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Continuous Fiber Ceramic Matrix Composites for Gas Turbine Applications

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ABSTRACT

Continuous fiber ceramic composites (CFCCs) are being considered as high temperature structural materials for gas turbine applications due to their high temperature capability, toughness, and durability. Polymer impregnation and pyrolysis (PIP) derived CFCCs are one class of these materials that can be fabricated using widely available polymer composite processing methods. This paper will discuss the general PIP fabrication process and thermo-mechanical properties of these materials, and show examples of complex prototype gas turbine components that have been fabricated and evaluated.

INTRODUCTION

Gas turbine development has progressed to the point where high temperature, lightweight CFCC materials are needed to replace currently used metal alloys that are operating close to the limits of their thermal and mechanical properties. The use of CFCC materials will enable turbines to operate at higher temperatures, improving performance and efficiency.

During the past ten years, Dow Corning Corporation has been developing continuous fiber ceramic composites (CFCCs) under the tradename SYLRAMIC™ as high temperature structural materials for use in both land-based and aircraft gas turbines. These materials are non-oxide silicon-based ceramics with a matrix derived from polymeric precursors. This work has been sponsored, in part, by the U. S. Department of Energy[*], U. S. Air Force, and NASA.

MATERIALS AND PROCESSING

The primary constituents of a continuous fiber reinforced CFCC are shown schematically in Figure 1. The ceramic fibers are coated with a thin interface layer to control the degree of bonding of the fibers to the matrix. This is required in order to obtain the desired crack deflection behavior which translates to a graceful failure mode. A ceramic filler material is typically added to the matrix phase to modify properties and processing behavior. A small amount

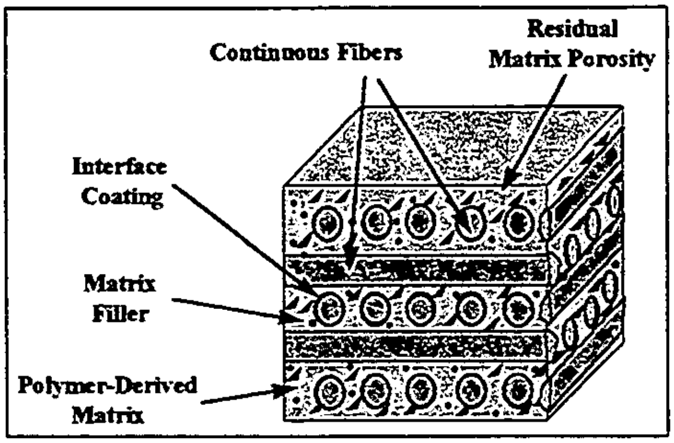

Figure 1. Schematic of a CFCC.

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of residual porosity and matrix cracks are also present, the latter being formed during conversion of the matrix precursor to a ceramic phase.

The CFCCs described in this paper were fabricated using a Polymer Impregnation and Pyrolysis (PIP) process. This process is widely recognized as a versatile method to fabricate large, complex shaped structures. It consists of the impregnation of ceramic fabric with the matrix precursor, pyrolysis to convert the polymeric precursor to a ceramic phase, and then repeated reimpregnation and pyrolysis of the component until the desired level of density is attained. In comparison to other ceramic composite fabrication processes, the PIP process offers significant flexibility. By utilizing low-temperature forming and molding steps typically used in polymer matrix composites (PMCs), the PIP approach allows the use of existing equipment and processing technology developed for those materials. This includes the ability to machine details into components before they are converted to the ceramic phase, greatly reducing the cost and time for machining.

The ability to fabricate preforms having the desired shape and architecture is of primary importance for ceramic composites. Gas turbine applications require versatile approaches to produce the wide range of structural shapes, wall thicknesses and tolerances required. Techniques such as filament winding, resin transfer molding, and ply lay-up followed by autoclaving can be used to fabricate a variety of shapes and sizes of components. When the PIP process is completed, net shape parts result that require a minimum of final machining. When final machining is required, conventional diamond tooling as well as laser and ultrasonic machining can be used.

