CERAMICS FOR TURBINE ENGINE APPLICATIONS

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Abstract

Wide spread application of ceramics to military, aerospace, and commercial markets depends on demonstrated performance within a given cost limit. Structural ceramics, particularly those based on silicon nitride and silicon carbide, are rapidly evolving into true engineering materials, ready for application in small turbomachinery. Reliability and durability of both static and rotating structures have been demonstrated to temperatures in excess of 2500°F. Turbocharger rotors are now very successfully in production in Japan. While the cost effectiveness of such structures remains to be demonstrated, the expanding manufacturing technology base can be expected to drive costs to an acceptable level in many applications.

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Introduction

Wide spread application of ceramics to military, aerospace, and commercial markets depends on achieving demonstrated performance within a given cost limit. The focus on cost within the commercial marketplace is, of course, particularly intense. The viability of the gas turbine engine as a powerplant for vehicles rests solely with the successful application of advanced structural ceramic materials in the hot section. Current monolithic ceramic materials offer the hot strength and corrosion resistance needed to operate at very high rotor inlet temperatures (RIT) without component cooling. However, because of the extremely brittle nature of ceramic materials a completely new technology, one that focuses on material flaw management, must be developed. This technology, which includes new methods of component design based on probabilistic analysis, net-shaped component manufacturing, and component inspection, must be cost affordable.

Monolithic "ceramics" have been considered for turbomachinery applications since the middle 1940s when ceramals were examined as potential blade materials. (1) As is the case now, the major stumbling block in the 1940s was the brittle nature of these materials. The level of technology was insufficient to the task and the exploitation of ceramics had to await future developments. Interest in high performance ceramics was rekindled in earnest in the U.S. some 25 years later with the initiation of a Defense Advanced Research Projects Agency (DARPA) sponsored effort at Ford and Westinghouse. (2) Since that time, significant growth in materials capability and manufacturing processing has been made, not only in the U.S. but in Japan and Europe as well. Such growth brings ever closer the day when structural ceramics will become true engineering materials.

Advanced Ceramic Materials Technology

Ceramic Materials Capability

Since the last meeting at Seven Springs, significant advances in materials capability have been made. Improvements in hot strength, time dependant behavior, toughness, and environmental resistance have been made, particularly in the case of silicon nitride based materials. This has occurred as a result of improvements in processing and modification of microstructure through heat treatment. Today's structural silicon nitride materials are conceptually similar to many conventional superalloys in that heat treatment is being relied upon to develop microstructures with unique properties. This includes the careful control of grain size and shape, phase content, and grain boundary structure.

A good example of the improved materials is the family of hot isostatically pressed silicon nitrides being developed by Norton/TRW Ceramics (3) NT-154 is a 4% Y_2O_3-doped composition with an exceptionally good balance of properties that was developed in the 1987 time frame. However, as is the case with many silicon nitrides, NT-154 exhibits a rather high creep rate which is attributed to grain boundary cavitation (Figure 1). To improve creep behavior Norton/TRW development efforts focussed on making slight changes to the glass phase composition along with adjustments to selected heat-treatment schedules. The result of this effort is an enhanced material, NT-164, with improved high temperature strength and creep resistance (Figure 2). The improved creep behavior can be directly related to modification of the grain boundary microstructure, as can be seen in Figure 3. The grain boundaries of NT-154 typically contain significant amounts of an amorphous (glassy) phase. This intergranular glassy phase has been completely eliminated from NT-164. This type of grain boundary engineering is now a key feature of development activities at most of the major ceramic houses throughout the world today.

Manufacturing Methods

Most monolithic ceramic components are generally produced via the powder processing route. A variety of very complex shapes can be produced (Figure 4). Among the many manufacturing steps ranging from raw material synthesis and preparation to final inspection typically required for ceramic structures, the shape-forming process has perhaps the most influence on producibility and production cost. Net shaped processing methods including various types of "plastic" molding, pressure casting, and gel casting are of most interest, primarily for cost reasons. One of the keys to achieving both high qual-

