Advanced Materials for Aircraft Engine Applications

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A review of advances for aircraft engine structural materials and processes is presented. Improved materials, such as superalloys, and the processes for making turbine disks and blades have had a major impact on the capability of modern gas turbine engines. New structural materials, notably composites and intermetallic materials, are emerging that will eventually further enhance engine performance, reduce engine weight, and thereby enable new aircraft systems. In the future, successful aerospace manufacturers will combine product design and materials excellence with improved manufacturing methods to increase production efficiency, enhance product quality, and decrease the engine development cycle time.

STRUCTURAL MATERIALS SURROUND US AND SERVE AS THE fabric of modern technology. These materials bear stresses and loads in housing, civil works, transportation vehicles, and machines. Although some of these materials are naturally occurring and only require shaping and treatment, most are the product of invention and synthesis or discovery and reconfiguration. Today, materials scientists and engineers push the evolution of metallic, ceramic, and polymeric materials (and combinations thereof) to meet the ever increasing demands of materials applications in a wide range of products and markets.

Aerospace technology, and aircraft engine propulsion in particular, has provided development impetus for many of the innovative structural materials that have emerged since World War II. These materials have been as diverse as high-strength titanium alloys, high-temperature superalloys, and the burgeoning class of organic, metallic, and ceramic matrix composites. New processes and a supporting manufacturing base have been built to produce these materials. Manufacture of modern aircraft engines has depended upon new technology such as vacuum melting of reactive alloys, investment casting of complex, hollow, thin-wall castings, and fabrication of multiply composite components. These processes were not available as few as 40 years ago. Aircraft engine propulsion technology has been the catalyst for improving the understanding, design, and processing of structural materials.

The advance of aerospace technology has been important to our society. Aircraft are relied upon for national defense, transportation, and travel, and our scientific and technological horizons are expanded by satellite and exploratory space programs. This technology has also provided economic benefit in the form of employment and favorable trade balances to those nations that have become aerospace leaders. For example, in 1989, the U.S. aerospace industry had net exports of $29 billion, which is twice as large as those of any other industrial sector. In the years to come, the manufacturing leaders will be those who achieve excellence in product design and who simultaneously speed the development cycle and provide high-quality products that exceed customer expectations.

The development of materials for aircraft engines has been both extensive and diverse. In this article, we focus on describing recent turbine disk and blade improvements that have provided major advances in turbomachinery performance. We discuss some of the emerging materials and new production approaches, which include major changes of industrial culture, that are being introduced to position this industry for future global competition.

Aircraft Engine Development

Aircraft engines provide some of the most demanding applications for structural materials. Modern turbine engines operate at high temperatures and stresses, and engine components are often subject to damaging corrosion, oxidation, and erosion conditions. These engines, which convert fuel energy into propulsive thrust, operate by compressing inlet air in the front fan and compressor stages, heating the air within the combustor, mixing this air with fuel and igniting it, and then extracting energy from the hot, high-pressure gas in the turbine to operate the fan and compressor. Turbomachinery designers formulate the thermodynamic cycle of the engine to optimize the increase of momentum for the turbine exhaust and fan airflows—the source of engine thrust. During the past several decades, higher engine performance has been achieved by increasing turbine gas temperature and by increasing the efficiency of each engine stage.

The increase of engine performance has been paced by the development of improved materials and processing technologies for turbine disks and blades. The turbine blades are attached to the periphery of the turbine disk and extend across the flow path of the turbine (Fig. 1). The high-velocity turbine gases flow over the turbine blade airfoil to create lifting forces that are transmitted through the disk to the shaft that drives the fan or compressor. Turbine disks and blades have traditionally been made with a high-strength, high-temperature class of nickel-, cobalt-, and iron-based alloys (*1*) known as superalloys (Table 1). Materials development and application research has focused on improving both the design and processing of these alloys.

Turbine Blades

Turbine blade temperatures exceed 1200°C and are higher than the temperature of any other rotating components within a turbine engine. Surface temperatures are generally highest at the midspan location along the leading edge of the airfoil, whereas stresses are highest at the airfoil root since this location must bear the complete centrifugal load of the airfoil. The blade airfoil is vulnerable to a number of potential failure modes including creep rupture, thermal

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fatigue, and environmental attack at the airfoil leading edge and tip. The turbine blade transmits load to the turbine disk through a dovetail, which is subject to fretting wear, high-stress low-cycle fatigue, and low-stress vibratory damage.

