oxidizing environments. (Note: the resistance to dimensional change exhibited by the experimental alloy demonstrates dramatically improved performance)

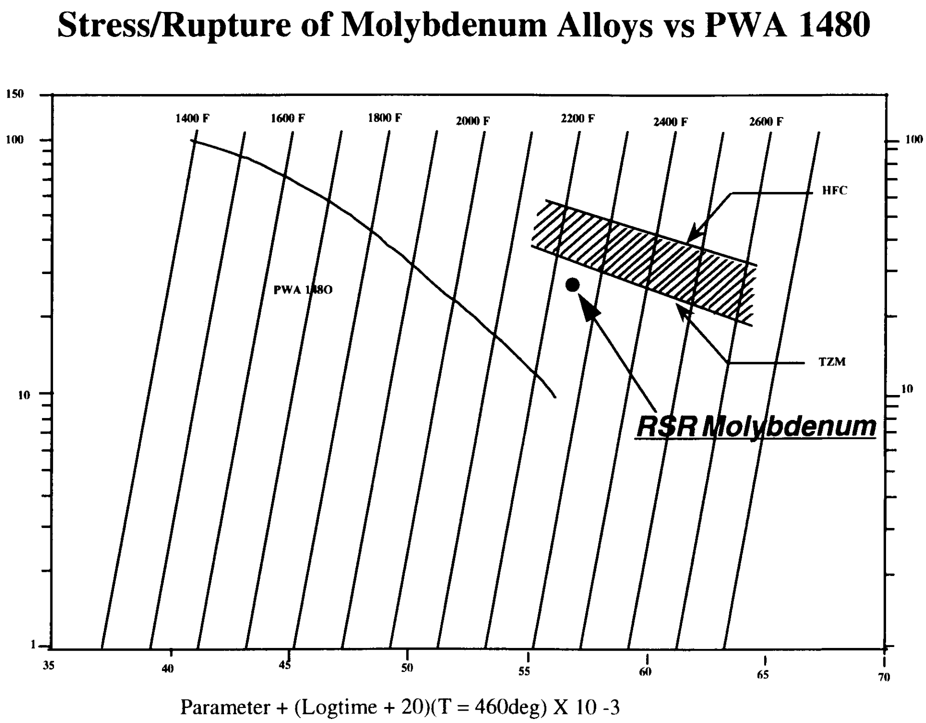

Figure 8.3. Comparison of the stress/rupture properties of an experimental Mo alloy (denoted RSR Molybdenum) with those of existing Mo alloys and also a high performance Ni-base superalloy single crystal (PWA 1480)

useful combinations of properties, an example being Be-31Al-2Si-2Ag. The toxicity of BeO has been carefully studied, and many of the causes for concern have been shown to be inappropriate. Hence, there is a possibility that materials such as beryllium will find application in the future. This metal and its alloys are candidates for fan blade (cores) because of its high strength, very high stiffness, and ease of processing, permitting use of inexpensive solid fan blades. Such possible long term shifts in the historical view of materials can open entirely new horizons for component design and higher-performance engines.

- *Ceramic composites/oxide fibers*: There has long been a desire to include more ceramic-based materials in gas turbine engines, since these materials are usually of moderate density and permit higher operating temperatures. As explained above, any increase in temperature translates into increased efficiency, either applied as increased power or reduced specific fuel consumption. And, as noted, an additional advantage of operating combustors at higher temperatures involves a marked reduction in emissions, particularly nitrous oxides. Application in combustors is projected in the 10 to 15 year timeframe, but if certain property limitations of these types of materials may be overcome through innovative research and development, then more general application in critical components in the engine may be realized in the longer term. For example, application as advanced airfoils, permitting virtually uncooled turbines, may be possible. This eventuality requires significant improvements in the properties of fibers and coatings to enhance compatibility and interface properties. In the long range, fiber manufacturing is envisioned to be so well understood and routine that fibers may be made to order, tailored to specific component or system needs. Such fibers may be produced in situ as composites are fabricated and may have locally tailored properties.

