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# A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing

Joseph E. Grady and Michael C. Halbig
NASA Glenn Research Center
Cleveland, OH, USA

Mrityunjay Singh
Ohio Aerospace Institute
Cleveland, OH, USA

## Abstract

In a NASA Aeronautics Research Institute (NARI) sponsored program entitled "A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing", evaluation of emerging materials and additive manufacturing technologies was carried out. These technologies may enable fully non-metallic gas turbine engines in the future. This paper highlights the results of engine system trade studies which were carried out to estimate reduction in engine emissions and fuel burn enabled due to advanced materials and manufacturing processes. A number of key engine components were identified in which advanced materials and additive manufacturing processes would provide the most significant benefits to engine operation. In addition, feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and ceramic matrix composite were demonstrated. A wide variety of prototype components (inlet guide vanes (IGV), acoustic liners, engine access door) were additively manufactured using high temperature polymer materials. Ceramic matrix composite components included first stage nozzle segments and high pressure turbine nozzle segments for a cooled doublet vane. In addition, IGVs and acoustic liners were tested in simulated engine conditions in test rigs. The test results are reported and discussed in detail.

**Keywords:** Additive manufacturing, polymer matrix composites, ceramic matrix composites, turbine engine applications

## Introduction

During the last decades, advanced lightweight and high temperature materials have made tremendous impact on the aerospace components and systems in terms of weight reduction, high operating temperature, reduced fuel burn, and reduced emissions. In particular, advances in composites materials and manufacturing technologies enabled the first polymer matrix composite (PMC) fan blades and fan containment system in gas turbine engines in the 1990's. More recent advances in ceramics and coatings will soon enable the first ceramic matrix composite (CMC) components in commercial aircraft engines in 2016. Recent high TRL demonstration of CMC exhaust nozzle components will lead to introduction of CMC exhaust nozzles in commercial engines in the near future [1].

In-spite of many successes and upcoming plans for the introduction of PMCs and CMCs in gas turbine engines, the percentage of advanced composites in these engines is relatively small, on the order of 10-20% compared to nearly 50% for airframe structures, with most of it consisting of metallic components. Advanced composite materials have created new opportunities for innovative component designs and opportunities for new gas turbine designs/architectures that can take full advantage of their unique properties. Recent advances in ceramic matrix composite materials and technologies could enable the replacement of a wide variety of metallic components in the hot sections of current gas turbine engines, leading to reduction of engine weight and the need for cooling air, and therefore increasing engine efficiency and reducing emissions and fuel burn. However, comprehensive engine design studies has to be conducted to develop design and architecture concepts for a fully non-metallic gas turbine engine that can be enabled by effective use of PMC and CMC materials and integration of components through additive manufacturing of complex components.

In this paper, system analysis studies were conducted to assess the benefits of a fully non-metallic gas turbine engine in terms of fuel burn, emissions, reduction of part count, and cost. In addition, technical activities were carried out to assess the feasibility of additive manufacturing technologies for fabricating complex polymer matrix composite (PMC) and ceramic matrix composite (CMC) gas turbine engine components. The technical work was carried out by multidisciplinary, multi-organization NASA-industry team that included experts in engine design and analysis, and system analysis, additive manufacturing, polymers and PMCs, structural engineering, ceramic materials and CMCs, and sub-component testing under simulated engine conditions.

## System Analysis Studies

The systems analysis efforts were focused on evaluating the potential fuel burn, landing-takeoff (LTO) $NO_X$ and acoustic benefits of polymer matrix and ceramic matrix composite materials in a regional jet class engine. The first step in the process was the development of the current technology, small thrust (i.e., regional jet class) engine to serve as the baseline. Details of the analysis approach [2-4] and results from these studies are given in a recent report [5]. The baseline engine and airplane data used for the system analysis of engine (CF34-8C5 "like") and the airframe (CRJ900LR "like"). The analysis effort commenced with the generation of initial performance and weight benefits from inserting polymer matrix composites (PMC) and ceramic matrix composites (CMC) into the baseline engine.