Materials

SYLRAMIC™ CFCCs have a versatile chemistry and can consist of various fibers, interface coatings, and matrix chemistries. The currently available systems are divided into 3 classes of materials denoted as follows:

- SYLRAMIC™ S100 CFCCs*: carbon-coated CG NICALON™ fiber** in an amorphous SiOC matrix. The maximum use temperature is <450°C in oxidizing environments since the carbon coating will be lost, but temperatures up to 1100°C can be tolerated in inert environments. High-temperature oxidative exposure can be acceptable in limited life applications.
- SYLRAMIC™ S200 CFCCs: various coatings (typically boron-containing) on CG NICALON™ fiber in an amorphous SiNC matrix. These materials can be used at temperatures up to 1200 - 1250°C in an oxidizing or inert environment, and can tolerate temperatures up to 1400°C for limited lifetime applications.
- SYLRAMIC™ S300 CFCCs: various coatings on SYLRAMIC™ SiC fiber in an amorphous SiNC, or crystalline Si_3N_4/SiC or SiC matrix for higher temperature applications.

Fabrication Methods

In the PIP process shown schematically in Figure 2, one of three methods is typically used to fabricate the preforms for the components, depending on the geometry of the component. These methods are described individually below.

Complex shapes may require resin transfer molding. The ceramic fibers, in the form of a woven fabric, are assembled inside a mold to create a specific shape. The mold is heated and then injected with a solventless liquid resin. When enough resin has been injected to completely impregnate the fabric, the temperature of the mold is raised to cure the resin. After cooling the mold, the part is removed and pyrolyzed. This method is useful for components with flanges or other complex features.

For cylindrical shapes, the method of choice is frequently filament winding, in which the component is created by winding a continuous length of fiber onto a spool or mandrel until the desired component length and thickness are attained. Resin may be

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applied to the fibers before they are wound onto the mandrel by running the fibers through a slurry of the matrix precursor and filler, or the resin may be applied after winding by pouring or painting the slurry onto the wound fibers. The entire spool is then heated to cure the resin, and then the component is cooled and removed from the mandrel for pyrolysis.

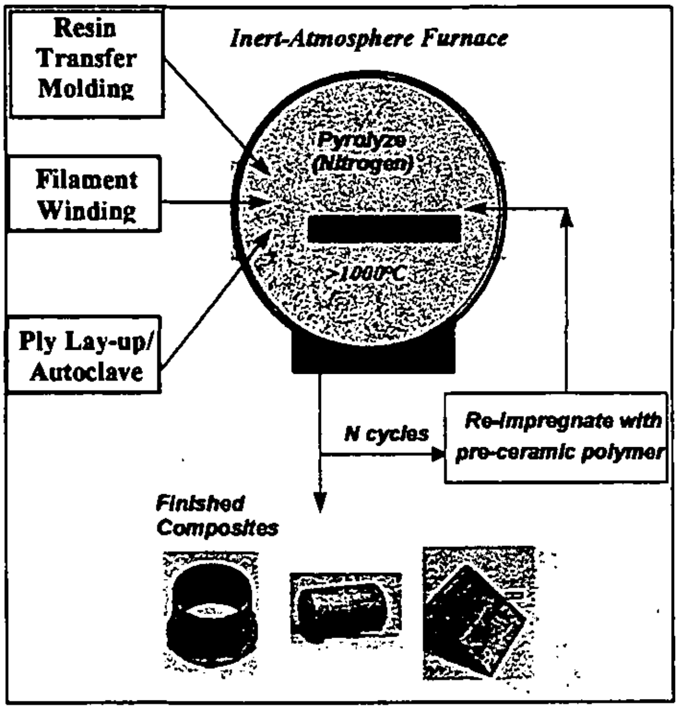

Figure 2. The PIP Process for Fabricating CFCCs.

A third fabrication method is typically used for making flat panels. This method consists of laying-up flat plies of fabric which have been prepregged with the resin and filler slurry. The stacked plies are then vacuum-bagged and autoclaved under pressure to consolidate the layers and cure the resin.