Engineers have applied three complementary tactics to improve blade lives and provide the capability to operate at higher temperatures and stresses (2). The first approach applies metallurgical principles to provide more stable, higher strength, and temperature-tolerant microstructures. The second approach applies design principles to increase the effectiveness of blade cooling schemes. Cooling air, taken from the compressor, flows through internal passages within the blade to reduce blade temperature. The third approach involves the use of special coatings for control of environmental attack of the blade material. Execution of these tactics has required the development of improved processes and manufacturing methods.

Turbine blades are made by using the investment casting process. This process begins with the production of a wax pattern that replicates the blade shape (with allowance for solidification shrinkage). Ceramic cores are positioned within the wax pattern to form the internal cooling passages, and wax runners and gates are attached externally to permit pouring of molten metal into the finished mold. Next, the assembly is dipped in a series of ceramic slurries to build a shell (investment) that encases the blade-shaped pattern and runner system. The shell is then heated to strengthen the investment and melt out the wax. Molten superalloy is poured into the resulting cavity, and the casting is solidified under controlled conditions. Finally, the investment, cores, and runner system are removed, the casting is cleaned and heat-treated, machining is performed, and environmental coatings are applied.

Improved turbine blade superalloys. During the last two decades, the chemistry of superalloy turbine blade alloys has been improved to better exploit high-temperature strengthening mechanisms, improve environmental resistance, enhance castability, and complement the advantages of improved processing methods. For conventional investment cast blades, molten alloy within the mold is solidified naturally with minimal intervention to regulate the pattern of freezing. Under these conditions, blades solidify with a polycrystalline dendritic microstructure containing equiaxed grains.

Achieving high-temperature service capability requires that the alloy chemistry provide a high-volume fraction of a second phase (γ', coherent nickel-aluminide precipitate) for grain strength, tailored grain boundary structure containing carbides and borides for avoidance of grain boundary sliding, and interdiffusion with applied

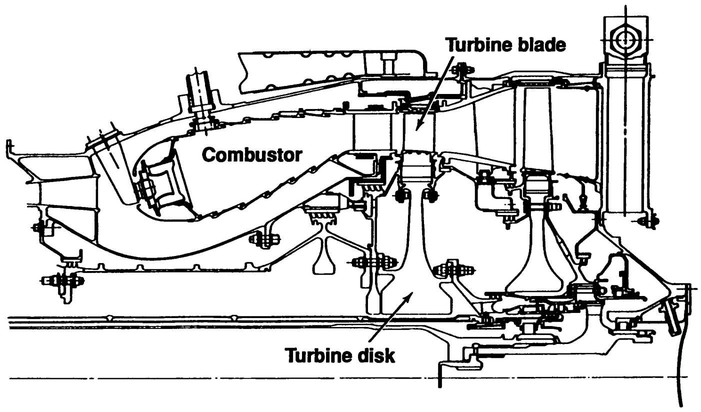

Fig. 1. Cross-sectional view of an F404 gas turbine engine showing the combustor and turbine hot section components.

coatings that enhance coating life. Improvements have been numerous, and development of specific alloys have exploited these strategies in different ways.

Alloy designers have continually striven to increase the γ' volume fraction by increasing the concentration of aluminum, titanium, and refractory elements. However, as the content of alloying elements increases, alloy castability decreases and the danger of brittle phase (such as Laves and Mu phases) formation increases. Also, the volume fraction of large, isolated phase regions (eutectic γ') rises such that higher temperature, prolonged solution heat treatments are needed to produce a more homogeneous microstructure. In the early 1970s, alloy designers began to add hafnium to produce grain boundary structures with increased ductility. This advance, which was widely adopted, increased both castability and transverse rupture ductility.

