Turbine Airfoil Manufacturing Technology

CONTRACT INFORMATION

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Contractor PCC Airfoils, Inc.
25201 Chagrin Blvd., Suite 290
Beachwood, OH 44122
(216) 766-6253
(216) 766-6217

Contractor Project Manager Charles S. Kortovich

Principal Investigators Craig Hayes
Peter O' Neill

DOE Project Manager Robert S. Holcomb

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Schedule and Milestones

FY98 Program Schedule

	O	N	D	J	F	M	A	M	J	J	A	S
Alloy Melt Practice												
SX Casting Process												
Core Materials/Design												
Grain Orientation Control												

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 number of technical advances have allowed the designs and innovations to be applied on a high volume, cost effective scale in the aircraft gas turbine market.

Examples of these advances 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) product 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.

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 inches 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 expand 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.

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 program objective is to define manufacturing methods that will allow single crystal (SX) technology to be applied to complex-cored airfoil components for power generation applications. A number of specific technical issues 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.

The specific objectives for these tasks are listed as follows:

Alloy Melt Practice: Establish a process to reduce sulfur in castings to a sufficiently low level to promote the adhesion of a protective oxide scale.

SX Casting Process: Define manufacturing methods that will allow SX technology to be applied to complex-cored and solid airfoils for land based turbine applications.

Core Materials: Provide ceramic cores for the SX casting process for the complex cored component which can control wall thickness to tight requirements over long spans.

Grain Orientation Control: Provide data to enable decisions to be made concerning the establishment of grain limit defect criteria to reduce the risks associated with liberalizing the criteria.

PROJECT DESCRIPTION

The Program comprises five tasks which include a planning task (Task 1) and four tasks (2-5) of technical effort. The Program Schedule for FY98 was shown on the Contractor Information page.

Task 1 - Program Plan

Program planning involved the creation of a work breakdown structure and program schedule to allow close coordination between program elements and provide a clear blueprint for program review and management. To include the desire for extended time environmental testing, additional casting trials to optimize the single crystal casting process for large cored airfoils, and a final decision relative to the second configuration chosen to demonstrate the single crystal process, the Program Plan and schedule were revised accordingly.

Task 2 - Alloy Melt Practice

Alloy Melt Practice activity is shown in Figure 1. Four uncoated conditions will be studied - a baseline composition with no desulfurization, a desulfurized condition using the PCC alloy desulfurization method, and both of these conditions to which hydrogen anneals will be applied. Two coated conditions will also be evaluated in the testing including the baseline material without desulfurization and the melt desulfurized material. No hydrogen anneals will be applied to these materials and both will be diffusion aluminide coated. Each of these conditions will be tested on specimens in GE Power Generation cyclic oxidation and corrosion test rigs.

Ingot preparation includes making the vacuum induction melted (VIM) master metal for casting test pin configurations 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 will employ molds 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.

Table 1. Test Plan for Evaluating Desulfurization

Condition	N5 Baseline	N5 De-S Alloy	N5 H_2 Anneal	N5 De-S Alloy H_2 Anneal	Coated N5 Baseline N5 De-S Alloy
1900°F Oxidation	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	
2000°F Oxidation	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr 1 @ 12,000 hr	3 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hrs. 1 @ 12,000 hr	2 @ 2,000 hr 2 @ 4,000 hr 2 @ 8,000 hr
1700°F 40 ppm Na, 1 % S Corrosion	3 @ 1,000 hr 2 @ 2,000 hr 2 @ 4,000 hr	3 @ 1,000 hr 2 @ 2,000 hr 2 @ 4,000 hrs.	3 @ 1,000 hr 2 @ 2,000 hr 2 @ 4,000 hrs.	3 @ 1,000 hr 2 @ 2,000 hr 2 @ 4,000 hr	

Task 3 - SX Casting Process

SX Casting Process activity is shown in Figure 2 and includes a series of iterative casting trials for cored buckets and nozzles. The cored bucket, a GE Power Generation Prototype Bucket, features complex cooling and is approximately 15 inches long while the nozzle (another prototype) will be approximately 10 inches long.

Efforts for the bucket will encompass a total of 8 mold trials totaling 50 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 nozzle 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 3. Core body characterization involves an evaluation of a number of silica based core compositions available for application to the SX casting process. 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.

Task 5 - Grain Orientation Control

Grain Orientation Control activity is shown in Figure 4 and includes LCF testing of cast specimens containing defects. Defects will include high angle boundaries, freckles, and porosity. Specimens with no defects will provide baseline information. The LCF test plan is shown in Table 2.

It is planned that the castings produced as part of the casting trials will be examined to elect regions which would be appropriate for machining into specimens for the LCF tests.

For the testing, cycles to crack initiation will be reported for each test. Post test characterization will consist of light metallography as well as Scanning Electron Microscopy of selected areas to aid in interpreting the LCF data.

Table 2. Planned Test Matrix for Evaluation of Casting Defects

Defect Type		Rene N5	
		1000 °F	1200 °F
High Angle Boundary (HAB):	0.050 in. - DIA.	3	4
	0.100 in. - DIA	3	4
Freckles:	0.125 in. L x 0.060 in. W	--	4
	0.250 in. L x 0.060 in. W	--	4
Porosity:	0.015 in. - DIA.	--	4
	0.030 in. - DIA.	--	4
Baseline:	Defect Free (001)	3	4
Low Cycle Fatigue (LCF), Strain-Controlled, 2-Minute Hold Time			

RESULTS

Task 2 - Alloy Melt Practice

Work was conducted on the alloy melt practice activity described in the plan of Figure 1. Test pins have been produced, given the appropriate thermal exposures and are undergoing burner rig testing at GE.

Specimen Preparation. An ingot of standard N5 master metal alloy was obtained to serve as the baseline and its sulfur level was 2.1 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. 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.

A 6-pin candelabra configuration was cast with each pin within the candelabra solidified from the same single crystal starter geometry. Each mold was comprised of four such candelabras with pins being cropped to the desired length to accommodate the GE burner rig.

