Turbine Airfoil Manufacturing Technology

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Introduction

The efficiency and effectiveness of the gas turbine engine is directly related to the turbine inlet temperatures. The ability to increase these temperatures has occurred as a result of improvements in materials, design, and processing techniques. A generic sequence indicating the relationship of these factors to temperature capability is schematically shown in Figure 1 for aircraft engine and land based engine materials. A basic contribution that is not captured by the Figure is the significant improvement in process and manufacturing capability that has accompanied each of these innovations. It is this capability that has allowed the designs and innovations to be applied on a high volume, cost effective scale in the aircraft gas turbine market.

Examples of these processing developments are:

- Vacuum melting for the nickel-base superalloys.
- Ceramic technology that produces complex, dimensionally reliable, stable cores that can be readily removed.
- Casting methods and furnace designs that allow both directionally solidified (DS) and single crystal (SX) produce to be produced in aircraft airfoils at yields approaching 90%.
- Advanced nickel-base alloy compositions, which utilize hafnium, rhenium, and in some cases small quantities of yttrium to improve the required DS and SX properties.
- Coatings that protect the airfoils from oxidation and provide thermal barriers.

Figure 1. Development History of Aircraft and Land Base Engine Materials

Future efforts are being directed toward further reducing manufacturing variation so that
yields will approach 95% and costs will come down accordingly, more advanced and challenging thin-wall cooling schemes, and lighter weight materials (intermetallics and high temperature composites).

Although land based turbines can make use of the technology developed by the aircraft engines, some very real challenges and differences are present. Land base turbines operate under different duty cycles. Therefore designs have different creep and low-cycle fatigue criteria. In addition, alloy compositions are often aimed at greater sulfidation resistance (higher chromium content).

The major limiting factor, however, in directly transferring aircraft engine technology to land base designs is increased size and weight. The largest SX complex-cooled part for a military engine is approximately 10” in length. DS parts in this range are routinely produced at high yields. Both of these applications have relatively small root sections and pour weights compared to industrial gas turbine applications.

A need exists to shift the capability of the complex-cored airfoil technology to larger sizes so that higher turbine inlet temperatures can be attained in land base hardware in a cost effective manner. The Department of Energy has recognized this need as part of the planning effort for the Advanced Turbine Systems (ATS) Program to develop advanced gas turbines for power generation in utility and industrial applications. It was assessed that a need exists to extend the capability of SX complex-cored airfoil technology to larger sizes so that higher turbine inlet temperatures can be attained in land base hardware in a cost effective manner.

In response to this need the Turbine Airfoil Manufacturing Technology Program has been initiated at PCC Airfoils, Inc./General Electric Power Generation Group which envisions using the available methods for producing SX airfoils and scaling them up to much larger land base components.

Objectives

The specific goal of this effort is to define manufacturing methods that will allow SX technology to be applied to complex-cored airfoil components for power generation applications. A number of specific technical issues are being addressed and these form the task structure of the program and include the following:

- Alloy melt practice to reduce sulfur content in alloys.
- Modification/improvement of SX casting process.
- Core materials and design.
- Grain orientation control.

Within the task structure represented by these technical issues specific objectives have been identified, the achievement of which will produce a resultant process that is cost effective. The specific objectives for these tasks are listed as follows:

Alloy Melt Practice

The objective of this task is to establish a process to reduce sulfur in castings to a sufficiently low level to promote the adhesion of a protective oxide scale. Activity will focus on N5 alloy (containing no yttrium) evaluated in GE burner rig oxidation/corrosion tests.
SX Casting Process

The objective of this task is to define manufacturing methods that will allow SX technology to be applied to complex-cored and solid airfoils for land based turbine applications. The results will define process details that can be successfully used to determine a cost effective production process.

Core Materials

The objective of this task is to provide ceramic cores for the SX casting process for the complex cored component which can control wall thickness to tight requirements over long spans. The results will be a definition of the capability of the core bodies with respect to their ability to produce complex serpentine cores for SX applications.

Grain Orientation Control

The objective of this task is to provide data to enable decisions to be made concerning the establishment of grain limit defect criteria. It is anticipated that the information will reduce the risks associated with liberalizing the defect criteria.