PMCs were envisioned for use in several locations in the front portion of the engine (inlet acoustic duct, fan stator, and the first 4 rows of high-pressure compressor vanes). In the engine's hot section, 2600 °F CMCs were substituted in the combustor liner, high-pressure turbine (HPT) vanes/blades, low-pressure turbine (LPT) vanes/blades and core nozzle. The cycle was re-optimized to eliminate all turbine blade/vane cooling. The "advanced" cycle produced ~2.6% improvement in specific fuel consumption. The inclusion of the composite materials enabled the engine weight to decrease by ~14.5%.

Figure 1 shows the analysis of regional jet fuel burn sensitivities indicating influence of engine weight reduction on the reduction in fuel burn. The combination of fuel efficiency improvement and engine weight reduction would indicate an airplane that has a 4.9% reduction in total fuel burn versus the current technology baseline.

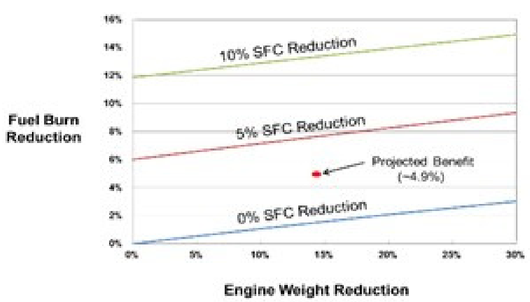



**Figure 1: Regional jet fuel burn sensitivities showing reduction in fuel burn and engine weights.**

The second part of the assessment was to allocate the projected 4.9% fuel burn benefit between the PMCs and CMCs. Table 1 shows the influence of different materials and components on the system level benefits. In addition to the weight reduction versus the metallic parts replaced, CMC usage enabled the elimination of all turbine blade and vane cooling. By removing the need for cooling and the associated mixing losses, an efficiency improvement in the HPT (1.5 pts) and LPT (0.5 pt.) was assumed. The PMC benefits were entirely weight reduction based and had no impact on the engine performance. As such, the vast majority (~90%) of the fuel burn improvement is attributed to the hot section CMCs [5].

**Table 1: Effect of key materials technologies on various system level benefits.**

| | Baseline | Advanced (All Techs) | Advanced (PMCs only) | Advanced (CMCs only) |
|---|---|---|---|---|
| SFC (cruise) | 0.6900 | 0.6719 (-2.6%) | 0.6900 | 0.6719 (-2.6%) |
| SFC (SLS) | 0.4105 | 0.3902 (-4.95%) | 0.4105 | 0.3902 (-4.95%) |
| Engine Weight (lb) | 3760 | 3215 (-14.5%) | 3600 (-4.3%) | 3375 (-10.2%) |
| Aircraft Weight (lb) | 84500 | 81970 (-3.0%) | 83965 (-0.7%) | 82540 (-2.3%) |
| Block Fuel (lb) | 15730 | 14960 (-4.9%) | 15660 (-0.5%) | 15040 (-4.4%) |

## Additive Manufacturing and Testing of PMC Components

In this project, several target components for the PMC manufacturing efforts were identified based on the operational requirements, material properties, manufacturing capability of commercially available and developmental polymer composites. Figure 2 shows few of the high-payoff engine components identified for advanced materials and manufacturing technologies Polymer based components included inlet guide vanes (IGVs) and acoustic liners. The inlet guide vane (IGV) is a static structural component currently made of Ti-6Al-4V alloy. This component is subjected to low pressures and temperatures suitable for the polymer matrix composite material systems assessed in this program. There has been industrial experience with manufacturing and testing a PEEK thermoplastic IGV.

The polymer composite IGV components are expected to provide benefits from effective weight reduction, superior strength and temperature capability as well as advanced manufacturing processes of this program.