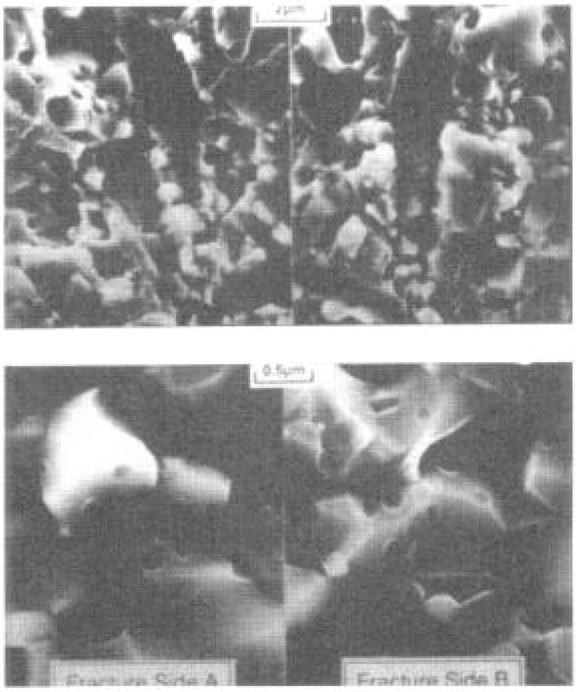

Figure 1 - Grain boundary cavitation in NT-154 at 2500°F.

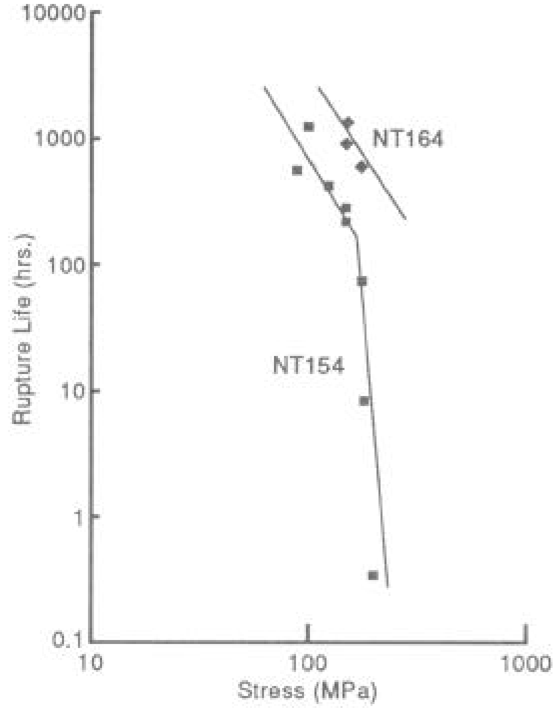

Figure 2 - Creep behavior of NT-154 and NT-164 silicon nitride materials at 2500°F.

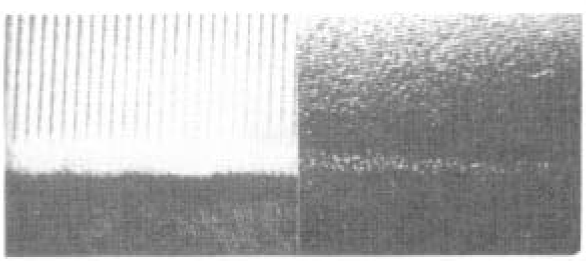

Figure 3 - TEM of grain boundary structure; (a) NT-154 and (b) NT-164.

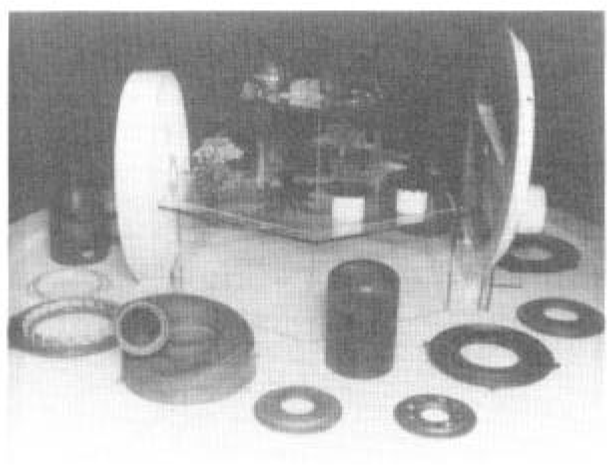

Figure 4 - Ceramic turbine components designed and tested at Allison.

ity and low cost is in process control. The key to effective process control rests with the judicious use of process modeling, which can establish the important variables to control and the level of control required.