Approach

The technical approach to define manufacturing methods that will allow SX technology to be applied to complex-cored airfoils for land base turbine applications was developed by a program team consisting of PCC Airfoils, Inc. and GE Power Generation. The program philosophy is to expand and modify as required the existing, well-established techniques for aircraft engine airfoils to larger size components. This approach will confirm the ability to use the extensive and competent industrial base, which has been used for military and commercial aircraft applications for the expanding markets available to land base turbines. The technical approaches to meet the task objectives are described below.

Alloy Melt Practice

To reduce sulfur in the N5 alloy, activity will include evaluating desulfurization methods in the melt with the principles demonstrated by applying them to the remelt operation. Four conditions will be studied - a baseline composition with no desulfurization, and desulfurized condition using the PCC alloy desulfurization method, and both of these conditions to which hydrogen anneals will be applied. Each of these conditions will be tested on specimens in GE Power Generation cyclic oxidation and corrosion test rigs.

SX Casting Process

To define SX manufacturing methods a number of casting variables will be examined through experimental designs used for the production of cored as well as solid blade configurations in several iterations. This iterative approach will result in a fixed casting process which will be verified by a series of molds specifically cast for this purpose.

Core Materials

To provide ceramic cores for the SX process the low pressure core manufacturing method will be applied to meet the wall thickness dimensional requirements. Core injection does not require large equipment and the core materials used tend to be more stable during core firing and casting. Without the need to fill very fine features, coarser and therefore more stable ceramic mixes can be used.
Grain Orientation Control

To provide data to enable decisions to be made relative to grain defect criteria, the planned approach will include testing of cast specimens containing grain defects which will be tested at conditions critical to root sections where fatigue life margin can be reduced. Testing will include low cycle fatigue (LCF) types of tests which will also incorporate a hold time, which more closely simulates a part cycle where there is a period of steady state operation between startup or shutdown.

Project Description

The Turbine Airfoil Manufacturing Technology effort is comprised of five tasks which include a planning task (Task 1) and four tasks (2-5) of technical effort. The Program Schedule is shown in Figure 2. The following sections describe the planning and technical effort to be conducted during the program.

Program Schedule

<table>
<thead>
<tr>
<th>PROGRAM ACTIVITY</th>
<th>CY '95</th>
<th>CY '96</th>
<th>CY '97</th>
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</thead>
<tbody>
<tr>
<td>TASK 1 - PROGRAM PLAN</td>
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<tr>
<td>TASK 2 - ALLOY MELT PRACTICE</td>
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<tr>
<td>Ingot Preparation</td>
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<tr>
<td>Rig Test</td>
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<tr>
<td>TASK 3 - CASTING PROCESS</td>
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<td></td>
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<tr>
<td>Core Barrel</td>
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<td></td>
<td></td>
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<tr>
<td>Sand Barrel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TASK 4 - CORE MATERIALS / DESIGN</td>
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<td></td>
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<tr>
<td>Core Alloy Characterization</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Optimum Core Processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TASK 5 - GRAIN ORIENTATION CONTROL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core Barrel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCF Testing / Characterization</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 2. Program / Task Schedules for TAMT Program

Task 1 - Program Plan

Program planning activity involved the creation of an exact work breakdown structure that will allow close coordination between program elements and provide a clear blueprint for program review and management. The Program Schedule was also finalized during this planning activity.

Task 2 - Alloy Melt Practice

Alloy Melt Practice activity is shown in Figure 3 and includes ingot preparation, mold preparation/casting, hydrogen heat treatment and GE burner rig testing.

Figure 3. Work Breakdown Structure for Task 2 - Alloy Melt Practice

Ingot preparation includes making the vacuum induction melted (VIM) master metal which will be cast into the test pin configuration for rig testing. An ingot of standard N5 as well as a desulfurized ingot will be produced. The desulfurization will be accomplished in the melting operation with the sulfur aim being less than 0.5 parts per million (ppm).

