Turbine Airfoil Manufacturing Technology

CONTRACT INFORMATION

Contract Number	DE-AC05-84OR21400
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Period of Performance	February 20, 1995 to June 30, 1999
Schedule and Milestones	Program was completed June 30, 1999

OBJECTIVES

The program objective was 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 formed the task structure of the program and included 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.

BACKGROUND INFORMATION

The efficiency and effectiveness of the gas turbine engine are 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 for 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-cored 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 was conducted by PCC Airfoils, Inc./General Electric Power Systems Group which envisioned using the available methods for producing SX airfoils and scaling them up to much larger land-base components.

PROJECT DESCRIPTION

The Program comprised five tasks which included a planning task (Task 1) and four tasks (2-5) of technical effort. The program was completed in June 1999.

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 were studied - a baseline composition with no desulfurization, a desulfurization condition using the PCC alloy desulfurization method, and both of these conditions to which hydrogen anneals were applied. Two coated conditions were also evaluated in the testing including the baseline material without desulfurization and the melt desulfurized material. No hydrogen anneals were applied to these materials and both were diffusion aluminide-coated. Each of these conditions were tested on specimens in GE Power Systems cyclic oxidation and corrosion test rigs.

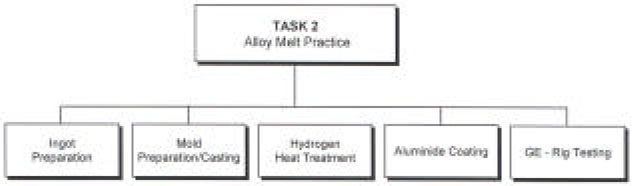


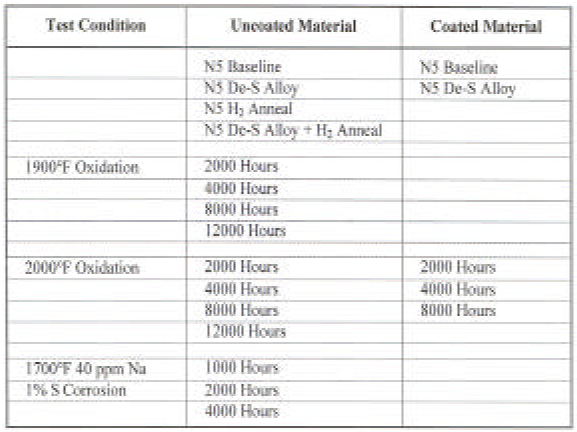
Figure 1. Work Breakdown Structure for Task 2 Alloy Melt Practice

Ingot preparation included 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 were produced. The desulfurization was accomplished in the melting operation with the sulfur aim being less than 0.5 parts per million (ppm).

Mold preparation employed molds configured such that 24 pins each 0.180 inches in diameter by 6 inches long were produced and these pins were then cropped to the desired length for the GE tests. The cast pins were solution heat treated to homogenize the structure and one half the pins were given a hydrogen heat treatment to further reduce sulfur levels.

Rig testing including oxidation and hot corrosion tests were conducted as per the test matrix shown in Table 1.

Table 1
Test Plan to Evaluate Desulfurization



Test Condition	Uncoated Material	Coated Material
	N5 Baseline	N5 Baseline
	N5 De-S Alloy	N5 De-S Alloy
	N5 H_2 Anneal	
	N5 De-S Alloy + H_2 Anneal	
1900°F Oxidation	2000 Hours	
	4000 Hours	
	8000 Hours	
	12000 Hours	
2000°F Oxidation	2000 Hours	2000 Hours
	4000 Hours	4000 Hours
	8000 Hours	8000 Hours
	12000 Hours	
1700°F 40 ppm Na	1000 Hours	
1% S Corrosion	2000 Hours	
	4000 Hours	

Task 3 - SX Casting Process

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

Efforts for the bucket encompassed a total of nine mold trials. Thermal simulation modeling was conducted in conjunction with the trials to establish the effects of important casting variables. The initial trial addressed mold structural integrity including survivability during the casting process. Subsequent trials addressed process optimization with variables being selected as a result of earlier trial activity. The final trial addressed process verification 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 encompassed one mold trial. The activity was directed towards mold structural integrity and process refinement.

The castings resulting from the trials were subjected to thorough evaluations including NDT, chemistry, microstructural characterizations, and selected mechanical property testing.