Regardless of the method chosen for fabricating the preform, all components are processed the same way after the initial steps. As shown in Figure 2, an inert-atmosphere furnace is used to pyrolyze the matrix precursor at temperatures of >1000°C, which converts the polymer to a ceramic phase. During this process, there is a reduction in the volume of matrix material as it is converted from resin to ceramic and increases in density. The resultant void space is filled by reimpregnating the composites with additional resin, followed by further pyrolysis. This process loop is repeated until the desired levels of density and porosity are achieved. A bulk density of 2.1-2.2 g/cc and an open porosity of <5% are typical.

Microstructure

The microstructure of a typical CFCC is shown in Figure 3. Individual fibers are approximately 15 microns in diameter. The fibers are surrounded by the matrix phase which is continuous except for a small number of voids and cracks which form during processing. Filler particles are less than one micrometer in size and therefore not visible at this magnification.

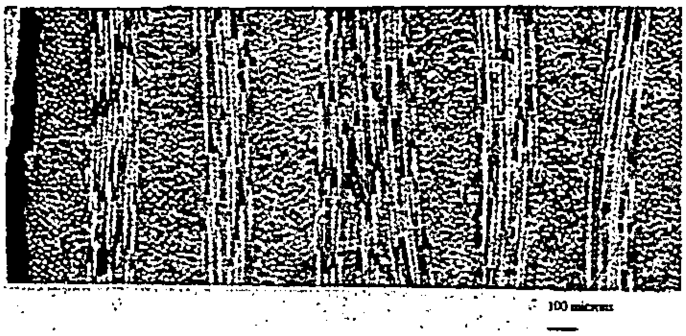

Figure 3. Microstructure of a CFCC.

Density and Porosity

The increase in bulk density and decrease in open porosity as a function of PIP cycle number are shown in Figure 4. These parameters and the weight gain are measured and recorded to monitor progress during PIP processing. Both the density and porosity tend to level-out as processing is completed, and a point of diminishing returns is reached with further PIP cycles.

Mechanical Properties of SYLRAMIC™ S200 Composites

The mechanical properties at 20°C and 1000°C are given in Table 1. There is about a 15% increase in tensile strength at the elevated temperature which is attributed to the redistribution of residual stresses. Concurrently, there is a decrease in shear strength

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with temperature. The latter behavior is a matrix-dominated property. In this case, the higher temperature condition results in a decrease in stiffness but an increase in tensile strength. This stress-strain behavior is shown graphically in Figure 5 for tensile data at three temperatures.

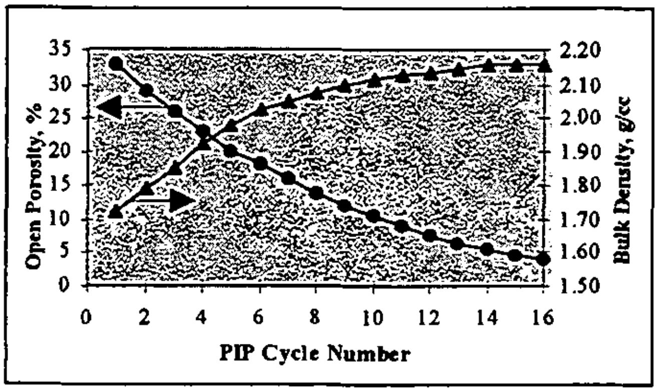

Figure 4. Density and Porosity as a Function of PIP Cycle Number.

Table 1. Mechanical Properties of SYLRAMIC™ S200 CFCCs.

	Tensile Strength, MPa (ksi)	Shear Strength, MPa (ksi)	Flexure Strength, MPa (ksi)	Compressive Strength, MPa (ksi)
20°C	262 (38)	38 (5.5)	379 (55)	434 (63)
1000°C	300 (43)	24 (3.5)	414 (60)	NA

	Tensile Modulus, MPa (ksi)	Proportional Limit, MPa (ksi)	Proportional Strain, %	Strain-to-Failure, %
20°C	96 (14)	96 (14)	0.09	0.5
1000°C	90 (13)	90 (13)	0.08	0.7

Thermal Properties

The thermal conductivity as a function of temperature is shown in Figure 6. This data shows that thermal conductivity is a relatively isotropic property and is only slightly affected by temperature over the range from room temperature to 1200°C. The constant nature of this property in the x, y, and z planes in the CFCC occurs because both the fiber and matrix are amorphous and have similar conductivities.