Innovative Synthesis of New Materials

Beyond 20 years, realized visions in synthesis and characterization will bring entirely new opportunities for materials. R&D will lead to the design and synthesis of high-temperature engine materials that will be tailored for specific applications/components from predictions based on computational methods. The ability to understand, control, and design materials will experience a revolution brought on by evolving computational, processing, and investigative tools. These new materials, which will tend to have microstructures which are designed and controlled beginning at the nanometer scale, may be selectively synthesized atom-by-atom as a result of an evolving revolutionary process method, and will exhibit heretofore unimagined levels of defect control. Such synthesis capability leads to a revolutionary view of materials. For example, today's engine materials are commonly viewed as a load-carrying monolithic structure and a coating added to engineer surface properties. In the future, such distinctions between the material and coating will become irrelevant since the materials will be tailored through nanoscale synthesis methods for specific components. The materials will be composites engineered from the nano- to macroscopic length scales. Structural and engine components will see the revolution in design and manufacturing that electronic devices have experienced for more than a decade. Such methods open the possibility of breaking down age-old design philosophies, such as no primary reliance on a coating, thereby opening the door to entirely new applications for materials. The essential computational tools are now in the beginning stages of evolution and, to realize our futuristic visions, materials characterization methods will need suitable advances. Just a decade ago, simple analysis of the chemistry and crystal structure of the constituent phases in an engineering material required several person-years of effort. Today, improved characterization techniques and computer control permit such analyses in a mater of several weeks. Such growth brought the maturity of the discipline of materials science as opposed to the historical fields of metallurgy and chemistry. In 20 years time and beyond, still further improvements in characterization tools, coupled with integration of such tools with computational materials science methods, will bring revolutions in many materials. Such techniques offer the first real hope for shortening the development cycle, so often discussed but never realized.

- *Laminated materials*: There is an increasing interest in laminated materials. These range in scale from about 1 mm down to about 1 nm. Consideration of these materials for engines is divided here into two scales, one appropriate for metallic structures with interlayer thicknesses ranging from ~1 mm down to ~100 nm, and the other for ceramic-based materials with interlayer thicknesses on the nanometer scale. Schematic representations of the way in which these materials function are shown in Figure 8.4. In the case of the former, referred to here as laminated materials (compared with nanoscale materials below), recent experiments involving layered composites of alternating layers of brittle high-temperature intermetallic compounds and tough metallic refractories have shown some exciting elementary mechanical properties. Equally or perhaps more importantly, the process methods envisaged for fabricating such nanometer multilayers may lead to revolutionary concepts for processing components and entirely new classes of alloys. Research is currently focused largely in the areas of innovating synthesis of laminates, however, the expectation is that improved properties such as non-fatiguing alloys, fracture-tough intermetallics and unprecedented levels of creep resistance will be realized. At first, it is envisaged that laminated composites would be used in critical regions of components, largely as outer structures on a substrate of an existing advanced material, for example metal-toughened intermetallic composite airfoil skins. Longer-range concepts include possible substitution of casting by use of deposition techniques in the production of complete components, such as airfoils. An example of the microstructure of an intermetallic/metallic multilayer is shown in Figure 8.5, and a schematic representation of the possible application of these materials as coatings is shown in Figure 8.6. Eliminating the necessity of foundry techniques would of course imply that casting defects, such as chemical segregation (micro- and macro-), and microstructural variations, would be eliminated. Materials could be fabricated having nearly complete freedom in combining elements rather than being constrained by natural limitations of current processes, leading to completely unknown new materials.

- *Nanoscale materials*: These types of materials will have broad applicability; initially in thin films such as coatings, and ultimately in entire engine components.