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. 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. The following summarized the sulfur levels for the various materials/conditions planned for the GE burner rig tests:

Condition	Sulfur Level (ppm)
N5 Baseline	2.1
N5 De-S Alloy	0.4
N5 H_2 Anneal	0.7
N5 De-S Alloy + H_2 Anneal	0.3

Specimen preparation was also completed involving the coating of test pin specimens for oxidation testing at 2000 °F. For these tests baseline N5 alloy as well as melt desulfurized alloy pins were diffusion aluminide coated. The specimens did not receive an H_2 heat treatment. Testing will be initiated during the final quarter of CY98.

Burner Rig Testing. Burner rig testing involved conditions shown in the testing plan of Table 1.

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 are examined metallographically and the thickness of the remaining metal and the depth of internal attack is measured as an indication of resistance to the environment.

Oxidation/Corrosion Results. The 2000, 4000 and 8000 hour oxidation exposures at 1900 and 2000 °F have been completed and the 12000 hour exposures at both temperatures are approaching 11000 hours. Approximately 90% of the samples submitted for exposure in the 1700 °F hot corrosion burner rig has been removed from the test. The rest are expected to be completed by the end of this year.

The N5 (without yttrium) oxidation mechanism has been established as the result of previous studies conducted at GE Power Generation. During the course of the oxidation a thin alumina-rich oxide scale forms at the specimen surface. The adjacent surface layer becomes depleted of gamma-prime as a function of the loss of aluminum. In addition, aluminum nitrides form primarily within the depleted zone, further lowering the amount of aluminum available to participate in the gamma-prime formation reaction. The metallographic examination of the test pins was conducted with this oxidation mechanism in mind.

For all of the material conditions a surface depleted zone was observed the depth of which varied considerably as a function of the material condition. The zone was characterized by the absence of gamma-prime particles and was somewhat depleted in chromium and aluminum. The extent of this loss of chromium and aluminum (thought to occur as a function of surface scale formation/spallation during environmental exposure) is considered an indication of resistance to environmental attack. A relatively thin depleted zone is considered more desirable than a thick depleted zone. Al-rich nitrides were also observed in the depleted zone. The results to-date indicate that desulfurized material exhibits superior environmental resistance to oxidation compared to standard N5. The beneficial effects become more apparent at higher temperature and longer exposure time. The results for the 4000 and 8000 hour tests at 2000 °F (shown in Table 3) include the sulfur levels as measured by glow-discharge mass spectrometry.

This table presents the average oxidation attack (defined as the metallographically measured depth of any internal oxides, nitrides and gamma-prime depletion at the surface due to the high temperature exposure) of duplicate test specimens tested at this condition. The results are expressed as a percentage of the non-desulfurized N5 alloy average oxidation attack which is taken as the baseline of 100%.

Table 3. 2000 °F Oxidation Results

Material Condition	Sulfur Content (ppm)	Oxidation[1] Attack	
A-N5 Baseline (Standard)	2.1	100	100
AH-Standard + H_2 Anneal	0.7	20	20
B-Desulfurized	0.4	20	25
BH-Desulfurized + H_2 Anneal	0.3	25	20

[1] Normalized Relative to Attack on Standard Alloy (Defined as 100%)

Examples of typical surface microstructures illustrating the appearance of surface depletion zones are shown in Figures 5 and 6 for the 2000 °F/8000 hour test condition. Figure 5 compares Condition A (standard alloy) with Condition B (melt desulfurized) while Figure 6 compares the oxidized surfaces of both conditions with the hydrogen desulfurization heat treatments.

From the Table 3 results and the appearance of the surface microstructures it is apparent that desulfurization offers a significant benefit to the oxidation resistance of the alloy. That the benefit is significant is manifested by the fact that the oxidation attack exhibited by the desulfurized samples is only approximately 20-25% of that exhibited by the non-desulfurized standard alloy.

It can also be concluded from the results to-date that the method of desulfurization is not critical to achieving the improvement in oxidation resistance. Whether desulfurization was accomplished by an annealing treatment in hydrogen or by melt desulfurization does not appear to be a critical process variable. Since hydrogen anneals are time consuming and expensive the results further suggest that melt desulfurization is a more economical method to accomplish the desired sulfur reductions. Finally, it was noted that superimposing a hydrogen anneal onto melt desulfurization did not result in a significant additional increment of benefit.

The results of the 1700 °F hot corrosion testing indicate no apparent trend with alloy sulfur content. There is a large amount of scatter in the data, with some samples showing significant amounts of attack in only a few hundred hours and others showing relatively little attack after 1000-2000 hours exposure. This scatter is common to all sample groups tested, including the non-desulfurized baseline alloy. Evaluation indicated it was not possible to distinguish between the different conditions given the severity of the test for this alloy system. It would appear that sulfur does not have any appreciable effect on the (poor) hot corrosion resistance of this alloy. Examples of typical cross-sections are shown in Figure 7 for AH (Standard N5 / H_2 Treatment) and BH (Desulfurized N5 / H_2 Treatment) specimens tested for 1000 hours at 1700°F. There appears to be less general attack and more unaffected pin material in the higher sulfur (AH) specimen. Observations such as these tend to make generalizing the effects of sulfur on corrosion somewhat difficult for these aggressive corrosion tests. At this point, therefore, the conclusion is that sulfur level has little influence on the hot corrosion resistance of N5 alloy under these particular, and fairly aggressive conditions.

Task 3 - SX Casting Process

Work was conducted on casting activities described in the plan of Figure 2 related to the cored bucket and included the evaluation of an additional eight casting molds and modeling.

Casting Trials. The casting trials all focused on the cored bucket configuration, the GE Power Generation 7EC Stage 1 Prototype Bucket, a complex cooled part approximately 15 inches long.

Each mold was constructed to yield three castings. The castings were oriented tip-down so that solidification initiated in the thinner cross section and proceeded upward into the thicker shank/root mass. Ceramic rods were selectively positioned to offer support to avoid mold cracking.

The castings were processed through the production routing including the various NDT characterizations.

TRIALS 1/2

Evaluation of the four Trial 1 molds (Mold Structural Integrity) and the initial two molds for Process Optimization (Trial 2) were reported previously. Trial 1 results indicated the presence of several different types of grain defects on the casting surfaces. These included (1) numerous columnar grains emerging from the single crystal starter, (2) freckle-chain equiaxed grains, and (3) groupings of other equiaxed grains in a more random pattern on the casting root surfaces and angel wing areas. The FPI revealed localized surface indications which were mainly in the form of irregularly shaped empty depressions or cavities. These indications were traced to core breakage. It was significant to note that no lacy dross or surface connected microshrinkage was revealed by the FPI operations. X-ray inspection failed to detect the presence of any subsurface defects. It was assessed that these X-ray results would meet anticipated specification criteria.