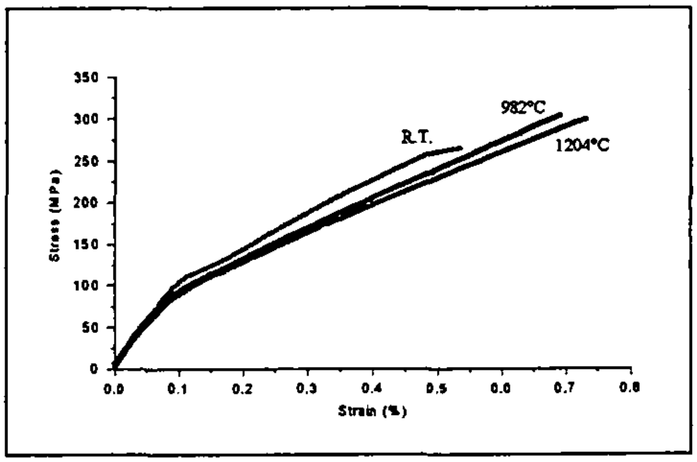

Figure 5. Tensile Stress-Strain Behavior vs. Temperature.

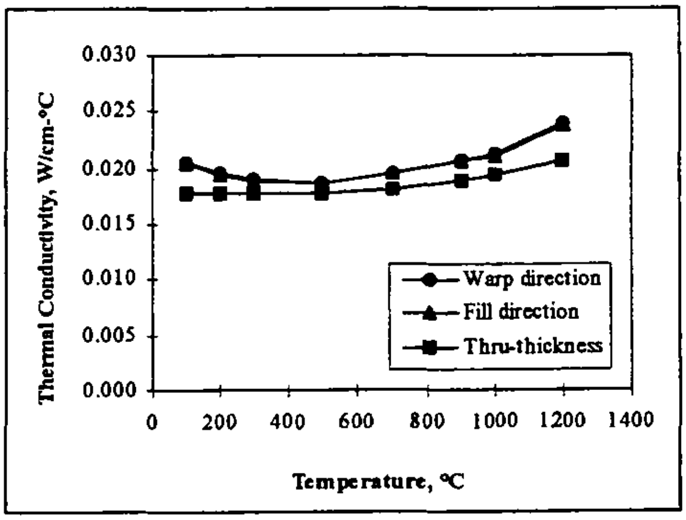

Figure 6. Thermal Conductivity as a Function of Temperature.

Representative Components

A large number of components have been fabricated for evaluation in both aerospace and industrial applications. After fabrication, some of these components have been subjected to testing in simulated application environments.

Figure 7 illustrates a number of exhaust flaps for a General Electric F-110 aircraft engine. The CFCC flaps (approx. 6" x 24") are being evaluated as replacements for metal flaps which have limited life capability under the severe thermal and oxidative environment of the engine exhaust[1]. Fig. 7 shows a

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SYLRAMIC™ S200 flap as well as flaps fabricated by GE, HITCO, and Dupont Lanxide.

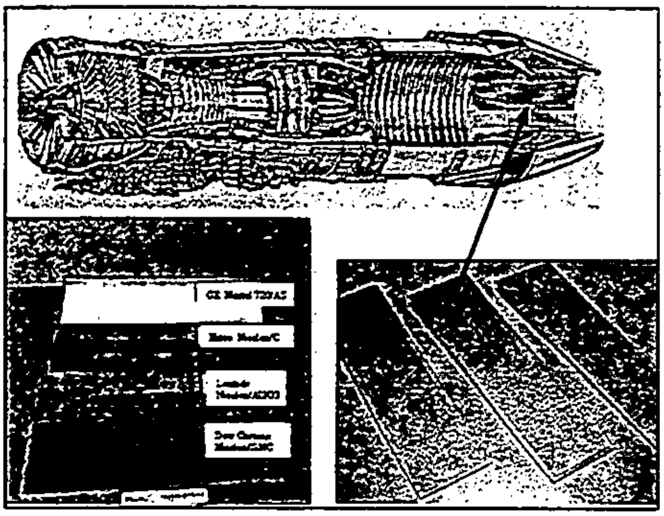

Figure 7. Exhaust Flaps for General Electric F-110 Engine (provided by J. Staehler & L. Zawada, AFML)