Directional solidification. Despite efforts to strengthen superalloy grain boundaries, creep rupture ultimately progresses by formation and linkage of grain boundary cracks, culminating in separation. This limitation of conventionally cast blades can be addressed by two processing alternatives (3) that either alter or eliminate the grain boundaries. First, directional solidification was applied to achieve a columnar grain structure to eliminate transverse grain boundaries—those that are perpendicular to the predominant centrifugal stresses within the blade. Directional solidification of columnar grain blades is achieved by solidifying an investment casting from the blade tip toward the root in the presence of a thermal gradient. Heat is

Table 1. Nominal chemical compositions for several recent turbine disk and blade superalloys. Only major alloying elements have been included in the tabulation; bal, balance.

Alloy	Composition (percent by weight)										
	Co	Cr	Al	Ti	Nb	Mo	W	Hf	C	Fe	Ni
					Blade superalloys						
Mar-M 200 + Hf*	10.0	9.0	5.0	2.0	1.0		12.5	1.8	0.14		bal
Mar-M 247*	10.0	8.4	5.5	1.0		0.6	10.0	1.4	0.15		bal
Rene′ 80 H†	9.5	14.0	3.0	4.8		4.0	4.0	0.75	0.08		bal
Rene′ N4†	7.5	9.3	3.7	4.2	0.5	1.5	6.0	0.1			bal
					Disk superalloys						
Inconel 718‡		19.0	0.5	0.95	5.1	3.0			0.05	18.5	bal
MERL-76§	18.5	12.5	5.0	4.4	1.4	3.2		0.4	0.04		bal
Rene′ 95†	8.0	13.0	3.5	2.5	3.5	3.5	3.5		0.05		bal
Rene′ 88 DT†	13.0	16.0	2.1	3.7	0.7	4.0	4.0		0.05		bal

*Martin Marietta Corp. †General Electric Co. ‡International Nickel Co. §Pratt & Whitney.

extracted with a water-cooled chill and either the furnace power is gradually reduced or the solidifying mold is slowly extracted from the directional solidification furnace. Directional solidification of single crystal blades, the second advance, follows an identical process except that grain reduction and selection techniques are used in the early stages of solidification to assure that the solid blade grows from a single grain of select orientation.

New alloys have been developed for directional solidification processing because the performance of these blades depends less upon grain-boundary behavior. For example, the amount of grain boundary strengtheners such as boron, carbon, hafnium, and zirconium has been reduced to improve temperature capability. The most recent alloys retain some strengtheners to accommodate unintended low-angle grain boundaries, thereby increasing blade producibility. In addition, rhenium has been added to a number of alloys, including Rene′ N5, PWA 1484, and CSMX-4, to increase temperature capability. Rhenium raises the melting temperature of nickel and is thought to produce "ordered clusters" that hinder dislocation motion. Also, some of the more recent alloys have more favorable ratios of aluminum and titanium content and have exploited additions of rare earth elements such as yttrium to improve oxidation resistance by increasing the adherence of oxide scales. Modern superalloys are indeed a very sophisticated melange of chemical elements that have been carefully selected for their known function in alloy performance.

Improved alloys and investment casting processes have evolved simultaneously with radical changes in turbine blade design to obtain more effective blade cooling. The progression of flow designs for turbine blade cooling started with simple cylindrical radial cooling holes and now consists of complex serpentine passages containing turbulators and channels, which provide impingement and film cooling. A photograph of a typical design for an airfoil-cooling passage and the core used to produce it is shown in Fig. 2. The cooling passages are produced by placing a ceramic core within the investment casting mold. The higher temperatures and longer exposure during directional solidification have required the use of higher temperature ceramic cores (such as alumina) and the use of core positioning aids (such as chaplets) to counteract the tendency for core distortion and sagging. The blade design changes, which are based on recognized heat-transfer principles, certainly have challenged directional solidification processes.