Mold preparation and casting will follow procedures established for the production of SX castings. The molds will be configured such that 24 pins each 0.180 inch in diameter by 6 inches long will be produced and these pins can then be cropped to the desired length for the GE tests. The cast pins will be solution heat treated to homogenize the structure and one half the pins will be given a hydrogen heat treatment to further reduce sulfur levels.
Rig testing including oxidation and hot corrosion tests will be conducted as per the test matrix shown in Table 1. A decision point occurs after the testing has reached 2000 hours in that surface degradation will be evaluated at this point and if the molten desulfurization results are not better or equal to the hydrogen annealed results, the remaining task of the program will not be conducted.

Table 1. Test Plan for Evaluating Desulfurization

<table>
<thead>
<tr>
<th>Condition</th>
<th>NS Baseline</th>
<th>NS De-S Alloy</th>
<th>NS HyAnneal</th>
<th>NS De-S Alloy HyAnneal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900°F Oxidation</td>
<td>3 @ 2,000 hrs.</td>
<td>3 @ 2,000 hrs.</td>
<td>3 @ 2,000 hrs.</td>
<td>3 @ 2,000 hrs.</td>
</tr>
<tr>
<td>2000°F Oxidation</td>
<td>3 @ 2,000 hrs.</td>
<td>3 @ 2,000 hrs.</td>
<td>3 @ 2,000 hrs.</td>
<td>3 @ 2,000 hrs.</td>
</tr>
<tr>
<td>1700°F Corrosion</td>
<td>3 @ 1,000 hrs.</td>
<td>3 @ 1,000 hrs.</td>
<td>3 @ 1,000 hrs.</td>
<td>3 @ 1,000 hrs.</td>
</tr>
</tbody>
</table>

Task 3 - SX Casting Process

SX Casting Process activity is shown in Figure 4 and includes a series of iterative casting trials for a cored part and a solid part. The cored part, a GE Power Generation Prototype Bucket, features complex cooling and is approximately 15 inches long while the solid part (another prototype) will be approximately 24 inches long.

Efforts for the cored configuration will encompass a total of 6 mold trials totaling 20 molds in an iterative manner. Thermal simulation modeling will be conducted in conjunction with the trials to establish the effects of important casting variables. The initial trial will address mold structural integrity including survivability during the casting process. Subsequent trials will address process optimization with variables being selected as a result of earlier trial activity. The final trial addresses process verification and will act to provide statistical significance to the existing data as well as determine the possible extent of process variability associated with casting procedures.

Efforts for the solid configuration will encompass a total of 3 mold trials totaling 10 molds in an iterative manner. The activity is directed towards mold structural integrity and process refinement.

The castings resulting from the trials for both configurations will be subjected to thorough evaluations including NDT, chemistry, microstructural characterizations and mechanical property testing.

Task 4 - Core Materials

Core Material activity is shown in Figure 5 and includes core body characterization and optimized core processing. Core body characterization involves an evaluation of a number of silica based core compositions available for application to the SX casting process. Raw materials characterization will
include purity, particle size distribution and specific surface area measurements on all raw materials associated with the core body compositions. Cores will be processed and evaluated for a number of characteristics including shrinkage, modulus of rupture, stability and porosity. The characterization data on the various core bodies will be analyzed and a downselection will be made for the initial casting trials. As part of the casting trials, evaluations of core performance will be conducted including resistance to core/metal reactions, stability, additional shrinkage during the casting process and core removal kinetics. Assessments of this core performance will be made for the selection of cores required for the subsequent casting trials.

Optimized core processing will include the manufacture of cores for the subsequent casting trials and will be evaluated for the same characteristics established during core body characterization. The purpose of these evaluations is to ensure that the cores selected for subsequent casting trials are representative of those evaluated during the first trial.

Table 2. Planned Test Matrix for Evaluation of Casting Defects

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>1000°F</th>
<th>1200°F</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Angle Boundary (HAB):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05° - DIA.</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0.10° - DIA.</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Freckles:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.125' x 0.060&quot;W</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0.250' x 0.060&quot;W</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Porosity:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.015° - DIA.</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0.030° - DIA.</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Baseline:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defect-Free (001)</td>
<td></td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

It is planned that the castings produced as part of the casting trials will be examined to select regions which would be appropriate for machining into specimens for the LCF tests. Defects located on relatively flat portions of the casting surfaces would be most appropriate for specimen machining whereas defects located in regions of high curvature would not.