Trial 2 included a modified starter configuration in combination with selectively placed grain bars and resulted in considerable improvement in the grain quality. Freckle chain formation continued to occur but was limited to root surfaces where it is anticipated that finish machining will remove enough stock to eliminate the defects. Selective placement of grain bars in the angel wing areas significantly reduced the occurrence of spurious grains in these areas. Of major importance was the fact that modification of the starter configuration completely eliminated the multiple grains nucleating in this area. Some isolated columnar grains were still observed on the airfoil surfaces but these were traced to core print window locations at the tip of the bucket and not the starter. It was anticipated that improved wax dressing would eliminate their occurrence. Some columnar grains were seen to emerge from the platform and grow towards the root but it was expected that wrapping techniques would address this issue. The FPI and X-ray inspection results were similar to those reported for Trial 1. Surface indications were related to core break issues and X-ray failed to detect the presence of any subsurface defects.

TRIAL 3

Evaluations were conducted on the four Trial 3 molds cast as part of the Process Optimization effort. The casting procedures (mold/pour temperatures, withdrawal rates) for these molds were identical to those used for the initial optimization effort. A number of changes, however, were incorporated in the procedures used to prepare the molds and conduct the trial. These included (1) the use of single crystal seeds in the starter configuration for two of the molds (to assess control of secondary orientation), (2) selective positioning of mold wrap around grain bars and platform areas, (3) improved wax dressing in the core print window locations and (4) casting in a furnace configuration employing an alternative diameter susceptor.

The FPI and X-ray inspection results were similar to those reported previously for the initial trials. The readings were such that the castings would be acceptable relative to conventional reject criteria associated with industrial gas turbine components. No evidence of dross shrinkage was observed in the castings. Considerable improvement was also noted in the core break situation and these results will be discussed more fully in the Task 4 - Core Materials.

The grain read examinations indicated that grain quality was inferior to the two Trial 2 molds. There appeared to be little difference in overall quality as a function of the use of seed starters or the normal starter configuration. Selective positioning of platform mold wrap in conjunction with grain feed bars did not reduce the occurrence of spurious grains in the angel wing and platform areas. It was difficult to assess whether improved wax dressing in the core print window locations eliminated the isolated columnar grains previously observed on airfoil surfaces. These were traced to core print window locations at the tip of the starter and not the bucket. What was observed in Trial 3 was numerous columnar grains on the airfoil surfaces rather than simply isolated grains traceable to a single source. It appeared that these more numerous grains could not be traced to any single source such as a core print window.

Several examples of the typical grain condition observed in Trial 3 are shown in Figure 8. The casting on the left was poured in a mold featuring a seed starter while the casting on the right was poured in a mold featuring the normal starter configuration. Both castings exhibit numerous columnar grains in the airfoil which then extend into the shank portions of the buckets. Other grains can also be seen nucleating in the shank regions. At the extreme top of both castings (in the root base area) freckle chain grains can also be seen.

These results of the grain read examinations suggested that the furnace configuration change (alternative diameter susceptor) has a negative effect upon grain quality for the casting procedures used in this trial (i.e., mold/pour temperatures, withdrawal rates). The furnace configuration change was made in order to conform to other designs within the foundry (i.e., accomplish furnace standardization).

TRIAL 4

On the basis of Trial 3 an eight-mold designed experiment was conducted for the alternative diameter susceptor configuration. Designated Trial 4, a number of variables were intended to be evaluated including starter designs, concave platform feed/insulation, ramp profile, casting orientation and core positioning.

During mold preparation, however, four of the molds developed cracking to the extent that the molds could not be used for the casting trials. Because of this situation only 12 castings resulted from the molds which did not break (each mold yields three castings).

In spite of this, however, a number of observations were able to be made relative to these 12 castings. The FPI and X-ray inspection results were similar to those reported previously for the initial trials. The readings were such that the castings would be acceptable relative to conventional reject criteria associated with industrial gas turbine components. No evidence of dross or shrinkage was observed in the castings. The improvement in the core break tendency noted previously was maintained and these results will be discussed more fully in Task 4 - Core Materials.

The grain quality for Trial 4 was significantly improved relative to Trial 3 and was also improved relative to Trial 2, the initial Process Optimization trial. The first important observation was that improved baffle positioning eliminated all occurrences of freckle chain grains at the very bottom of the casting root faces. Prior to this, all of the previous castings exhibited these freckle chain grains on the root faces.

Other types of grain defects, however, were observed to nucleate in specific locations. Platform corners and overhangs appeared to be a particular problem with equiaxed grains being observed to nucleate in these areas. It was significant to note, however, that feed bars were helpful in minimizing the problem. Nine of the castings had bars feeding the concave platform and none of these castings exhibited grain nucleation in these areas. Three of the castings had insulating wrap at the concave platform and one of these castings exhibited grain nucleation in this area. This suggests that feed bars in the platform area are more effective in eliminating grain nucleation on the concave platform. The situation was different for the convex platform corners. Neither feed bars nor insulating wrap were used on the convex platform and in 10 / 12 castings grains were seen to nucleate in these areas. Clearly, this situation also calls for the placement of feed bars at the convex platforms.

One other grain problem was noted and that was nucleation of a grain at the ceramic rod supporting the grain selector ramp. This was observed in 3 / 12 pieces and these grains grew in a columnar manner into the airfoil and root of the castings. At the point of nucleation in each case metal flash was present at the junction where the support rod emerges from the mold shell. This suggests the possibility that thermal expansion / contraction differences between the ceramic support rod and shell system may form a gap during mold fire. During the casting operation this gap would fill with metal forming a thin flash which might nucleate a grain because of thermal gradient anomalies at the flash site. Aside from the above grain observations, none of the other system variables indicated any other significant trends relative to the grain results.

Several examples of the typical grain condition observed in this latest trial are shown in Figure 9. The casting on the left exhibits a columnar grain (which nucleated at the ceramic support rod) running its entire length while the casting on the right exhibits no grain defects along the airfoil. Neither casting exhibit freckle chain grains in the root base area.