One of the processes currently being pursued is automated pressure slip casting. This process has net shape capability, thick section capability, high through put rates, and no adverse environmental limitations. It is used to make a variety of inexpensive commercial products in large volume. The process utilizes external pressure to force filtration of the ceramic particles in a slip against a porous mold wall. The mold is typically made of a porous plastic which is permanent and reusable. A variety of shapes are possible including integral rotors and scrolls.

The Development of Ceramic Turbomachinery

Allison Gas Turbine has been involved in the development of ceramic technology since the early 1970s. Initial work, which was funded by theDOE through NASA, used a heavy-duty truck engine as a development test-bed. (4) This engine was a two-spool, regenerative, axial-flow machine (Figure 5). The program goal was the development of an entire hot flow path capable of an average RIT of 2265°F. The resulting all-ceramic gasifier section is shown schematically in Figure 6. The gasifier nozzle assembly, fabricated from various types of silicon carbide, was subjected to 900 hours of cyclic endurance testing at 2070°F average RIT. This assembly suffered absolutely no distress.

Full-up gasifier sections complete with injection molded silicon carbide blades were also tested on two separate occasions to temperatures of 2070°F. While several hours of testing were completed in both cases, catastrophic failure ultimately occurred (Figure 7). In at least one instance this appeared to be the result of foreign object damage (FOD) associated with ingestion of hard ceramic insulating material. The general FOD problem was common among many development programs, and was aggravated by the limited toughness of many of the materials available at that time. Susceptibility of blading to FOD was the key technical barrier to the aggressive exploitation of ceramics in small turbines through the mid-1980s. (5)

Advanced Turbine Technology Applications Project (ATTAP)

The overall intent of the ATTAP effort is to bring vehicular gas turbine technology to a state of readiness which will allow the automotive industry to make sound commercialization decisions. (6) The cornerstone of this effort is the development and demonstration of structural ceramic component technology. A critical element in this effort is the evaluation of ceramic component reliability and durability in an actual engine environment. An automotive engine developed by GM's Advanced Engineering (AE) is being used as a development test-bed. The engine, designated the AGT-5, is shown in Figure 8. It is a two-shaft, regenerative configuration with axial gasifier and power turbines. Two specialized test rigs have also been built which are based on the AGT-5 flow path. Conceptually, they are engines with the power turbine sections removed and replaced by observation and instrumentation ports. These rigs match the environment of the actual engine within the limits of practicality, and are extensively used for both evaluation and proof testing individual ceramic components prior to full-scale engine testing. Only through such testing can a real assessment be made of technology readiness.

Evolution of Axial Flow Ceramic Gasifier Rotors:

The development of an integral axial flow gasifier rotor for the AGT-5 was initiated in 1982 at AE. The initial rotor was a high aspect ratio, 38-bladed design produced from silicon carbide as shown in

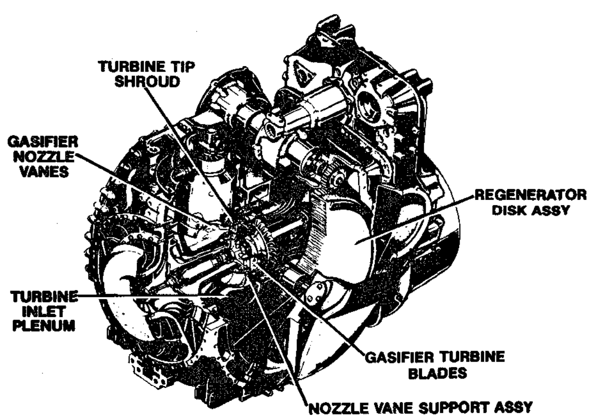

Figure 5 - IGT 404 gas turbine engine used as a test-bed for development of ceramic turbine components.

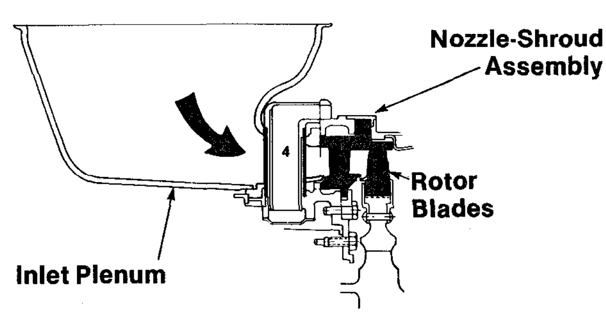

Figure 6 - All-ceramic gasifier turbine section.