For the testing, cycles to crack initiation will be reported for each test. Comparisons will be made to the baseline material containing no obvious surface defects. Post test characterization will consist of light metallography as well as Scanning Electron Microscopy of selected areas to aid in interpreting the LCF data.
Results

Task 2 - Alloy Melt Practice

**Specimen Preparation.** Work was initiated on the alloy melt practice activity described in the plan of Figure 3. Test pins have been produced, given the appropriate thermal exposures and burner rig testing has been initiated at GE.

Initial activity included preparing the master metal for subsequent remelting into the test pin configuration. An ingot of standard N5 alloy was obtained to serve as the baseline and its sulfur level was 2.5 ppm. The desulfurized ingot was produced using the practice of reducing sulfur during the melting operation and its sulfur content was 0.4 ppm.

Molds were prepared following procedures established for the production of molds used for SX castings. This included wax injection, mold assembly and dipping. Dipping the assembled wax pattern was done sequentially in ceramic slurries to build a mold of the required thickness.

Casting involved remelting the alloy ingots and pouring the molten metal into the molds to produce the SX pins for GE rig testing. This included vacuum melting using the mold preheat conditions of 30 minutes at 2650°F and a pour temperature of 2850°F. The mold withdrawal solidification cycle was programmed for a withdrawal speed of 6 inches/hour for the first 30 minutes of solidification followed by a 8 inch/hour withdrawal speed for 50 minutes.

The appearance of a typical 6-pin candelabra grouping after the casting knock-out operation is shown in Figure 7. Each pin within the candelabra solidified from the same single crystal starter geometry. Each mold was comprised of four such candelabras. The pints can be cropped to the desired length to accommodate the GE burner rig.

![Figure 7. Test Pin Candelabra Casting After Mold Knock Out](image)

Heat treatments including homogenization cycles and hydrogen desulfurization cycles were applied after the casting operation. All of the pins received the standard N5 heat treatment to homogenize the structure by minimizing any chemistry gradients resulting from the casting operation. Hydrogen heat treatments were applied to one half of the pin specimens intended for rig testing. These treatments were conducted in a production facility with a standard 50 hour cycle under a partial pressure of 7 mm of hydrogen. Both the standard N5 alloy and the desulfurized alloy were similarly heat treated. Sulfur levels were measured for materials of the various conditions.
making up the test matrix shown in Table 1. It has been experienced that sulfur pick-up can occur during the remelting operation and in these instances repeat measurements are taken. The following summarizes the sulfur levels for the various materials/conditions planned for the GE burner rig tests:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Sulfur Level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N5 Baseline</td>
<td>2.5</td>
</tr>
<tr>
<td>N5 De-S Alloy</td>
<td>0.4</td>
</tr>
<tr>
<td>N5 H₂Anneal</td>
<td>0.7</td>
</tr>
<tr>
<td>N5 H₂ Anneal</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Burner Rig Testing.** Burner rig testing was initiated for all specimen conditions shown in the testing plan of Table 1. Testing was initiated with the 1900 and 2000°F oxidation tests and the 2000 hour exposure times for these tests are scheduled to be completed by the end of October.

A schematic illustration of a burner rig unit is shown in Figure 8. Each rig consists of a tube inside a tube furnace, with an atomizing fuel nozzle at one end and an exhaust at the other. Atomized fuel is combined with air in the combustion chamber and burned, resulting in hot gases which flow past a double beam fixture suspending test samples in the hot gas stream. Up to 21 pin or disk samples can be housed in a sample fixture.

Upon completion of the designated exposure times, the pins will be examined metallographically and the thickness of the remaining metal and the depth of internal attack will be measured as an indication of resistance to the oxidizing environment.

**Task 3 - SX Casting Process**

Work was initiated on planned Task 3 activities related to the cored configuration and
included preparations for the first trial and involved tooling procurement and modeling.

Tooling involves modification effort directed at the current tooling available for the cored component. This component is currently produced with a columnar grained directionally solidified structure. In order to make the current wax tooling amenable to the SX casting process, certain feature additions are required including a ramp die, downpole tool and assembly plate. With these feature additions the current tooling can be used interchangeably to make a columnar grained or a SX version of the cored component. Design and build of the feature additions was initiated.