On the basis of these results activity was initiated for the next Process Optimization mold trial (Trial 5). The trial will incorporate results from Trial 4 and will investigate several variables (grain selector design and convex platform feed bars). Prior to beginning casting Trial 5, mold dipping experiments will be conducted on solid wax patterns, with no cores, to develop more robust mold configurations.

Modeling. Modeling activity continues to be based upon the 3-D solid model of the initial cluster configuration generated in Unigraphics using 2-D electronic part data as a starting point. The model was built as one sector of the three-piece cluster and includes the part with core, gating, ramp, starter, pour cup, downpole and plate geometry. A 2-D model of the surrounding furnace was also generated, as well as the scalloped baffling system. The solid model was then enmeshed to obtain a tetrahedral finite element model used for solidification analysis. The use of cyclic symmetry was employed in the analysis so that all three castings on the cluster were mathematically present during the thermal analysis.

Earlier baseline simulations were completed which identified two specific areas of concern. First, the solidification pattern indicated that the angel wing and root platform areas of the casting were potential grain nucleation sites, with a potential boundary developing on the concave side of the platform. Secondly, the starter, ramp, and tip areas were solidifying below the baffle, when ideally solidification should occur further up into the hot susceptor zone in order to ensure a better start for single crystal solidification. The baseline simulation predictions were validated by the initial casting trial results, and, as stated earlier in this section, significant changes were made in Trial 2 which addressed these issues.

In order to assist in the analysis of the Trial 3 and 4 castings as well as subsequent trials work was conducted to evaluate the solidification effect of changing susceptor configuration. Towards this end a new solidification model of the latest casting/furnace configuration was generated and verified. This model encompasses the modification in susceptor geometry. A simulation matrix was established which addresses both typical processing parameters as well as susceptor thermal profiles and their effect upon solidification. In order to validate the modeling assumptions being made for the susceptor profiles, thermocouple results for a representative industrial gas turbine bucket were obtained and compared back to the model-predicted profiles. Adjustments to the susceptor temperature calculations have been incorporated. Simulations are being used to help identify the appropriate process conditions which would result in solidification profiles comparable to those seen in the latest trials cast with the new furnace geometry. These conditions would then be applied in order to improve overall grain yield. A typical example of the computer output generated through this modeling effort is shown in Figure 10, which highlights predicted platform grain nucleation areas.

Task 4 - Core Materials

Work was conducted on planned Task 4 activities and included evaluation of core body performance during casting trials. The preferred manufacturing method for the large cores needed for the prototype configuration is the low pressure method.

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.

As a result of the evaluation of a number of silica based core compositions the PCC SRI 200-SXA core body was selected for initial casting trials.

As previously mentioned in the Task 3 - SX Casting Process discussions the occurrence of core break was consistently observed throughout casting Trials 1 and 2. Core break indications were observed during FPI and X-ray inspection operations. In FPI the indications appear as surface connected cavities. The cavities result when broken core pieces float in the metal and become attached to the mold surface. During the core removal process these pieces are leached out resulting in the surface connected cavities. In X-ray the core break appears as indication sites on the X-ray film.

Examination of the cores indicated that cracking was observed predominantly in three locations during removal from the core die or during wax injection and these are shown schematically in Figure 11. In the majority of cases cracking was limited to the fine webs forming the trailing edge cooling slots. To a less significant degree some cracking was also observed at the leading edge core center and the passage chutes near the junction of the airfoil and shank portions of the core. As mentioned previously hand filling wax between the webs prior to injection and patching alleviated these cracks. Since all wax patterns are X-ray inspected prior to mold assembly it could be concluded that the core break observed within the castings was the result of (1) undetected cracks forming during wax injection, (2) cracks propagating from patch areas, and (3) cracks caused by the impact of turbulent metal flow during filling of the mold cavity.

Given the previous observation that molten wax (during wax injection) can cause cracking in the fine webs forming the trailing edge cooling slots it seems reasonable to assume that turbulent metal flow during mold fill could have a similar result. In addition to the trailing edge slots it is possible that the passage chutes could also be prone to this type of cracking.

For the subsequent casting trials planned for Task 3 - SX Casting Process efforts focused on eliminating the core break problem. Selective strengthening devices were incorporated in the trailing edge slot and the passage chute areas. In the trailing edge slots, vertical exit ties connect between the individual core segments making up the slots thus reinforcing the general area. The exit ties are features which can be incorporated by modifying the core tool. Quartz rods were positioned in the passage chutes to reinforce these areas.

In addition to addressing core break issues, activity was directed towards an assessment of the core body itself being used for the bucket castings. A review was conducted of the core making procedures and a decision was made to evaluate low pressure cores produced by Lake Erie Design (LED). These cores, designated as ICCP, consist of 80% SiO_2/20% $ZrSiO_4$ and have been used successfully for the production of equiaxed, DS-columnar grained and single crystal nickel-based superalloy castings. In particular, LED has had success in the production of cores for large size castings for land-based applications including the practice of selectively strengthening crack-prone regions in the various core configurations.

The preliminary assessments of the ICCP core body performance during Trials 3 and 4 indicate significant reductions in the levels of observed core breakage. It is believed that the combination of the ICCP core body plus modification of the core die tool (employing trailing edge exit ties) contributed to this improvement. In Trial 4, for example, it was noted that the yield from wax injection X-ray was 95% with no core break. Of the 12 blades actually cast in Trial 4, 9 of the cores showed no evidence of core break on the casting X-ray (a yield of 75%). The three cores exhibiting core break indicated that cracks were limited to the passages connecting the tip plenum to the main body of the core. Efforts for subsequent trials will focus on resolving the cracking in these areas.

Task 5 - Grain Orientation Control

Work was conducted on the planned Task 5 activities. The objective of this task is to provide data to enable decisions to be made concerning the establishment of grain limit defect criteria. The planned testing will employ the use of cast specimens containing grain defects which will be low cycle fatigue tested at conditions critical to the root sections where fatigue life margin has been reduced. Defects will include high angle boundaries, freckles, and porosity. Specimens with no defects will provide baseline information.

A review was made of the castings produced as part of the casting trials and a selection was made as to which would be appropriate for machining into specimens for the LCF tests. A total of six castings were selected and the castings are at GE Power Generation for machining into test specimen configurations and LCF testing.

Benefits

The anticipated program benefits include the definition of cost effective methods to produce large SX airfoil castings for land base power generation applications. These achievements 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.