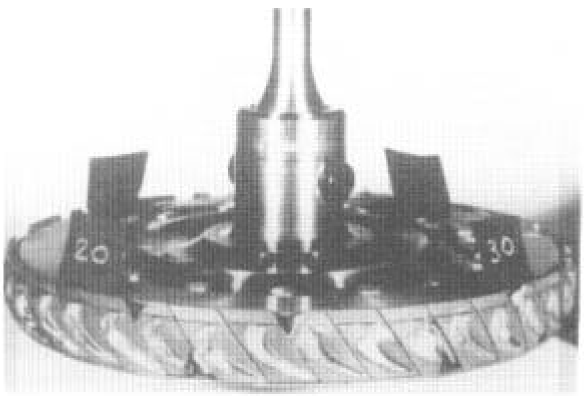

Figure 7 - Failed GT-404 ceramic gasifier turbine blades after almost 4 hours of testing at temperatures to 2070°F.

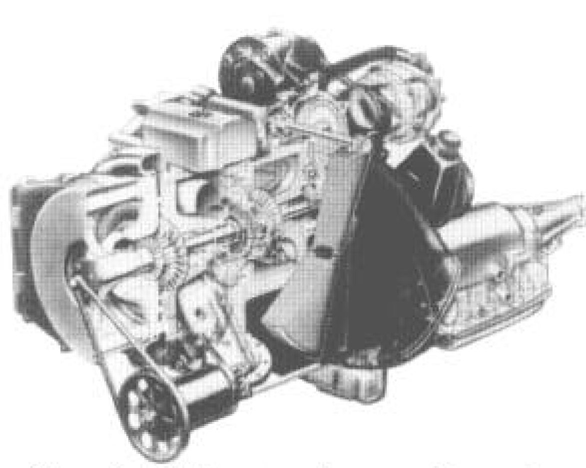

Figure 8 - AGT 5 automotive gas turbine engine used as a test-bed to develop and evaluate ceramic hot section structures.

Figure 9. This early configuration was especially sensitive to foreign object damage, and was redesigned in 1987 based on development experience generated on a ceramic radial inflow turbine rotor under the AGT 100 project. This second generation design was characterized by low aspect ratio blades (15) with significantly increased blade thickness. Further, it was fabricated from an improved toughness silicon nitride material produced by the Kyocera Corporation of Japan. The more massive blades and improved material toughness resulted in a configuration which was extremely resistant to FOD. Testing to temperatures in excess of 2500°F at 100% design speed were accomplished routinely without difficulty. The high time rotor accumulated over 350 hours without significant damage while experiencing a variety of FOD. While this design was less efficient aerodynamically, the loss in aerodynamic performance was more than offset by gains in RIT. From the system point of view, a practical compromise was established.

Subsequent work was directed at improving aero performance by increasing aspect ratio, while maintaining acceptable FOD tolerance. Correspondingly thinner airfoil cross sections were designed. The first of these was a 20-bladed design. Test results for this rotor configuration were highly successful. Short-time RIT levels exceeding 2600°F at 100% speed were achieved, with the high-time component accumulating 1000 hours. Almost 50% of this testing was accomplished under an automotive cyclic durability schedule. More importantly, this configuration was just as resistant to FOD and tip rub damage as the earlier 15-bladed design. Figure 10 shows the rotor after 1000 hours of testing. While some minor chipping at the blade tips is evident and chipping of the platform on the aft face has occurred, the rotor suffered no loss in performance and was fully functional and capable of additional running. Equally successful operation has been achieved with silicon nitride rotors of this design produced by the both Kyocera Corporation and Norton/TRW Ceramics.

Current effort focuses on a yet more efficient 26-bladed rotor design. This design is now being fabricated with testing expected to begin in the fall of 1992.

Development of Static Turbine Structures

The ceramic gasifier turbine static structure designed for the AGT-5 is shown in Figure 11. It consists of a scroll body, an inner vane platform, individual vanes, and a vane trapping ring. The scroll body itself represents the most complicated ceramic structure in the engine and, as such, is now a major focus of Allison's current development efforts. Both silicon carbide (Norton/TRW and Carborundum) and silicon nitride (Kyocera) versions of this component are being pursued. To date all versions have been successfully produced.