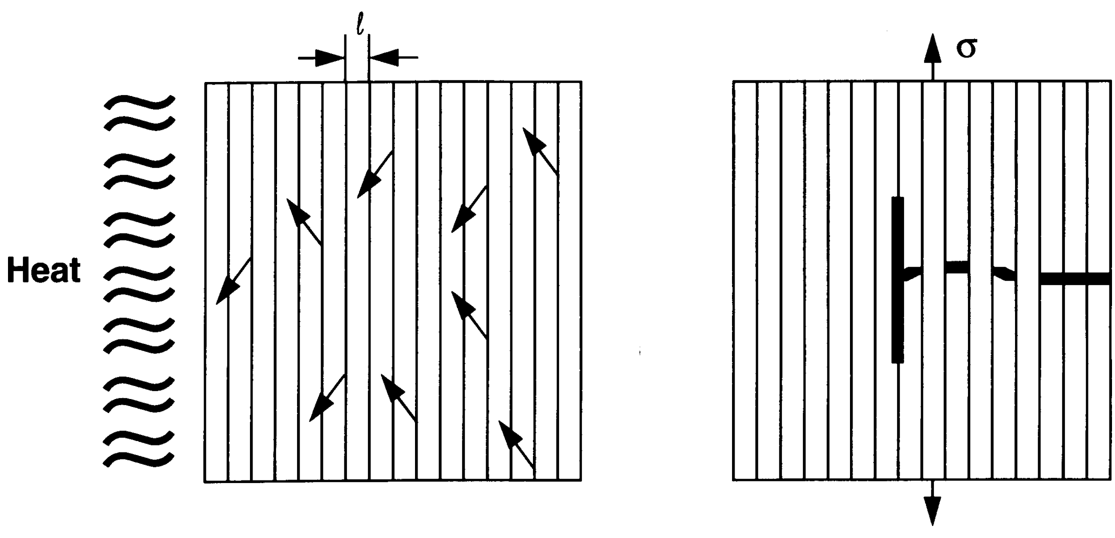

Figure 8.4. Schematic diagrams to depict a possible mechanism of the function of a nano-layered thermal barrier coating (left), and crack deflection in a microlaminated sample(right

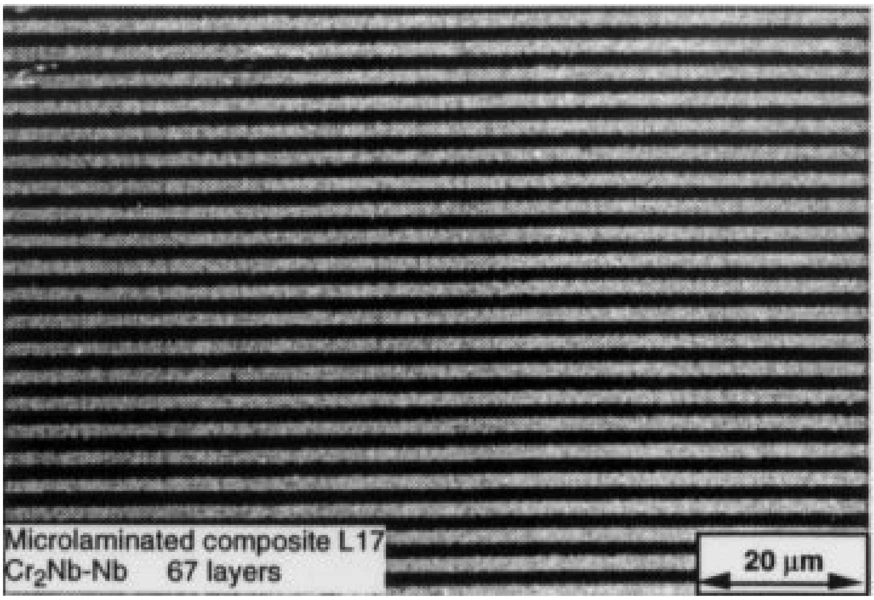

Figure 8.5. An electron micrograph of a microlaminated micro-composite consisting of 67 layers of Cr_2Nb/Nb

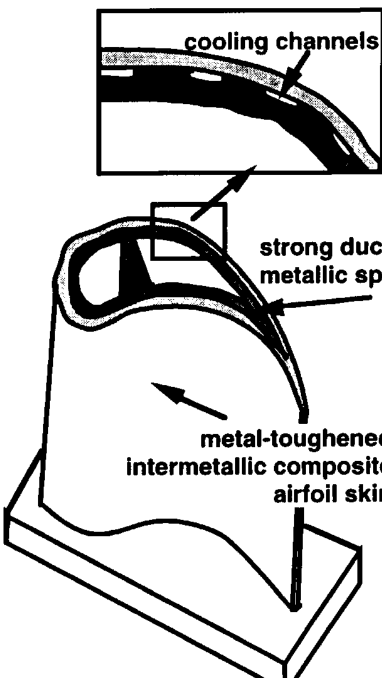

Figure 8.6. Schematic representation of the use of laminated micro-composites in turbine blade applications