An additional benefit which has been identified includes the demonstration of a new low cost process developed to remove sulfur from high temperature superalloys. The presence of sulfur as a contaminant in the metal causes the protective oxide (which normally forms during service) to flake/spall off, resulting in increased exposure to extreme conditions for the base metal. Reducing the sulfur content significantly decreases damage to the protective outer layer. Currently, the sulfur is removed by hydrogen annealing of the blades after the casting process. Through the melt desulfurization process demonstrated in the Turbine Airfoil Manufacturing Technology program, sulfur contents have been reduced to levels comparable to those achieved through heat treatment at significantly reduced costs. As a consequence of this, oxidation resistance for the melt desulfurized condition are also comparable to those for hydrogen treated material. This type of benefit will result in lower equipment costs for industry and electrical costs for consumers. This enhanced environmental resistance also represents a potential benefit to the aircraft industry, which has traditionally been the focal point for advances in gas turbine engine technology.

FUTURE ACTIVITIES

Future activities can be identified in the Program Schedule shown in Contract Information. During the upcoming year of effort the alloy melt practice activity will be continued as will development work in the SX casting process for the cored buckets and nozzles, core material work and testing involving LCF of specimens containing grain defects.

Task 2
Alloy Melt Practice

- Ingot Preparation
- Mold Preparation
- Hydrogen Heat Treatment
- GE-Rig Testing

Figure 1. Work Breakdown Structure for Task 2 — Alloy Melt Practice

Task 3
Modification/Improvement of SX Casting Process

- Cored Bucket Configuration
  - Trial 1 Mold Structural Integrity
  - Trials 2-7 Process Optimization
  - Trial 3 Process Verification
- Cored Nozzle Configuration
  - Trial 1 Mold Structural Integrity
  - Trials 2/3 Process Refinement

Figure 2. Work Breakdown Structure for Task 3 — Modification/Improvement of SX Casting Process

Task 4
Core Materials and Design

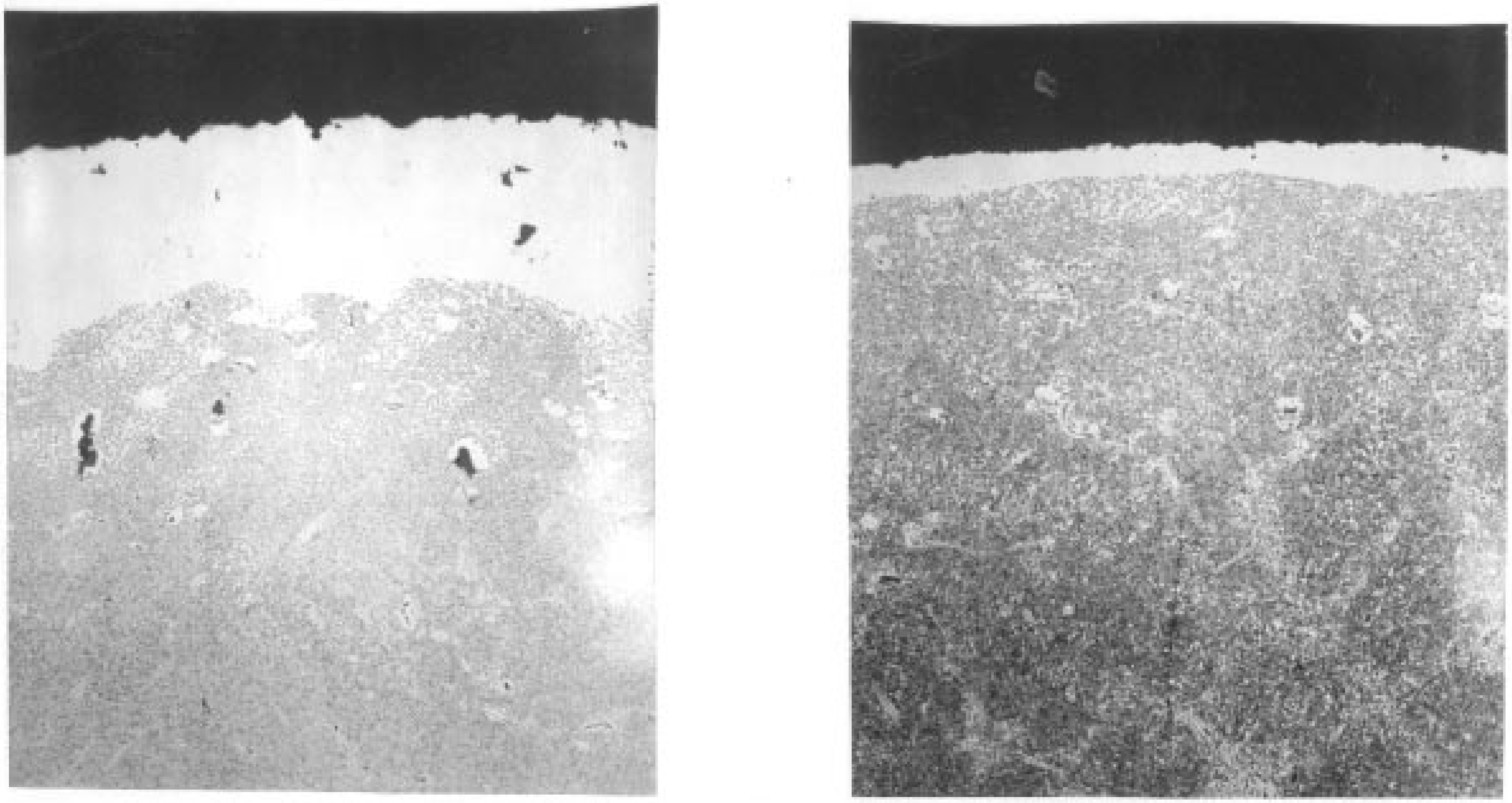
- Core Body Characterization
- Optimum Core Processing

Figure 3. Work Breakdown Structure for Task 4 — Core Materials and Design

Task 5
Grain Orientation Control

- Specimen Preparation
- 1000 °F LCF Tests
- 1200 °F LCF Tests
- Post Test Chacterization