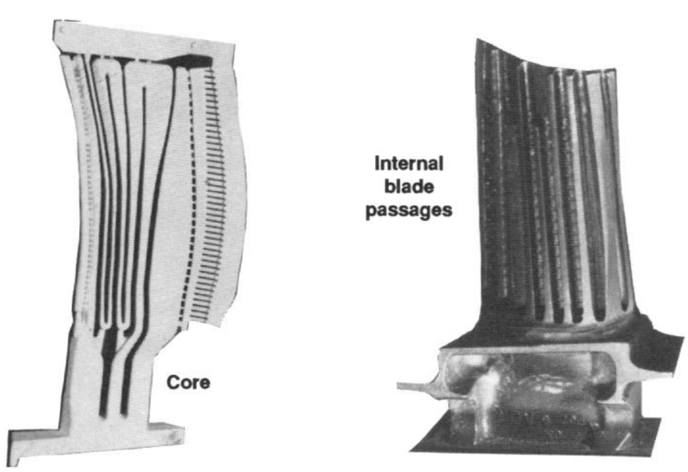

Fig. 2. Typical core (left) used to produce internal turbine blade cooling passages during investment casting. The turbine blade (right) has been machined to show the internal passages.

Thermal barrier coatings. Thermal barrier coatings (TBC) should provide the next increment of improved turbine blade performance because improvements from alloy chemistry and processing are nearing exhaustion. These coatings are produced by using either plasma deposition or physical vapor deposition to lay down a thin layer of stabilized zirconia on the blade surface. Such TBC coatings reduce blade-base metal temperature because the coating has low conductivity and reduces the heat flux from the hot surface to the cooled blade interior. Since blade metal temperatures are reduced well below the temperature of the surrounding gas, turbine efficiency can be improved either by increasing gas flow temperature or by decreasing the flow rate of cooling air through the blade. Although cooling air is necessary to prevent blade overheating, its use reduces engine thrust. These TBC coatings have also been applied to static components such as combustors and afterburner parts. Future developments of TBC are likely to be directed toward controlling the deposition process to produce fully reliable coatings with consistent long life. The goal of process control is to improve coating adherence and to deposit a stress-tolerant microstructure.

Turbine Disk Development

In the 1970s efforts to increase disk operating temperatures and stresses led to several alloys, including MERL76 and Rene′95, which contained unprecedented high levels of γ' phase. However, the high elemental content of γ' formers in these alloys made processing difficult with conventional techniques. Ingot castings contained excessive segregation and brittle regions that cracked during disk forging. Conventional disks are forged to refine the microstructure and improve strength and fatigue life.

Powder metallurgy processing. Powder processing represents a method to limit the degree of alloy segregation. An atomizer (Fig. 3) is used to produce superalloy powder, which is subsequently consolidated by hot isostatic pressing (HIP) or extrusion. Within the atomizer, a high-velocity jet of inert gases impinges on and disrupts a molten stream of superalloy to form a plume of fine droplets. These droplets cool and solidify rapidly because of their high ratio of surface area to volume; the resulting powders have a much smaller chemical segregation length scale (dendrite arm spacing) than an ingot. This property minimizes or eliminates the brittle phases.

Superalloy powder is further processed and tested prior to consolidation into a disk or billet preforms. The intermediate processing includes steps such as screening to achieve the desired powder-size distribution and blending of individual powder heats to reduce batch-to-batch variations. Testing includes examination of extracted powder contaminants and mechanical property measurements of consolidated test samples.

Early applications of superalloy powder used HIP processing to directly produce solid compacts from which disks could be machined. During HIP, the application of pressurized gas at elevated temperature to the powder (contained in a shaped steel can) causes the powder particles to plastically deform and bond, resulting in attainment of near theoretical compaction densities. The so-called as-HIP product originally promised low cost because manufacture entailed few operations and the densified article had a near–net-shape only slightly larger than the finished part (on the order of 0.25 cm). This excess envelope of material was required to facilitate nondestructive inspection, to allow for removal of any products of chemical reaction between the superalloy and steel can, and to accommodate fixturing inaccuracies during subsequent machining.

However, testing of as-HIP specimens and disk components highlighted the alloy design and processing challenges posed by powder processing. Whereas superalloy design and processing focused on attainment of high strength and long creep lives, as-HIP material exhibited lower than expected low cycle fatigue (LCF) lives. LCF is a failure mode for metallic materials in which atomic-scale dislocation and cracking damage accumulate during each major stress cycle (such as during takeoff and landing for an aircraft turbine engine). A classic lesson was relearned. The design and processing of all high-performance materials must provide properties balanced with the needs of the application. High strength must be balanced against the need for good ductility and fatigue life.