Modeling activity encompasses two areas including the construction of electronic models and simulation of the envisioned casting processes. Electronic models have to be complete before simulation modeling can take place. The modeling involves the construction of a three dimensional geometric model for subsequent CMM and layout measurements and an electronic file for the simulation activities. Modeling has progressed to the extent that both the external geometric model as well as the internal core configuration model have been completed and activity is now focusing on combining the external and internal models with the ramp die configuration.

**Task 4 - Core Materials**

Work was initiated on planned Task 4 activities and included core body characterization. The preferred manufacturing method for the large cores needed for the prototype configuration is the low pressure method as practiced by PCC Airfoils, Inc. A flowchart of the low pressure injection molding process is shown in Figure 9. The low pressure process differs from high pressure injection molding processes typically used in the manufacture of ceramic cores for investment casting applications in several aspects, the most significant being the use of gravity to fill the die cavity with a ceramic slurry. Low pressure is applied to the core mix to displace entrapped air only after the cavity is filled, as opposed to processes where high pressure is used to fill a die cavity.

![Flow Chart of the Low Pressure Core Injection Molding Process](image-url)
The process begins with the mixing of a silica slurry which is then blended with a binder catalyst in a high shear mixer. The core die cavity is then filled by low pressure injection and once the core body is hardened sufficiently to handle, the die is opened and the core body removed. Once the core body is shaped, it is fired to remove binder and presinter the part. The core is then fired a second time to induce shrink and generate strength through the formation of necks between adjacent ceramic particles. After firing, the core body is finished to remove the die flash and patch any surface defects, if required. Owing to the porous nature of the core body, a fired core can be dipped in resin or other organic material to increase strength through the wax injection process step at the foundry.

Core body characterization has been completed and the downselection made to produce cores for the first casting trial. The core body characterization included the evaluation of silica based core compositions for applicability to the SX casting process to produce the GE prototype bucket. For these evaluations ten (10) cores each were made from several core body compositions. A typical core is shown in Figure 10.

Important considerations in the downselection process included fine particle size to allow filling of the finely detailed core features particularly in the trailing edge regions. In addition, reasonable strength as represented by room temperature modulus of rupture (MOR) in a three-point binding type of test is required to survive handling and wax injection without core breakage. Finally, some level of porosity is required to accommodate some crushing during the cool down during solidification (to avoid generating high residual stresses in the castings) and create some degree of access into the internal regions of the core by core leach media. This access acts to facilitate the core removal operation.

On the basis of these considerations the PCC SRI 200-SXA core composition was downselected for the initial casting trial. The average properties exhibited by the cores made for the evaluations included the following: (Modulus of Rupture: 1850 psi, Porosity: 30%, Posi-Resin MOR: 2700 psi).

It can be seen that resin dipping had a significant impact upon increasing the core body MOR. The SRI 200-SXA downselection was made on the basis that these types of strength and porosity values are representative of cores currently in production for aircraft SX applications. It was reasoned that, as a first approximation, these levels warranted evaluation in the initial casting trials for the larger prototype bucket.

![Figure 10. Ceramic Core for GE Power Generation Prototype Bucket](image-url)
Benefits

This program provides a very focused approach aimed at solving the basic casting scale-up problems that currently limit the use of SX casting methods in land base turbine applications.

The specific benefits anticipated from the program include:

- Utilization of SX manufacturing methods to produce land base turbine airfoils in the 24 inch range for solid and simple-cored components and 14 inch range for complex-cored airfoils.

- Definition of cost effective casting methods to produce large land base airfoils.

- Correlation of mechanical properties to critical process characteristics (e.g., grain defects and orientation).

- Capability to produce large, easily removed complex cores with close dimensional control and high stability during casting.

- Ability to use the large and competent industrial base, which has been used for military and commercial aircraft airfoil applications for the expanding markets available to land base turbines.

Future Activities

Future activities can be identified in the Program Schedule shown in Figure 1. During the up-coming year of effort the alloy melt practice activity will be completed. Development work in the SX casting process area will have progressed to the end of process optimization for the complex-cored part and efforts will have initiated on the solid configuration. All core material work will have been completed and testing will be underway involving LCF testing of specimens containing grain defects.

Acknowledgement

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