CERAMIC COMPOSITES FOR ADVANCED

GAS TURBINE ENGINES

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Abstract

While the potential benefits that may accrue from the use of ceramic matrix composites in man-rated gas turbine engines are often calculated to be significant in extent and diversity, none of these materials have as yet entered into the production bill-of-material of any current propulsion system. Accomplishing this will require substantive changes in design philosophies, manufacturing methods and inspection techniques. Described are the range of potential applications and benefits that can be obtained and the obstacles that must be overcome before the ceramic composites can be used with confidence in the next generations of aircraft propulsion systems.

Superalloys 1992
Edited by S.D. Antolovich, R.W. Stusrud, R.A. MacKay,
D.L. Anton, T. Khan, R.D. Kissinger, D.L. Klarstrom
The Minerals, Metals & Materials Society, 1992

Introduction

As aircraft engine designers are challenged to increase the propulsion system performance, they have often looked to the higher temperature capability of ceramic materials which along with their lower density may provide a means of overcoming the limitations of the superalloys. These efforts culminated during the 1980's with the Integrated High Performance Turbine Engine Technology (IHPTET) initiative wherein ceramics were used as the model materials for combustor, turbine and exhaust system components that could operate at near stoichiometric conditions with little or no cooling air required, Figure 1. While this was ocurring in the U.S., similar strategies were employed in studies conducted in Europe and Japan, Figures 2 and 3.

However, except for use in non-structural and somewhat non-critical applications, such as thermal barrier coatings, the monolithic ceramics have not been successfully applied to any of the envisioned components. This is due primarily to the flaw sensitivity and catastrophic failure modes that are characteristic of the monolithic ceramic materials. Methods that have been pursued to overcome these characteristics have included the use of whiskers and particulates, ductile phase additions, phase transformations and continuous fiber reinforcement.

The continuous fiber reinforced ceramic matrix composites have shown the most promise for achieving the required flaw insensitivity and toughness for application to gas turbine engine hardware and as a result are the focus of all the current programs dealing with structural applications.

The attributes of the ceramic composites that result in benefits to the gas turbine engine are listed in Table 1. The current range of potential applications and the benefits that are being sought are shown in Table 2. In order to successfully apply ceramic composites to these various applications substantial changes to the design systems, manufacturing methods and inspection techniques must be developed and implemented.

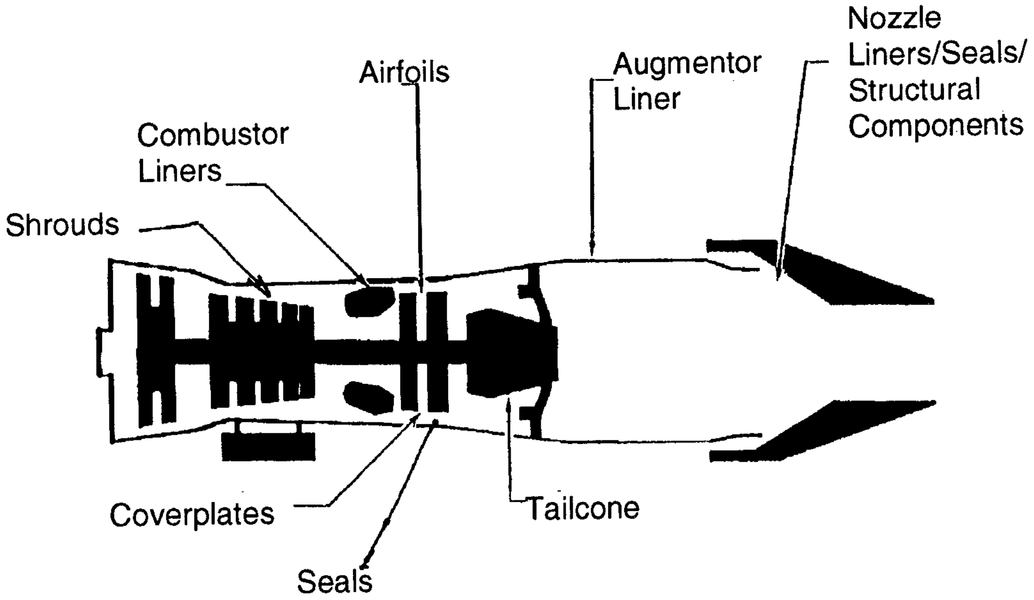
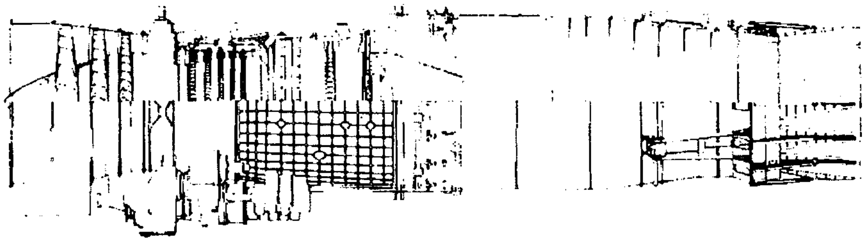