Figure 4. Work Breakdown Structure for Task 5 — Grain Orientation Control



Condition A **Condition B**

Figure 5. Surface Depletion Zones Observed in Condition A (Standard N5) and Condition B (Melt Desulfurized) N5 Alloy After 2000 °F/8000 Hours Testing, 200X Magnification

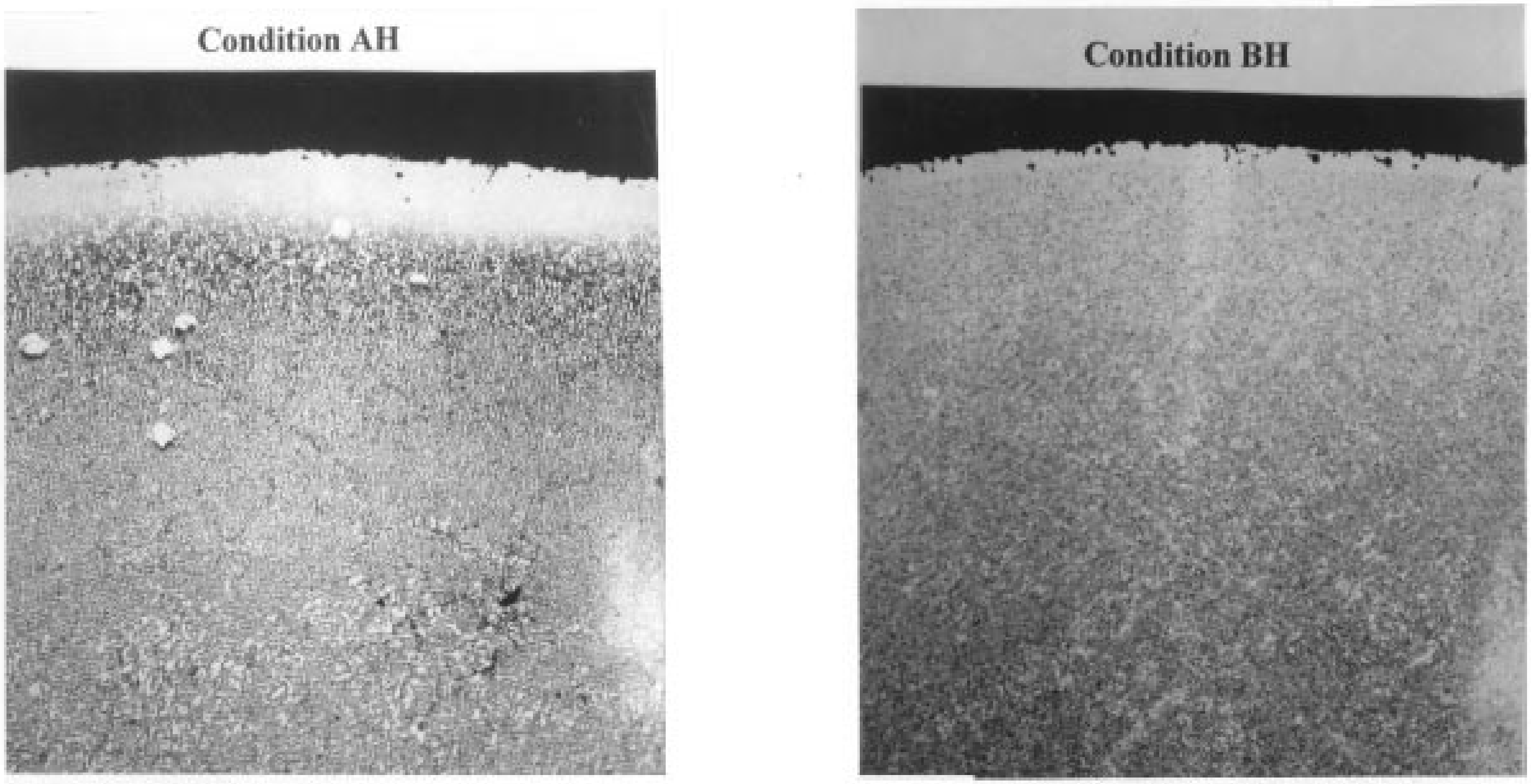


Figure 6. Surface Depletion Zones Observed in Condition AH (Standard N5 + Hydrogen Heat Treatment) and Condition BH (Melt Desulfurized + Hydrogen Heat Treatment) N5 Alloy After 2000 °F/8000 Hours Oxidation Testing, 200X Magnification