The flaps were tested in a GE F110-129 engine for up to 120 hours. The HITCO and Dow Corning flaps survived well, whereas the GE and DLC flaps exhibited some cracking and wear. More testing is planned.

Figure 8 shows an exhaust panel for the proposed NASA High-Speed Civil Transport (HSCT) aircraft[2]. The CFCC tiles will line the exhaust nozzle to provide high temperature structural stability to the acoustic damping system. The tile shown in Figure 8 has six fastener locations as well as a large number of perforations which permit the system to attenuate the acoustic energy. A four panel array was successfully tested in a hot acoustic rig at the Air Force Research Laboratory[2].

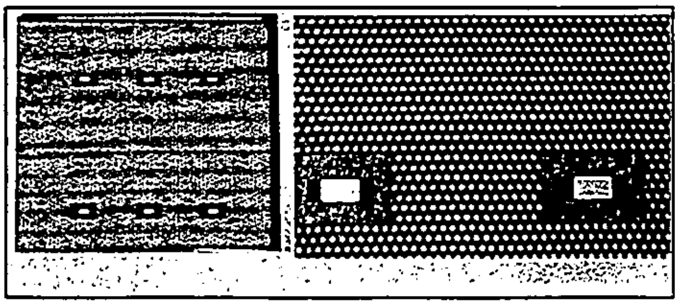

Figure 8. NASA-HSCT (High-Speed Civil Transport) Exhaust Panels

Figure 9 illustrates a prototype turbine exhaust nozzle, which is comprised of inner and outer rings (~5" and 8" diameter; 0.25" thick) connected by three struts. These components were fabricated separately and then joined to form the final assembly.

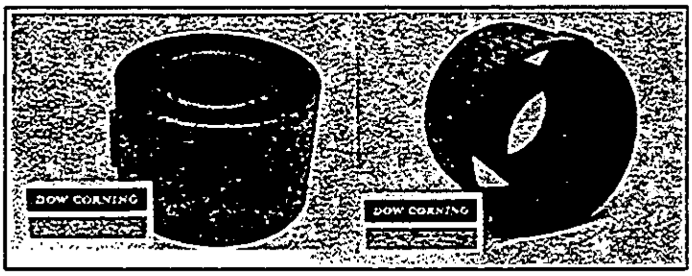

Figure 9. Prototype turbine exhaust assembly.

Prototype sub-scale components have been fabricated for land-based gas turbines also. Figure 10 shows a cross section of a typical land-based gas turbine and the location of components that are currently being evaluated. These components were selected because they represent the need in the turbine for higher temperature capability and more durable materials. Use of these materials will enable significantly improved efficiency and reduced emissions for these turbines[3].

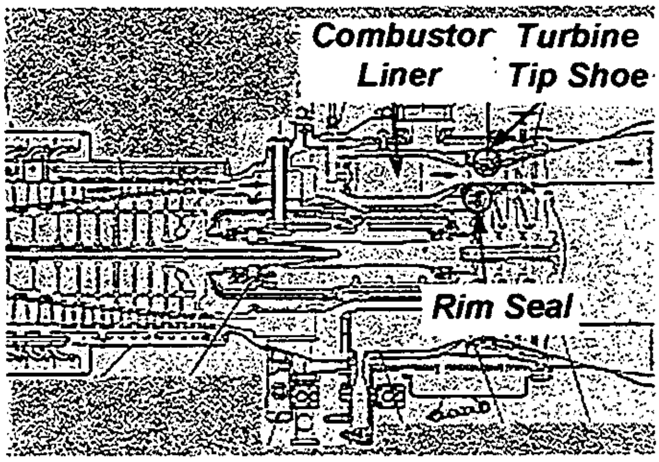

Figure 10. Location of CFCC Components for Land-Based Gas Turbines.