All-ceramic static structures have been tested both with and without ceramic rotors. All-ceramic assemblies have been successfully tested to 2500°F and 100% design speed. Scroll bodies of both silicon carbide and silicon nitride have been successfully tested. A rotor-scroll rub was sustained during one

Projected U.S. Market for High Performance Ceramics

In 1986, the U.S. DOE commissioned a two-level Delphi survey to examine the U.S. market development for ceramic components and ceramic intensive heat engines, particularly within the transportation sector. (7) The survey was conducted worldwide to examine market evolution in the U.S. through the year 2010. It addressed a variety of ceramic components, including monolithic, composite, and coated metal structures.

The limitations of the Delphi approach notwithstanding, a number of interesting general projections emerge with regard to market evolution. First, Japan will continue to be the leader in ceramic component technology and market introduction. Components first introduced in Japan will appear in the U.S. three to four years later. Japan will command almost 50% of the the World market for ceramic componentry by the year 2000. And finally, by the year 2000 ceramic componentry could represent a billion dollar-plus market in the U.S.

The projection of market evolution in the U.S. can be seen in Table I. Here the initial introduction and 5% market penetration time frames for both automotive and heavy-duty truck applications are presented. Component introduction dates range from 1990 to 1995, with significant penetration coming five or more years later. Turbocharger rotors, rocker arm/cam followers, and exhaust port liners were the leading candidates for initial production (50,000 units), each projected to be introduced by 1990. The initial introduction of ceramic intensive spark ignition and diesel engines is expected by the mid-1990s with 5% penetration coming some 5 years later. With the exception of the stationary market, introduction dates for nonhighway applications are in the year 2000 and beyond. Note that generally speaking, European respondents were slightly more pessimistic, while Asian respondents were generally more optimistic.

Table I - Projections of Ceramic Engine Component Market Penetration

Component	Stage of development	Cars/light trucks median year	Heavy-duty trucks median year
Turbocharger rotor	Introduction	1992	1990
	5% market	1997	1995
	Cost equality	2005	2000
Rocker arm/ arm follower	Introduction	1991	1990
	5% market	1996	1995
	Cost equality	2001	2000
Valve	Introduction	1995	1995
	5% market	2000	2000
	Cost equality	2010	2010
Piston cap	Introduction	1995	1995
	5% market	2002	2000
	Cost equality	2010	2005
Piston pin	Introduction	1995	1995
	5% market	2000	2000
	Cost equality	2010	2010
Cylinder liner	Introduction	1995	1995
	5% market	2001	2002
	Cost equality	2010	2010
Exhaust port liner	Introduction	1990	1990
	5% market	1995	1995
	Cost equality	2000	2000

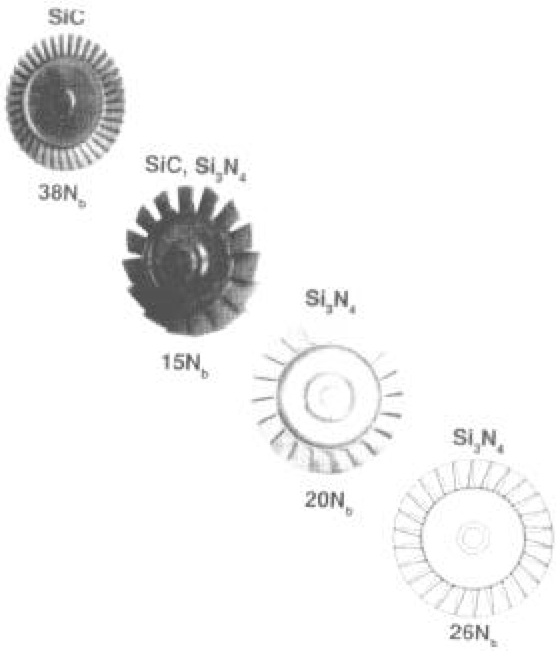

Figure 9 - Evolution of an axial flow ceramic turbine rotor.