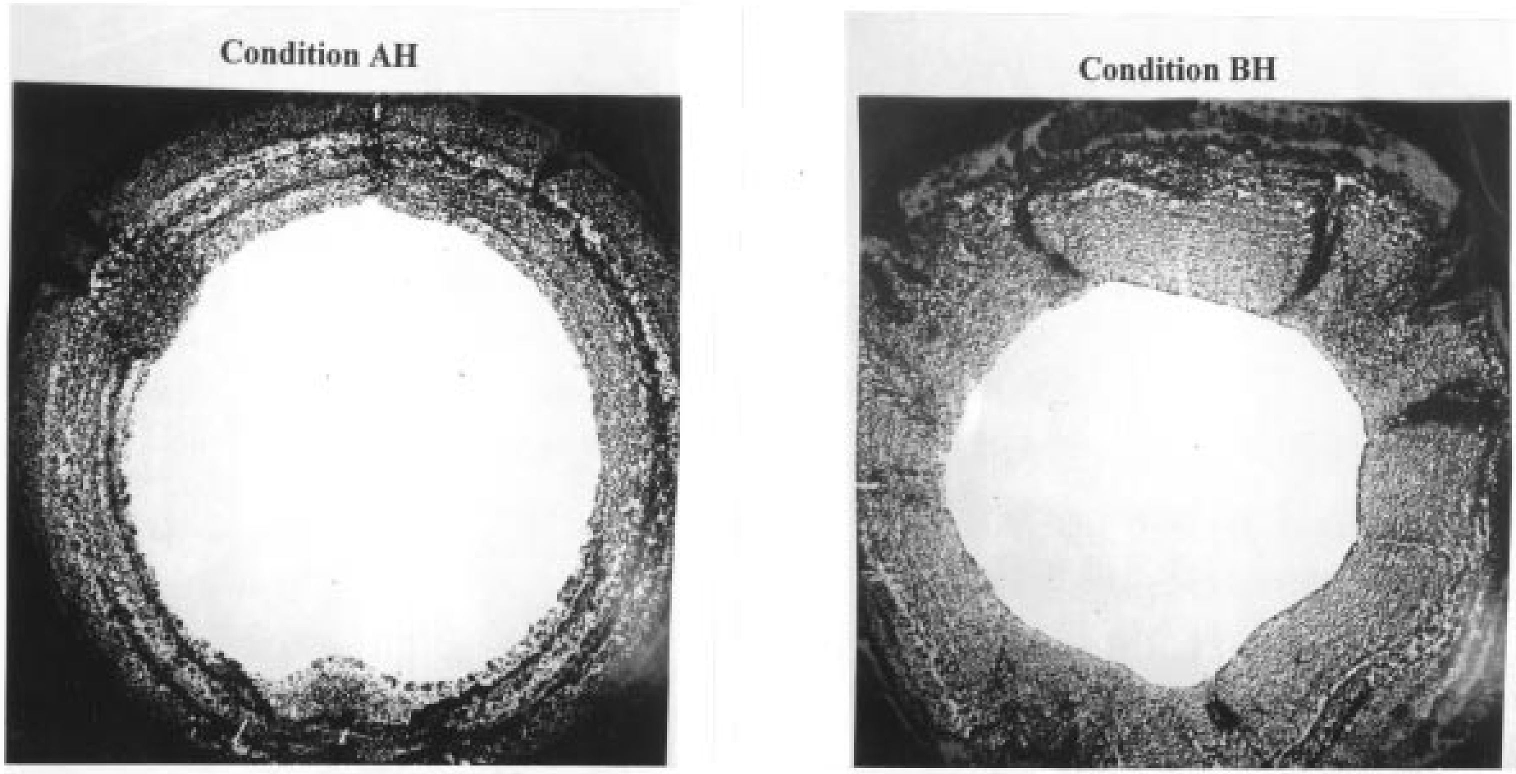


Figure 7. Typical Cross Section Appearance of Corrosion Pins Tested for 1000 Hours at 1700 °F, 40 ppm Na, 1% S, 35X Magnification

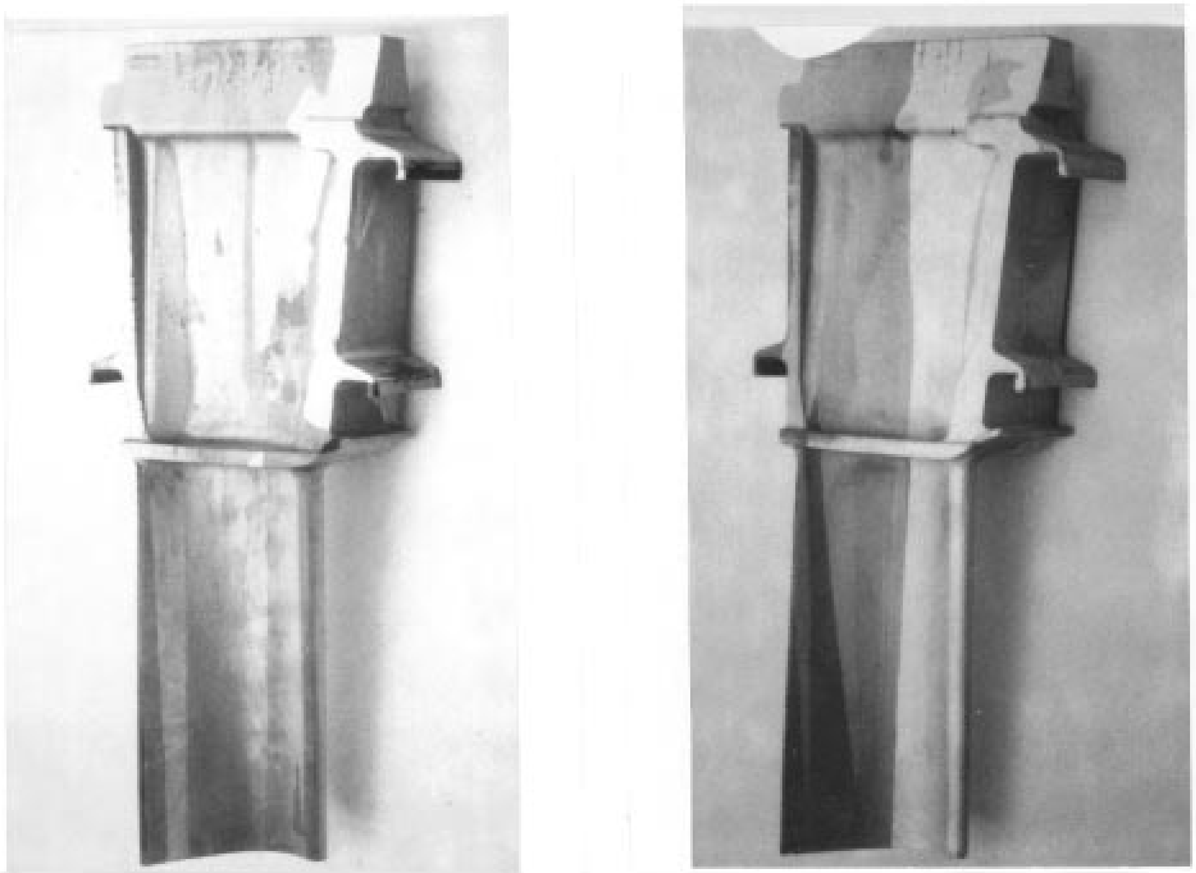


Figure 8. Typical Grain Condition Observed on Surfaces of 7EC Stage 1 Prototype Buckets Poured with Seed Starter (Left) and Normal Starter (Right) in Trial 3