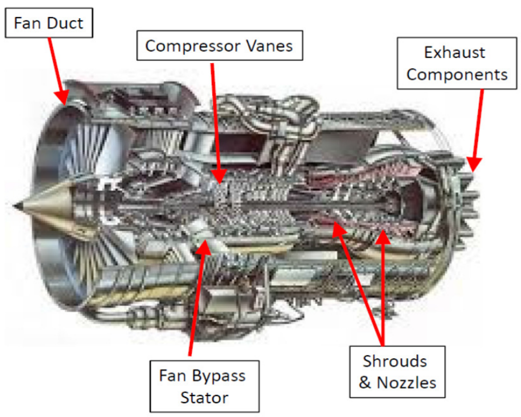



**Figure 2: High-payoff engine components identified for advanced materials and manufacturing technologies.**

Fused Deposition Modeling approach, used to fabricate polymer matrix composite components, has been described in detail in other reports [5-6]. Different types of materials were used including commercially available polyetherimides– Ultem 9085 and experimental Ultem 1000 mixed with 10% chopped carbon fiber. The testing details of inlet guide vanes fabricated using ABS and carbon fiber reinforced Ultem 1000 and acoustic liners fabricated from Ultem 9085. Figure 3 shows a number of components fabricated using the FDM process.

**Figure 3: Inlet Guide Vanes (IGVs) and Acoustic liner fabricated using Fused Deposition Modeling (FDM).**

## Inlet Guide Vane (IGV) Cascade Testing

A set of additively manufactured inlet guide vanes were tested in the Engine Research Building (ERB) SW-2 wind tunnel facility at NASA Glenn Research Center. The details of testing facility and set up (Figure 4) has been described in another publication [5]. This facility uses the lab-wide central exhaust system to draw atmospheric air through an acrylic wind tunnel. The four different inlet guide vane designs were tested. Two vanes were made of ABS and two were made of Ultem 1000 with 10% chopped carbon fiber. Additionally two fillet designs at the hub and tip of each vane were employed in this test. One set of vanes (ABS and carbon fiber Ultem) was fabricated with the standard Honeywell fillets, while another set of vanes (ABS and Carbon fiber Ultem) was fabricated with a larger reinforced fillet at the tip and hub. The vanes were roughly 6 in long, with an airfoil section 4.5 in long. Each vane was later painted with a speckled pattern to allow for imaging by the ARAMIS Digital image correlation) DIC system.

Tests were performed at various inlet velocities ranging from nominally 100 to 600 ft/sec and at angles from 0 to 60 degrees. Additionally the vane cascade was tested in a “closed” position i.e. vanes were set to 90 degrees to the inlet flow in an attempt to fracture the vanes. Deflection up to several millimeters was observed but no fracture was detected, even at the "closed" condition. As expected, for all vanes the displacement increases with increasing incidence angle. Also, the largest displacement generally occurs on the ABS vane with the baseline fillet design. The vane maximum displacement data for nominal velocities from 100 to 600 ft/sec and $20^o$, $30^o$, $40^o$ and $50^o$ angles were measured. Generally the ABS vanes (4 and 5) show higher deflection than the carbon reinforced Ultem 1000 vanes (6 and 7). In addition, the reinforced fillet improves the stiffness of the vane for the ABS but not so much for the Ultem.

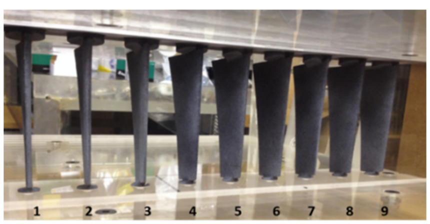



**Figure 4: Inlet Guide Vane Cascade Test Section**

It is important to note however, that these tests were conducted with a very limited number of trials and test specimens and more samples should be tested to confirm this result. The main objective was to determine if the vanes could withstand air speeds that may be typical of an actual IGV. While a fair amount of bending was observed, none of the 4 center test vanes (vanes 4-7) fractured during these tests.