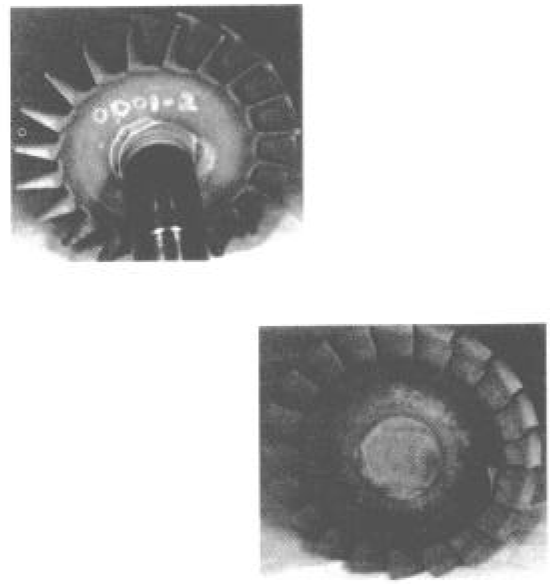

Figure 10 - Silicon nitride turbine rotor after 1000 hours of testing to temperatures exceeding 2600°F.

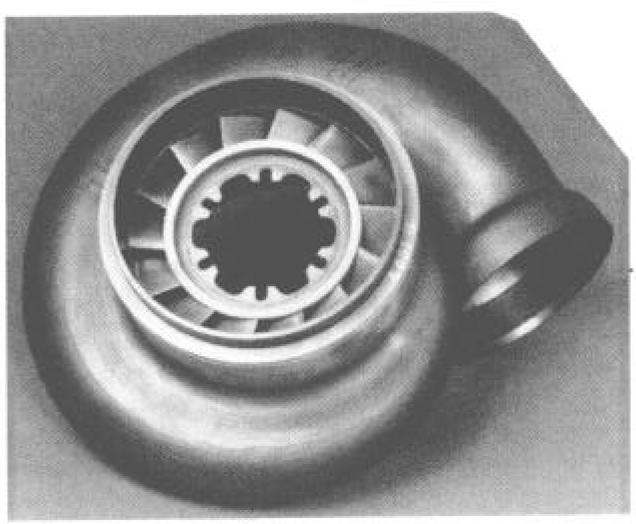

Figure 11 - All-ceramic static gasifier assembly.

build at 81% N1 without distress to the static structure. Recently 1 full-up assembly has completed 100 hours of durability testing with peak temperatures (RIT) of 2500°F.

Ceramic Component Cost Projections

As pointed out earlier, cost is a key element which will control market penetration, particularly as it relates to an automotive gas turbine engine. In the course of the component development activity great care has been taken to pursue only designs and manufacturing methods that have real potential to be cost competitive. Cost projections have been done for the designs and processes now being used and some interesting conclusions can be drawn. First, integral rotors would appear to be producible at costs compatible with the automotive market place. Second, vanes and much of the static structure also appears to be cost affordable. However, the scroll, the most complex of the structures under development, is presently projected to be more costly to produce in volume than is acceptable.

Now how do these projections measure up to reality in 1992, five years later? In Japan a variety of ceramic components have been introduced into at least limited production, Table II. (8) The most note worthy of these is the turbocharger rotor initially made available on the Nissan Fairlady Z in 1985. This was followed by Isuzu and Toyota in 1988 and 1989, respectively. While total production levels are not known, Kyocera alone produces rotors at a rate of some 30,000 per month from a highly automated factory. (9) None of these components are presently being imported to the U.S.

Table II - Commercial Production of Ceramic Components in Japan

Component	Production start	Engine	Manufacturer
Swirl chamber	1983	Isuzu	Kyocera
Intake heater	1983	Isuzu	Kyocera
Swirl chamber	1984	Toyota	Toyota
Rocker arm tip	1984	Mitsubishi	NGK
Turbine rotor	1985	Nissan	NTK
Rocker arm tip	1987	Nissan	NTK
Turbine rotor	1988	Isuzu	Kyocera
Turbine rotor	1989	Toyota	Toyota
Turbine rotor	1990	Toyota	Kyocera

At present there are no reciprocating engine components, including turbocharger rotors, in production. However, Detroit Diesel Corporation plans to introduce a ceramic cam roller produced by Kyocera into its Series 60 diesel by mid-1992. Many of the components listed have been examined and tested successfully by domestic automakers, but none have reached the market place. While there are several reasons for this, the main one is cost. At present ceramic valves and other components are just too expensive to produce to be considered even from a life cycle cost point of view. Given the progress in Japan and a three to four year lag, initial introduction of selected ceramic componentry could occur in the the U.S. within two years.

While the applications considered above in the main do not directly relate to the superalloy industry, the ceramic materials and manufacturing technologies under development around the world and being exploited in Japan represent a materials alternative that could develop into stiff competition for the metals industry. While market evolution is moving more slowly than predicted in the U.S. it is moving ahead worldwide. It can reasonably be expected that ceramics will certainly impact the use of superalloys in the aerospace sector during the later part of this decade.