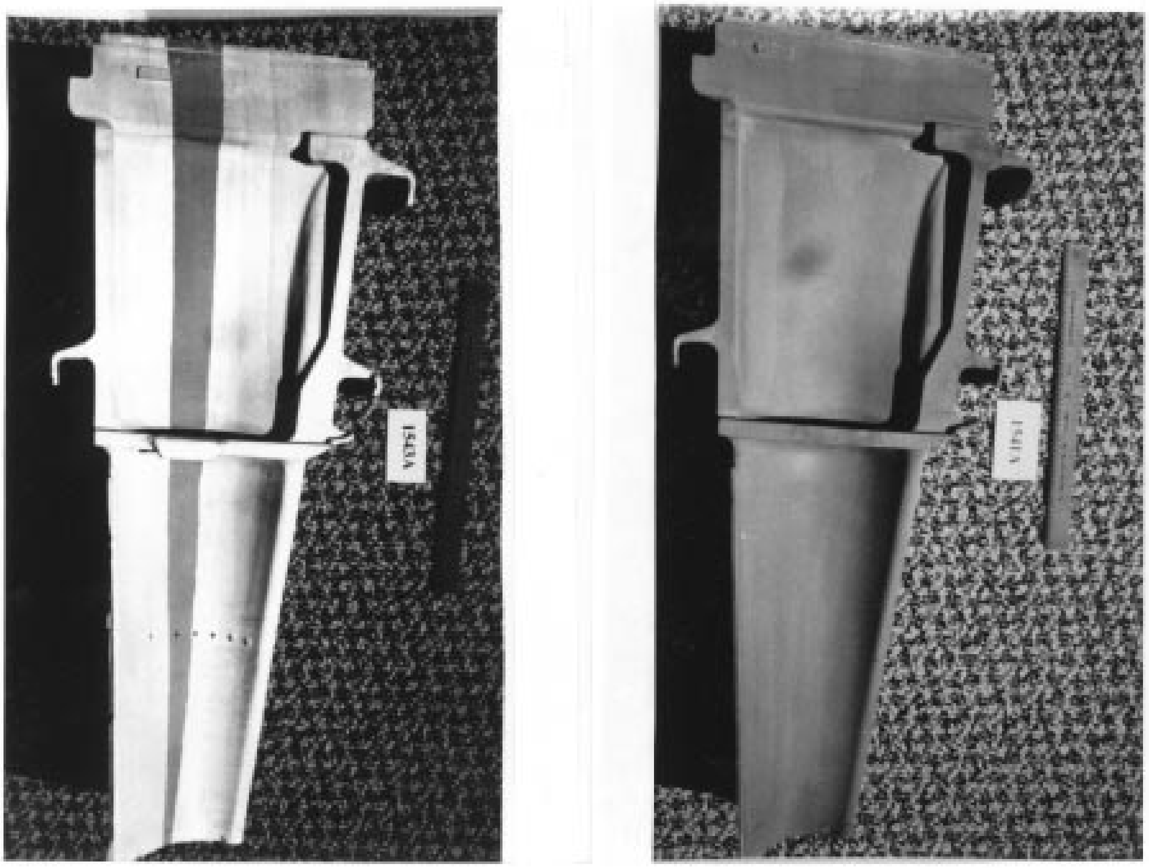


Figure 9. Typical Grain Condition Observed in Surfaces of 7EC Stage 1 Prototype Buckets Poured in Trial 4

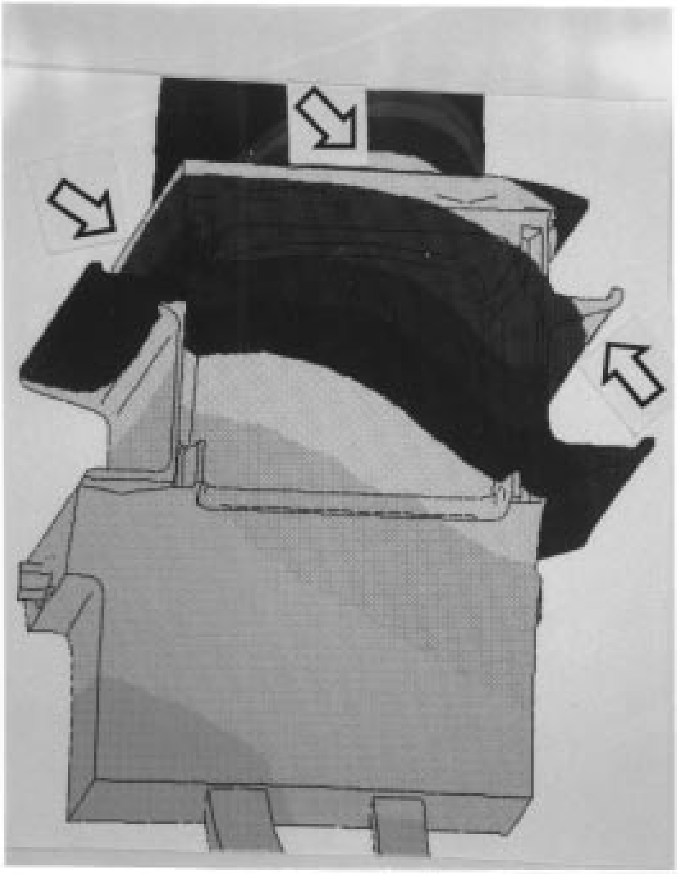


Figure 10. Potential Angel Wing/Platform Grain Nucleation Sights

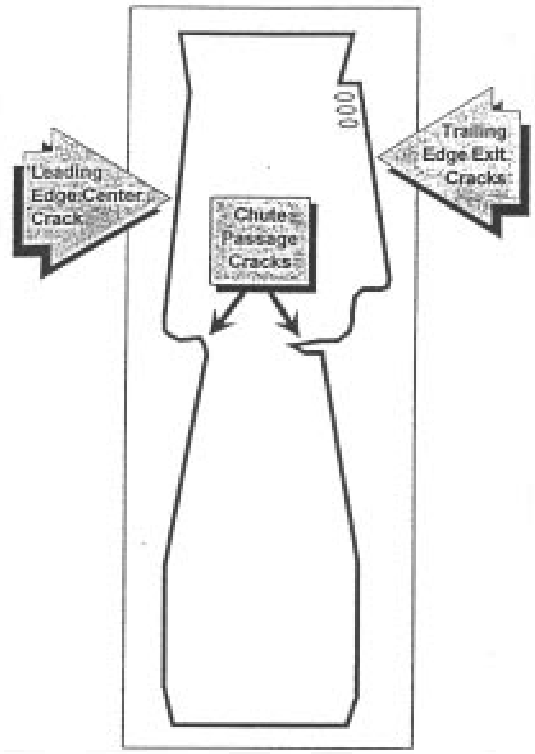


Figure 11. Schematic Diagram of Ceramic Core Showing Crack Locations Observed During Core Ejection or Wax Injection