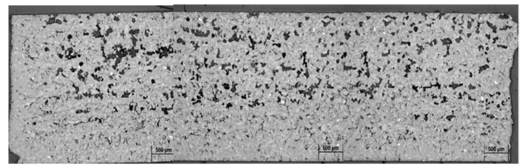
## Additive Manufacturing of CMCs

Binder jet process using an ExOne M-Flex print machine was used to fabricate ceramic matrix composite materials. Effect of powder size and powder spreading on the layer build up and the print quality was evaluated. The powder bed was filled with SiC powders or powder + fiber mix to manufacture CMCs. The SiC powders of different sizes were obtained from Washington Mills, MA and utilized to fill the powder bed. Fiber additions, ranging from 25-75 vol. %, were added to the powder bed powder mix to manufacture fiber reinforced composite materials. The fiber reinforcement was Si-TUFF SiC fiber (Advanced Composite Materials, LLC). The manufacturer reports fiber dimensions of 7 micron mean diameter x 65-70 micron mean length. Two types of infiltrants (SMP-10 and phenolic based) were utilized to densify the printed objects. For microstructural analysis and secondary infiltration studies, various specimens of approximately 12.7 mm wide x 25.4 mm long x 4.0 mm thick size were printed. For mechanical properties characterization, approximately 50.8 mm x 50.8 mm x 4.0 mm size plates were printed, and specimens were machined for mechanical testing. Optical and scanning electron microscopy (SEM) studies were carried out for microstructural evaluation.

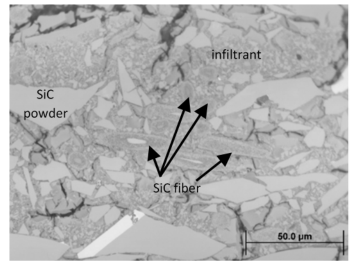
Microstructural analysis of polished cross-sections of samples was conducted using optical and scanning electron microscopes. In the following sections, micrographs from selected samples are presented to illustrate the results obtained using different constituents and infiltration methods. In order to further densify different types of printed materials, extra infiltration steps were conducted on 50.8 mm x 50.8 mm panels from several of the materials sets. Additional iterations of SMP-10 vacuum infiltration followed by pyrolysis in a furnace were conducted. Each infiltration and pyrolysis step increased the densities by 0.20-0.55 g/cc. Most of the increase in density occurred in the first two infiltrations with less effect from the third infiltration. Flexural strength specimens were machined from these plates. Mechanical testing of specimens was conducted using 4 point bend tests. Details of the results have been discussed in other publications [7-8].

The polished cross-section of a fiber reinforced sample from Set-O which underwent three extra infiltration steps is shown in Figure 5. This material consists of 35 vol. % of 67 wt. % 220 and 33 wt. % Carborex 600 SiC Powder mix and 65 vol. % Si-Tough SiC fiber. Multiple infiltrations were conducted with SMP-10 loaded with 17 wt.% 800 nano SiC particles. The Figure 5 (a) shows views of the polished cross-section at the two ends and in the middle of the sample. The sample does have some relatively larger pockets of porosity throughout the cross-section. However, in the close-up view (Figure 5 (b) it is seen that the infiltrant is filled in around the constituents and there is a good distribution of the SiC fibers.

Flexural strength testing results from two non-reinforced and two fiber reinforced panels are provided in Figure 6. Stress versus strain curves are shown for flexure tests of three bend bars from each panel. The two fiber reinforced CMC panels had higher strengths and strains to failure than the samples from the two non-fiber reinforced panels. The highest strengths were from Set N with 65 vol. % fiber loading which had an average strength of 66 MPa.



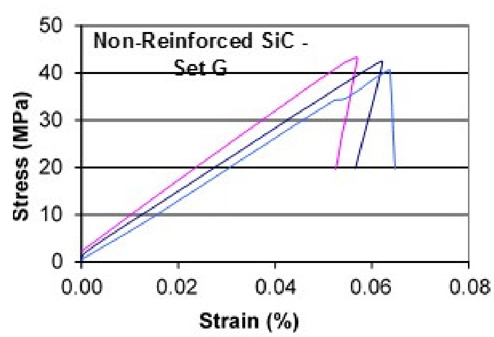
(a)