Examination of LCF-tested superalloy material showed that LCF failures originated at anomalous defects that could be traced to both organic and inorganic powder contamination (*4*). Powder contained ceramic particles from a wide variety of sources including melt stock, materials used in the melting system of the atomizer, and residual dirt from gas supply lines and valves. Organic materials entered the powder from cleaning materials, from the abrasive flow of powder over gaskets in the powder-handling system, and as airborne particles. Later during elevated temperature exposure, the organic particles decompose, volatilize, and decorate surrounding powder particles and prevent proper interparticle bonding during consolidation.

Defects from both sources provide sites where stresses concentrate and from which cracks can initiate during cyclic loading. Therefore, all powder manufacturers undertook painstaking efforts to remove all potential sources of contamination. Powder handling was performed under clean room conditions, equipment and can cleaning procedures were improved and standardized, and loose powders were heated to outgas volatile organics prior to consolidation. However, contamination sources are numerous, are not always easy to identify, are difficult to eliminate, and sometimes are even introduced by the added powder handling associated with cleaning.

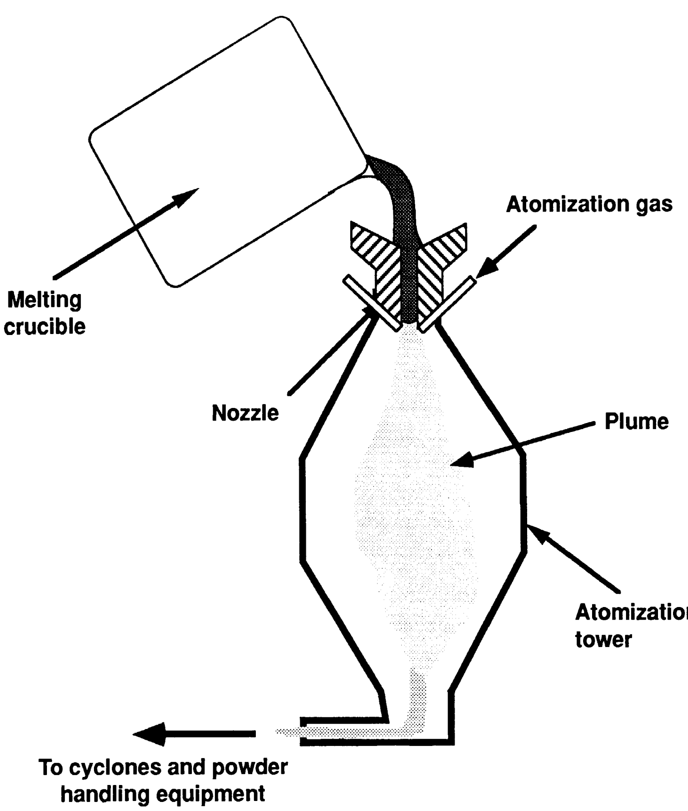

Fig. 3. A schematic representation of a gas atomizer used to produce superalloy powders.

The challenge of powder cleanliness strained manufacturing systems. Engineers had to reconcile conflicting test and inspection results performed throughout the manufacturing cycle. The testing added costs without adding value, and the rejection of poor material disrupted material flow through the factory. Also, life management engineers had to determine the in-service inspection intervals and field life limits for components based on mechanical test results specifically generated for each pedigree of material.

Improved processes for disks. In retrospect, the pursuit of powder metallurgy turbine disks shows the disadvantage of reactive research and development. A large proportion of the as-HIP materials introduction was directed toward "fixing" problems that were initially either unforeseen or underestimated. The as-HIP process relied on human diligence, material inspection, and life management of the resultant product. A better approach was needed that would be founded upon sound metallurgical principles, that would avert known problems by process design, and that would not rely on inspection.

Isothermal forging has become the most widespread mature process to mitigate the damaging influence of powder contaminants. Powder is consolidated and extruded to produce cylindrical billet, which is subsequently forged isothermally at creep strain rates. These conditions enable substantial deformation, which fosters breakup of defects but prevents high forging stresses and cooling that could promote cracking.