They are now beginning to find application as thermal barrier coatings on nickel-based superalloy turbine blades. A comparison in the variation in thermal conductivity with temperature for monolayer TBC and nanolayered TBCs is shown in Figure 8.7. Quite remarkable enhancements in temperatures may be realized, for example increases of ~260°C for HPT blades are expected for a fully developed system. More research is required in order to understand the mechanism of the reduced thermal conductivity of these nanolayered materials, despite the depiction of a possible mechanism shown in Figure 8.4. Such a detailed mechanistic understanding is required so that full exploitation of these types of materials may be effected. In other applications, nanoscale ceramic composites may be synthesized which exhibit very much enhanced erosion and wear properties, and these materials would find application as coatings. Combined with new process methods for base metal synthesis and multilayer technology, complete control of material composition and structure will be possible such that materials will be tuned to their specific function from sustaining load to tunable outer layers for signature control in a continuous component.

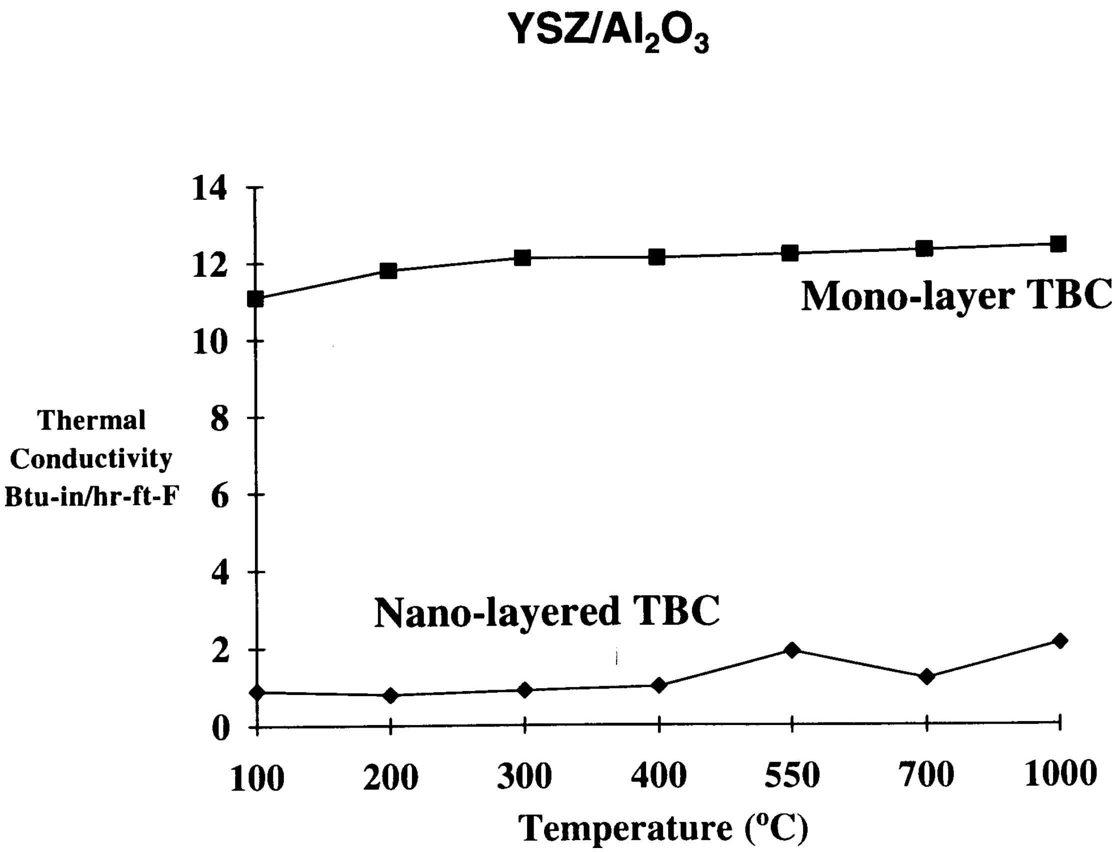

Figure 8.7 Comparison of the thermal conductivity as a function of temperature for mono-layered thermal barrier coatings and multilayered materials