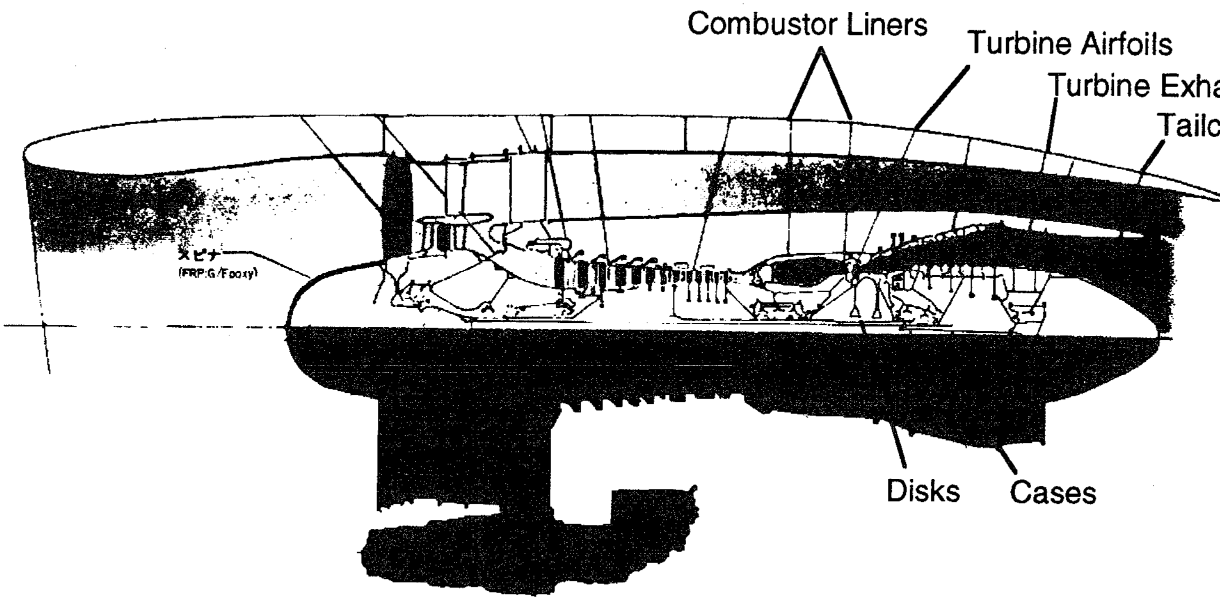
Figure 1. Potential Applications of Ceramic Composites in Future Gas Turbine Engines.



Glass/Glass Ceramic Composites
- Casings/Ducts/Nozzles
- Aerofoils

Ceramics Matrix Composites
- Turbine Casings
- Turbine Aerofoils
- Nozzle (& Reheat)
- Combustor
- Turbine Disc
- Reheat Components

Figure 2. Future European Military Engine.



FJR710ターボファンエンジンに将来適用可能な複合材料

Ceramic Composite Applications

Figure 3. Future Japanese Gas Turbine Engine

Table I. Sources of Benefits from Implementation of Ceramic Composites.