Metallurgical solutions have also been applied in combination with isothermal forging to increase the reliability of turbine disks. Alloys such as Rene′ 88DT offer excellent creep rupture and sustained load crack growth while maintaining good LCF, particularly at high temperatures. Proper design of the overall forging process and the use of supersolvus heat treatment yields larger grain size, which improves creep-related properties and increases damage tolerance.

Although improved powder alloy design and isothermal forging have reduced the damaging effects of powder defects, the drive toward increasing component life and reliability has continued. Efforts have been initiated to improve the cleanliness of both nickel-base and titanium-base alloys through the use of hearth melting. For this process, melt stock is melted in a water-cooled copper hearth by using either a plasma torch or an electron beam gun as the heating source. During processing, a "skull" of solidified alloy is maintained, separating the molten alloy from the hearth. Hearth melting promotes cleanliness in several ways. Since ceramics have been eliminated from the melting container, an important source of contamination has been eliminated. Also, melting rates are lower, which allows second phases that could produce defects to either dissolve or separate from the melt (either by rising to the surface or sinking to the hearth bottom, where they can be trapped or removed).

Also, a number of better and sometimes competing manufacturing routes have been established. For example, in the wake of early as-HIP superalloy disappointment, metallurgists returned to the well-known cast-and-wrought alloy IN718 in an attempt to stretch performance capability and thereby avoid powder-processing problems. The application temperatures of IN718 were increased 25°C by eliminating the solutioning heat treatment and directly aging forgings to yield a more effective distribution of strengthening precipitates.

More recently, billet spray-forming (*5*), as typified by the Osprey process, is emerging as a means to directly consolidate molten droplets from an atomizer while retaining fine-grain billet microstructure. This process eliminates the cost and potential contaminant sources prevalent during powder handling. Also, the dual alloy disk approach shows promise. This process addresses the differing material characteristics required at the disk bore (strength) and disk rim (creep) by joining two different superalloys into a single-part preform by HIP, forge-enhanced bonding, or coextrusion processes.

Future Turbine Material Trends

Although the application of traditional metallurgical strategies, as typified by superalloy advances, has been the principal paradigm for development of modern turbine materials technology, future improvements for metallic materials are expected to be modest. Many members of the materials development community are looking toward intermetallic materials and composites to provide the next significant increment of materials performance. A schematic engine cross section showing possible applications for these materials is shown in Fig. 4.

Most of these materials have technological roots that are older than turbine technology itself (*6*). However, materials developers only recently have begun to apply sustained, high-intensity effort to bring them to maturity. Initial uses of emerging materials are likely to be limited to static applications until an experience base of design, manufacturing, and reliability knowledge has been acquired. Unlike the earlier developments of superalloys, where elevated temperature strength was the principal driver, development of many of these materials is also motivated by the opportunity to reduce component weight (and hence stress within rotating components). In addition, for composite materials, the designer and materials engineer have the opportunity to tailor material properties and the inherent anisotropy of properties to meet specific stress distributions within the component.

For polymeric composites, this strategy and pathway to high-performance lightweight structures has already been demonstrated. Originally applied as a low weight replacement for static fan and compressor section components, polymeric composites have matured sufficiently that designers now are beginning to apply these materials in rotating hardware such as fan blades and for pressure vessels such as casings. The push toward higher engine thrust causes an increase in flow path area and a corresponding increase in engine inlet diameter. The use of polymers such as polyimide PMR-15 reinforced with high-strength graphite fibers achieves low component weight and stress while maintaining high strength capability. Composite architecture and processing methods can be designed to provide toughness in the presence of an impact event such as a bird strike.

Less mature intermellatic alloys, metal matrix composites, and ceramic matrix composites are being established to exploit low density in components that include shafts, disks, turbine blades, and exhaust components. For example, the weight of the intermetallic NiAl turbine blade is ~40% lower than a typical superalloy blade. Research is under way to improve the poor ductility of these materials without sacrificing their strength and creep properties. Achieving ductility and toughness is also a challenge for metal matrix and ceramic matrix composites. When properly designed, the bond between fiber and matrix is weak to allow crack deflection and promote fiber pullout (providing tough behavior). But weak interfaces, usually attained with fiber coatings, reduce the transverse composite strength. This limitation is being addressed by designing composite architectures that vary the fiber directions for each ply.