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Figure 11 shows a sub-scale outer combustor liner (~8" dia. x 10" long x 0.1" thick) that was evaluated in a 100 hour combustor rig by Solar Turbines[4]. Non-destructive evaluation of the liner indicated that it had several cracks, due to thermal stresses at atypical localized hot spots. The liner did not fail catastrophically, however, as would likely have happened with a standard monolithic ceramic.

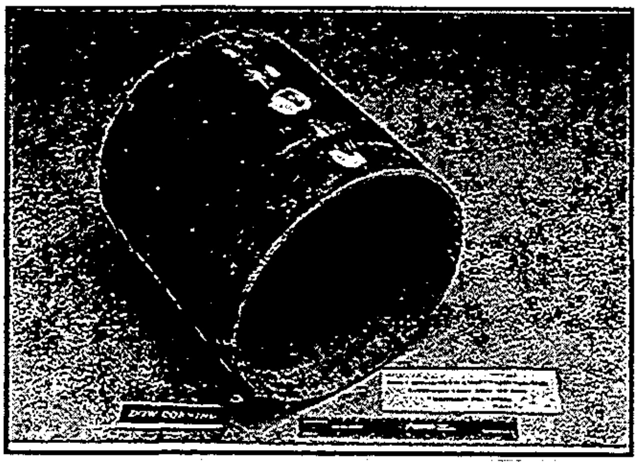


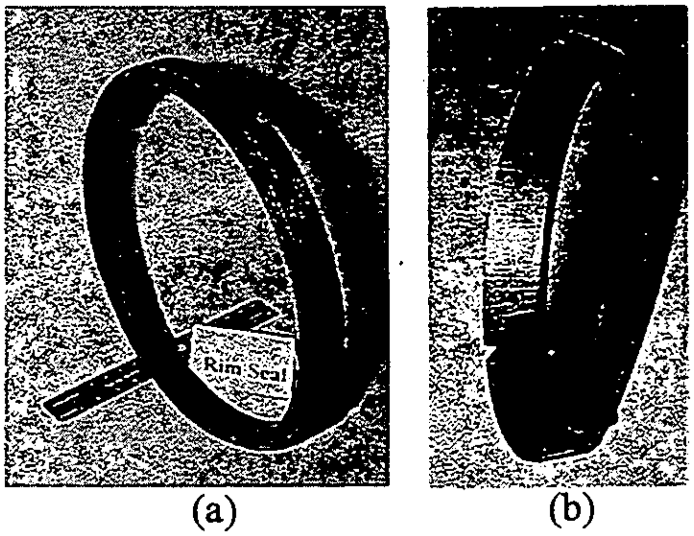
Figure 11. Post 100-Hour Rig-Tested SYLRAMIC™ S200 Combustor Liner.

Figure 12 shows the prototype sub-scale rim seal and turbine tip shoe that were fabricated (both approx. 8" diameter). These prototypes were made to demonstrate the ability to fabricate thick-section (~0.4") rings using the PIP process.

Both of these components have a need for surface abradability to allow rotating knife edges to cut into the surface and create a seal. Tests carried out on this material have shown that SYLRAMIC™ S200 can accept a rub from a hardened knife edge on a rotating disc without failure. Development work is continuing to demonstrate the ability to fabricate full scale prototype components for land-based gas turbine applications.

CONCLUSIONS

The polymer impregnation and pyrolysis process is a versatile method for producing both simple and complex net-shaped components. Various preform fabrication techniques and the ability to green-machine design details have been demonstrated. These CFCCs have excellent mechanical properties at both room and elevated temperatures. A number of prototype components fabricated by Dow Corning continue to be evaluated in aerospace and industrial applications.



(a) (b)

Figure12. Fabricated Sub-Scale Prototype Components; (a) Rim Seal, (b) Tip Shoe.

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