Emerging Materials - Ceramic Matrix Composites (CMCs)

Advances in materials technology coupled with improved component design methodology allows industry to consider monolithic ceramics as practical construction materials for "small" but highly loaded turbine structures. Large integral structures are, in general, not compatible with monolithic ceramics. This is primarily the result of the probabilistic nature of ceramic materials which demands strength be a function of component size (i.e., stressed volume). To deal with this effect, "reinforced" ceramics are being developed which are more resistant to catastrophic crack propagation than today's monolithic counterparts. By introducing energy absorbing mechanisms that blunt and deflect growing cracks, the materials scientist is developing a class of ceramics appropriate for large structures, particularly large shell structures, plate structures, and hollow airfoils.

Conceptually, these materials are not unlike organic matrix composites (OMCs) now common in many aerospace structures as well as a host of common everyday applications. A suitable matrix (e.g., low expansion silicon carbide, silicon nitride, or glass ceramic materials) is filled with particles, whiskers, or filaments. However, unlike OMCs where the reinforcing phase has high modulus, relative to the matrix, and carries most of the applied load, today's fibers are most often less stiff than the matrix into which they they are imbedded. The "reinforcing" phase functions as a toughening agent. Consequently, while these materials behave much like conventional composites, they often have less strength, but more toughness, than monolithics. As such, they represent a new class of materials that requires new manufacturing methods and design methodologies.

These materials have been applied to a variety of advance turbine structures by most of the major engine manufactures around the world. Most of today's efforts focus on fiber reinforced structures. The manufacture of such structures reduces to a two-step process of producing a preform of appropriate architecture and then "filling" that preform with the matrix material. Conventional continuous fiber composite structures are either laminated or filament wound. Such methods are appropriate to many 2-D structures like plates and shells. However, for many structures of complicated shape, or those with high levels of interlaminar shear, preforms must be produced by 3-D braiding or weaving. Figure 12 shows an example of AGT-5 gasifier rotor preform produced by a 3-D braiding process at Drexel University. (10) This is typical of the types of CMC structures being developed today.

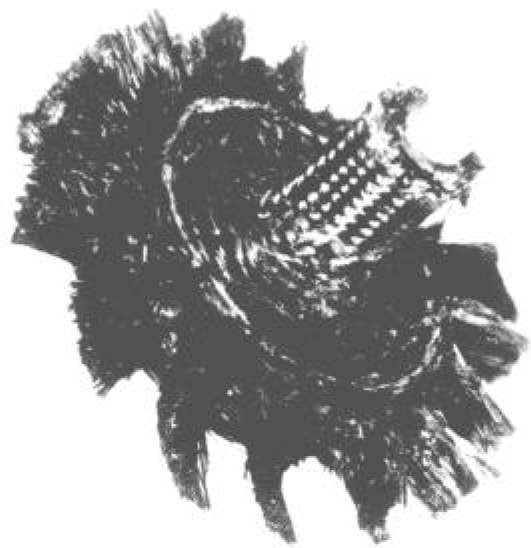

Figure 12 - 3-D braided ceramic fiber preform for an axial turbine rotor.

While CMCs hold tremendous promise for the future, significant improvements in design procedures, fibers, composite processing, and nondestructive inspection methods are needed before they will become engineering materials ready for use in advanced aerospace structures. Currently available materials are limited in use to temperatures of approximately 2000°F depending on the specific application. In addition, significant reductions in cost will be required if CMCs are ever to become materials with broad application, particularly in the commercial market place.

Summary

The wide spread use of structural ceramics as engineering materials depends on reaching a state of demonstrated performance within specified cost limits for each intended application. The class of structural ceramics based on silicon nitride and silicon carbide has evolved over the past 25 years to the point where the reliability and durability of ceramic structures have been demonstrated in a number of prime mover propulsion systems. Ceramic structures are clearly feasible for small size turbomachinery. Commercialization has already begun in Japan, where a number of components ranging from turbocharger rotors to wear parts are successfully in production. While the technology base is expanding rapidly, commercialization in the U.S. is lagging, primarily because manufacturing costs still remain above desired levels. As the manufacturing base further expands, however, costs can be expected to decline and a significant U.S. market could develop in the latter half of this decade.

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