Conventional and emerging materials often share common unit processes and benefit from process refinements regardless of the materials system motivating the advance. As such, processing technology represent a bridge across which progress can be disseminated among materials systems. For example, powder produced through clean melting technology can also be used in the production of metal matrix and intermetallic materials. In one approach to make metal matrix composites, powder is plasma-sprayed onto a fiber bed to make unidirectionally reinforced monotapes. Also, certain emerging intermetallic materials, such as some titanium aluminides, are difficult to cast and forge because of limited ductility. For these alloys, powder processing offers a promising alternative manufacturing route.

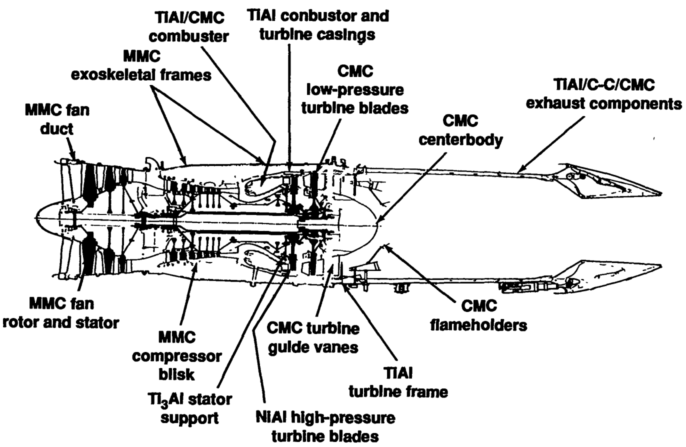

Fig. 4. Cross-sectional view of an advanced turbine engine showing the applications for advanced materials technology. Abbreviations: MMC, metal matrix composite; CMC, ceramic matrix composite; and C-C, carbon fiber in carbon matrix.

Emerging Cultural Changes

Manufacturing organizations throughout the world recognize that as product technologies mature, discrimination among producers relies more heavily on efficient, high-quality manufacturing (7). This recognition is changing the way aircraft engine manufacturers operate. Many producers are striving to embrace concepts such as intelligent processing of materials (IPM), total quality management (TQM), and concurrent engineering (CE). Each of these concepts encompasses new visions on how we engineer and manufacture products and requires cultural changes to be truly successful.

Intelligent processing of materials. In 1985, materials researchers initiated an integrated, comprehensive effort to apply mathematical modeling, sensor technologies, and control system methods to improve materials processes (*8, 9*). Although these tools had been in use, traditional materials manufacture depends upon empirical experimentation and the innate skills and experience of process engineers and operators. The IPM initiative strives to apply the scientific method to deduce process behavior and establish extensible theories governing process performance. Furthermore, IPM seeks to apply the newly gained knowledge through improved equipment designs, through direct measurement of material-performance attributes, and by implementing automatic control strategies that can evolve throughout the materials development and implementation cycle. To date, the IPM approach has been successfully applied to the products of HIP processing, powder atomization, sapphire single crystal fiber growth, and metal matrix and carbon-carbon composites processing. It has also been used to improve electronic materials processing such as single crystal GaAs.

A simplified representation of the IPM approach is shown in Fig. 5. Materials process understanding is established early in the process