Property	**Benefit**
Higher Temperature Capability	Reduced Cooling Air Requirements
Lower Density	Lower Weight Structures
Thermal Gradient Resistance	Durability (Life Cycle Cost Reduction)
Higher Melting Point	Safety Margin
Lower Thermal Expansion	Lower Leakage
Net Shape Manufacturability	Lower Cost
Wear Resistance	Durability

Table II. Potential Applications and Benefits from Implementation of Ceramic Matrix Composites

Engine Section	Component	Primary Benefits Sought			
		Efficiency	Weight Savings	Cost Reduction	Safety Margin
Combustor	Liners	X	X	-	X
	Structures	-	X	-	-
Turbine	Airfoils	X	-	-	X
	Disks	X	X	-	-
	Seals	X			X
	Cases	-	X	X	-
Augmentor	Liners	X	X	X	X
	Flame Holders	-	-	X	X
Nozzles	Flaps	X	X	-	-
	Sidewalls	X	X	-	-
	Liners	X	-	X	-
	Seals	X	X	X	X

Design Challenges

The design methodologies that are currently used for metallic components are based on well-known and highly quantified behavior of these materials in the gas turbine engine environment. Phenomena such as creep and low cycle fatigue are well understood and predictable. The manufacturing methods and inspection techniques for metallic materials are similarly well developed. This has resulted from extensive experience and iteration over the past 30-40 years. It is expected that the development of design, manufacturing and inspection systems for ceramic composites will require similar iteration and experience before these materials can be confidently applied to structural components.

The ceramic composites that are currently being developed for structural applications consist of high strength ceramic fibers which are usually coated to provide a weak, but controlled, bond to the ceramic matrix material. This weak bond provides the crack arresting and fiber pullout failure modes critical to achieving the toughness essential for confident use of the materials. Since the ceramic fibers are highly creep resistant and the weakly-bonded interfacial coatings provide a crack arresting feature, the creep and fatigue failure modes characteristic of metallic systems are generally not the basis for the design system that should be used with ceramic composites. Loss of fiber strength due to recrystallization or reactions with the interface coatings and loss of toughness due to oxidation or reaction of the interface coatings often dominates the deterioration mechanisms of these materials.

The design challenges with ceramic composites include more than just understanding the environmental effects because, as with other composite materials, the properties of the ceramic composite are strongly affected by the component configuration and the manufacturing methods. In order to obtain the required properties needed to achieve payoffs that are worth the investment in this new technology, designers must usually tailor the fiber architectures to match the stress state anisotropy and use minimum gage sections. This often results in highly anisotropic materials with properties substantially different from those obtained on simple flat panels with conventional fiber arrays. Understanding how to design the materials from the constituent properties and how to then predict the performance of the actual components is a major design challenge.

Conventional approaches to attachment design used with metallic systems are also not usually successful with ceramic composites. The need for larger bearing areas and larger edge-distance to hole-diameter ratio's may result in weight increases that significantly reduce the benefits that had been initially forecast. In addition, many conventional attachments will not work with these materials because of their low thermal expansion coefficient as compared to the metallic bolts or rivets.

Finally, the need to use multidimensional fiber architectures, such as shown in Figure 4, in order to provide the required toughness in all directions may limit the section sizes that can be used. Although this can be somewhat overcome with the use of smaller diameter fiber yarns, it can lead to increases in component manufacturing costs which may not be tolerable.