- *Amorphous metallic alloys*: Amorphous metallic materials have been developed with very attractive properties, including high strength (1.8 - 2.5 GPa), low coefficient of thermal expansion (CTE), reasonably low density ~4.5 g-cm^{-1} (for materials based on Ti-Zr-Cu-Ni-Be), and excellent resistance to corrosion. Interestingly, these amorphous materials may be formed in bulk quantities using reasonable rates of cooling, and because they solidify with essentially no shrinkage, they exhibit good net shape processing capabilities. They are stable over wide ranges of composition, and an obvious application involves the use of the material as a brazing alloy. More interestingly, because the CTE values of these amorphous metals are similar to those of ceramics, there is an implication of good compatibility with ceramic reinforcements. Therefore, further research is required to exploit this compatibility for application as matrix materials in novel ceramics.

- *Novel ceramic processing*: Structural ceramic materials offer major advantages for gas turbine and other propulsion systems. Often application is limited not only by certain properties but also by complicated processing routes, and therefore costs. There is a need for the development of innovative means of synthesizing and processing existing and novel ceramics, particularly methods involving near net shape capabilities. A continuing effort has been directed at ceramic processing from polymer and, more recently, metal precursors. Thus, in the case of polymer precursors sol gel processing is an example, and in the case of solid metal precursors, this technique has resulted in the production of oxide-based high-temperature superconductors. Other innovative means of processing ceramics involve displacement reactions, where ceramic/metallic composites may be produced in which the two phases are intimately mixed and continuous throughout the microstructure. Major enhancements in our ceramic materials synthesis and processing are a critical necessity for propulsion applications.

8.4 Materials in New Systems Applications

- *Magnetic bearings*: High temperature capabilities of new magnetic materials give rise to rather radical implications for design of disk systems (compressor and turbine). For example, in high-g turns, there is a tendency for components to impact one another. At these temperatures, there is a possibility of friction welding to occur, with obvious, disastrous consequences for component degradation. The application of magnetic bearings would not only minimize rotor axial loading, but also provide an opportunity to exploit the possibility of dynamic positioning of disks during operation. For example, it would then be possible to avoid bumping of seals, and also to provide dynamic balancing of disks during blade-out.

- *Alternative fuels*: Emphasis in the short to middle term is on the concept of single-liquid fuels to be used simultaneously for fuel and lubrication. The benefits of single fuels include significant weight reduction in engines by obviating the relatively heavy machinery for cooling and recirculating lubricants (greater than 100 pounds), elimination of the problem of thermal breakdown of the lubricant, avoidance of costs associated with disposal of spent lubricants, and simplicity in terms of the logistics of handling only a single fluid. Candidate approaches for single fluids are conventional fuels, which would need additives for elastohydrodynamic lubrication, endothermic fuels (see fuels section), and cracking of high molecular weight hydrocarbons. In addition to these alternative fuels, clean and abundant fuels include hydrogen and atomic energy. In the case of the former, environmental problems associated with conventional fuels do not exist. Advantages in terms of being able to apply materials, which would normally be limited by oxidation resistance, would be offset by the possible problems involving hydrogen embrittlement. The use of aircraft nuclear power is a long-term goal, but apart from the emotional issues remains a very strong candidate.

- *Hypersonic propulsion systems*: Far-term development of hypersonic vehicles will lead to routine access to space using SSTO vehicles. The vehicles will most likely be powered by air-breathing propulsion for most of the flight and a rocket for the space portion. An efficient, lightweight air-breathing propulsion system will require advanced new materials, such as beryllium composites or very high-temperature fiber-reinforced ceramics. These systems will also be the users of materials technologies just now entering research, such as nanostructures, functionally graded materials, high-temperature electronics, and multilayer functional coatings.