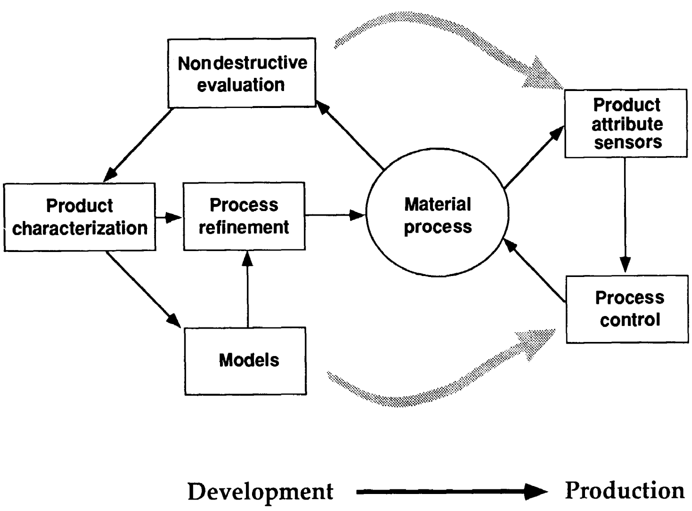

Fig. 5. Modern materials processing uses advanced sensors, process models, and control technology to provide consistent high-quality material. This strategy permits knowledge and expertise to transfer from the development laboratory to the factory floor more efficiently and quickly.

development cycle by conducting statistically designed experiments and formulating physics-based models of the process. The derived knowledge is encoded in a process simulator. Process sensors are established to validate process models and to characterize the material product and process conditions for the designed experiments. The models and sensors serve as the foundation for subsequent process control development and act as the vehicle for technology transfer between the development and production environments. Process control can be applied at a variety of levels. Closed-loop control is used to counteract process disturbances that have short time constants, whereas supervisory and expert system control modules mimic the process corrections made by process operators and engineers.

As an example, IPM is under development at the National Institute of Standards and Technology (NIST) (*10*) and at GE to improve the productivity and powder quality for the gas atomization process. At NIST, scientists have used laser holography, high-speed cinematography, and gas dynamics analysis to understand molten stream breakup during conventional atomization. Also, they have applied laser diffraction to measure particle-size distributions in real time. Research is now under way to refine this capability, apply it continuously during atomization, and use the resulting data to control the atomization gas supply and achieve the desired particle-size distribution.

At GE, researchers are augmenting these activities to control clean melting and subsequent atomization. Numerical fluid flow modeling has been used to predict the temperature variations within the melt and predict the trajectory of melt inclusions. The flow models account for all relevant physics including buoyancy, surface tension forces, surface shear at the melt-gas interface, and solidification heat transfer at the skull-liquid interface. Sensors are being developed to measure melt surface temperatures by using infrared imaging technology, melt surface elevation, and melt flow rate. Much of the control development activity is directed toward conditioning these signals and deriving relations usable in closed-loop process control.

Concurrent engineering. Traditional engineering, even for advanced systems such as aircraft turbine engines, has been performed in a sequential fashion with definite boundaries separating engineering design, materials engineering, and manufacturing. The objective of concurrent engineering, otherwise known as integrated product development, is to provide a communications environment, integration tools, and engineering methodologies that permit product design and associated manufacturing development to occur simultaneously. By considering the implications of each decision upon the entire product introduction and service processes, the number of design and manufacturing development cycles can be reduced and the interval between product conception and introduction can be shortened.

Total quality management. Several aerospace manufacturers are introducing programs to implement total quality management principles to continuously improve product quality, productivity, and the quality of worklife for their employees. These improvements are achieved by introducing many of the quality precepts made popular by Deming (*11*). Central to this is the focus upon process thinking and the application of statistical tools to design process improvement experiments and analyze both experimental and production data. Furthermore, proponents and practitioners of TQM recognize that many of the needed improvements can only be made if all members within an organization change the way they interact, practice teamwork, review programs, conduct meetings, measure performance, and recognize and reward personnel.

Conclusion

Despite current economic conditions and the stabilization of relations among the world's superpowers, aerospace technology will continue to grow and play an important role in national security, in civil transportation, and in the U.S. export balance. Improved engines for military aircraft, supersonic civil transport applications, and quieter, cleaner, more fuel-efficient subsonic aircraft are the new frontiers. As before, these advanced systems depend upon materials technology; higher performance materials and processes will emerge, mature, and join the current collection of materials and processes that have enabled the United States to be the preeminent manufacturer of aircraft engines. But timely, reliable technology growth and sustained manufacturing competitiveness will depend heavily on controlling processes and creating greater cohesion among those who design and build engines through an ongoing culture change. Those companies that successfully undergo this cultural change will emerge as world-class competitors. The next decade of global competition cannot be won by technology alone; rapid implementation of new technology by culturally transformed companies will be the key to competitiveness.

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