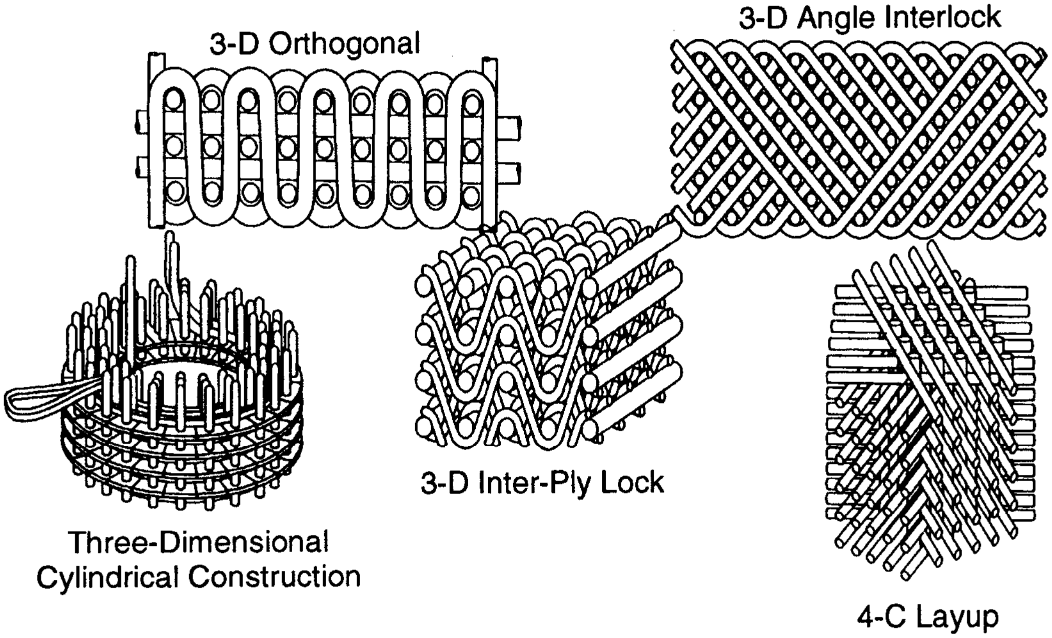


Figure 4. Multidimensional Fiber Architectures.

Manufacturing Challenges

The overall manufacturing methods for ceramic composites are not well developed. Techniques to manufacture the multidimensional fiber preforms currently are highly labor intensive and not well understood. Since each component design usually consists of a unique fiber architecture, there has been little incentive to automate the process. As a result the fiber architectures often vary from part to part as well as within each part. The effect of the manufacturing process variables on the fiber properties is not well known and may be nearly impossible to ascertain directly. This makes it difficult to define the real process limits on the manufacturing variables which results in over control and higher costs.

Densification processes for ceramic composites can be highly variable and a function of the component fiber architecture. Understanding this interaction of the design and manufacturing process will be essential to transitioning success in one component to confidence in designing and manufacturing other components.

Many conventional methods for machining metallic materials are not suitable for ceramic composites. Damage to the material at holes and bearing surfaces may be impossible to detect and may result in larger safety factors being needed in the design of the attachments.

In order to minimize the amount of machining required and to thereby minimize the cost and the amount of damage to the ceramic composite, net shape manufacturing methods are being pursued. In order for these to be cost effective, tooling methods are needed which can yield the required tolerance and surface finish of the final component.

Inspection Challenges

The ceramic composite materials pose a formidable challenge to the nondestructive inspection (NDI) community. Without a good understanding of what constitutes a "defect" it is ludicrous to expect the NDI community to establish reliable inspection methods. Conventional methods that have been developed for polymer composite materials such as ultrasonics, x-radiography, and vibro-holography may not provide the information needed with ceramic composites such as the interfacial bond strength, uniformity of the interface coatings, degree of uniformity of the densification, conformance of the fiber weave architecture to the design requirements or the integrity of the oxidation protection coatings.

As a result of this inability to provide a reliable nondestructive inspection protocol to ensure that the ceramic composite component meets the requirements, expensive proof testing of the ceramic composite hardware is often employed Alternatively, the designers may use even larger safety factors, further reducing any benefit obtained from the use of the ceramic composite materials.

Summary

Ceramic composites may provide significant benefits to the gas turbine engines when used in place of conventional superalloys. But for this to happen, substantive progress is needed in the design, manufacturing and inspection methods for these materials. Extensive engine experience with prototype hardware is also needed to provide the confidence to proceed to production implementation. Only when this has occurred will the potential benefits of the ceramic matrix composites, so often projected, so widely advertised, become reality.