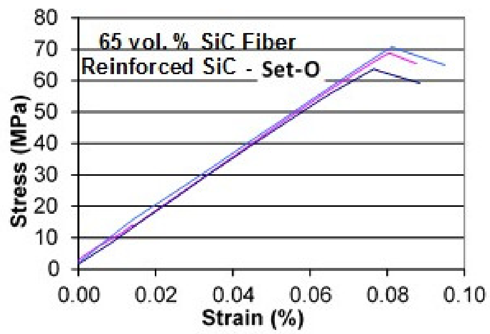

(b)

**Figure 5: Optical micrographs of fiber reinforced composite materials (Set-O).**

Figure 7 shows the demonstration of the additive manufacturing of turbine engine CMC components (20 vol. % SiC fiber). Two different sizes of turbine vanes were printed to include larger size high pressure turbine nozzle segments for a cooled doublet vane and two smaller first stage nozzle segments (Figure 7, top). Two cooled double vane sections were aligned to illustrate how the sections are placed to form a vane ring section (Figure 7, bottom). While the material processing may need further optimization to improve the properties, it is encouraging that such complex and relevant shapes can be made.




(a)




(b)

**Figure 6: Plots of stress versus strain for the results of three bend bar tests from each panel for the non-reinforced materials (a) and the Si-Tuff SiC fiber reinforced materials (b).**

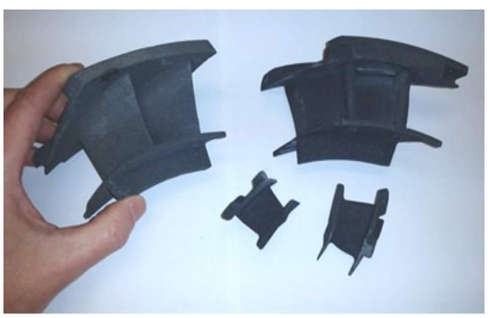


**Figure 7: Demonstration of the additive manufacturing of turbine engine CMC components (20 vol. % SiC fiber). Two smaller first stage nozzle segments in addition to two high pressure turbine nozzle segments for a cooled doublet vane (top). Aligned cooled double vane sections (bottom).**

## Summary and Conclusions

System analysis studies indicate that there are potential fuel saving benefits from PMC and CMC engine components for a regional-jet class system. The CMC components were combustor liner, the high-pressure and low-pressure turbine blade/vanes, and the core nozzle. The benefits included a weight reduction in the aforementioned components due to replacing metallic parts with ceramic-based alternatives, in addition to the elimination of requisite turbine cooling. The PMCs were applied in the inlet acoustic liner, the fan stator and the first 4 rows of the high-pressure compressor vanes and the PMC benefits consisted of weight reductions only in each component. The resultant propulsion system generated a 4.9% fuel burn improvement over the baseline and a 7.7% increase in landing-takeoff (LTO $NO_X$) margin with respect to the CAEP/6 stringency.

In the case of polymer composites, compressor inlet guide vanes, fabricated from ABS and carbon fiber reinforced Ultem 1000, were tested in wind tunnel to measure the deflection and strain. The ABS vanes show higher deflection than the carbon reinforced Ultem 1000 vanes. Additionally this data seems to show that reinforced fillet improved the stiffness of the vane for the ABS but not so much for the Ultem 1000.

In CMCs, the ability for the binder jet method to be used to fabricate relevant shapes for turbine engine component applications was demonstrated. Silicon carbide powders of different sizes and blends were used in the powder bed to investigate the printability during the printing process such as powder spreading and layer build up and the print quality, powder packing, porosity, and infiltration. Silicon carbide fibers were added to the powder bed to make ceramic matrix composite materials. Microscopy showed that the fibers were well distributed with no preferred orientation on the horizontal plane and fibers in the vertical plane were at angles as much as 45°. Secondary infiltration steps were necessary to further densify the material. Flexural testing of specimens showed that fiber reinforced specimens had higher strengths and strains to failure than the non-fiber reinforced specimens.

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