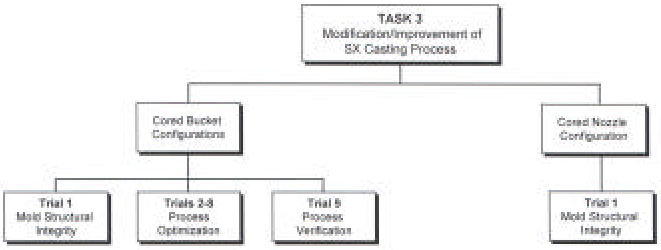


Figure 2. Work Breakdown Structure for Task 3 Modification/Improvement of SX Casting Process

Task 4 - Core Materials

Core Material activity is shown in Figure 3. Core body characterization involved an evaluation of a number of silica-based core compositions available for application to the SX casting process. Cores were processed and evaluated for a number of characteristics including shrinkage, modulus of rupture, stability, and porosity. The characterization data on the various core bodies was analyzed and a downselection was made for the initial casting trials. As part of the casting trials, evaluations of core performance were conducted including resistance to core/metal reactions, stability, additional shrinkage during the casting process and core removal kinetics. Assessments of this core performance were made for the selection of cores required for the subsequent casting trials.

Optimized core processing included the manufacture of cores for the subsequent casting trials and was evaluated for the same characteristics established during core body characterization.

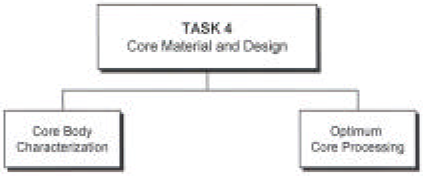


Figure 3. Work breakdown Structure for Task 4 – Core Materials and Design

Task 5 - Grain Orientation Control

Grain Orientation Control activity is shown in Figure 4 and included tensile, stress rupture and LCF testing of cast specimens containing defects. Defects included high and low angle boundaries and freckles. Specimens with no defects provided baseline information. The LCF test plan is shown in Table 2.

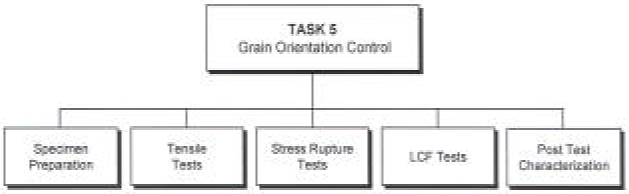


Figure 4. Work breakdown Structure for Task 5 - Grain Orientation Control

Table 2
Test Plan to Evaluate Grain Orientation Control

Tensile/Stress Rupture Test Plan

Defect Type	Defect Parameter	Tensile Tests Room Temperature/1400°F	Stress Rupture Tests 1600°F/80 ksi/1800°F 40 ksi
LAB	$\theta \approx 5.5°$	1/1	1/1
LAB	$\theta \approx 8.4°$	1/1	1/1
HAB	$\theta = 19.9°$	2/2	2/2
HAB	$\theta = 43.7°$	1/1	1/1
HAB	$\theta = 44.6°$	1/1	1/1

LCF Test Plan

Defect Type	Defect Parameter	Level 1 Temperature	Level 2 Temperature	A-Ratio	Specimen Type
LAB	$\theta = 11.0°$	4	2	-1	Round Bar
LAB	$\theta = 12.7°$	3	2	-1	Round Bar
HAB	$\theta = 20.6°$	3	3	-1	Round Bar
HAB	$\theta = 22.0°$	3	2	-1	Round Bar
HAB	$\theta = 31.0°$	2	2	-1	Round Bar
HAB	$\theta = 32.3°$	4	3	-1	Round Bar
Freckle	0.06-inch diameter	5	1	-1	Sheet
Baseline	Nominally defect-free	2	2	-1	Sheet
Freckle	0.06-inch diameter	-	6	1	Sheet
Baseline	Nominally defect-free	-	5	1	Sheet

Note
[1] *q -refers to a mismatch angle of LAB or HAB.*
[2] *Numbers represent quantity of tests.*

RESULTS

Task 2 - Alloy Melt Practice

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. Two desulfurized ingots were produced using the practice of reducing sulfur during the melting operation.

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.

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. 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.

Table 3 shown below lists the various material conditions included as part of this evaluation. The table also lists the sulfur levels for the conditions as measured by glow-discharge mass spectrometry. Note that two types of specimens are listed for the desulfurized conditions, B with a sulfur level of 0.8 ppm and B2 with a sulfur level of 0.4 ppm. Both conditions were included in order to evaluate desulfurized heats with a range of sulfur content.

Table 3. Test Material Used in Oxidation Tests

Material Condition			Sulfur content (ppm)
A	-	N5 Baseline (Standard)	2.1
AH	-	Standard + H_2 Anneal	0.7
B	-	Desulfurized	0.8
B_2	-	Desulfurized	0.4
BH	-	Desulfurized + H_2 Anneal	0.3

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

Each rig consisted of a tube inside a tube furnace, with an atomizing fuel nozzle at one end and an exhaust at the other. Atomized fuel was combined with air in the combustion chamber and burned, resulting in hot gases which flowed past a double beam fixture suspending test samples in the hot gas stream. Up to 12 pin or disk samples can be housed in a sample fixture.

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

Uncoated Oxidation Results. The N5 (without yttrium) oxidation mechanism has been established as the result of previous studies conducted at GE Power Systems. 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.

Upon completion of the environmental tests, the oxidation pins were examined metallograhically for the extent of surface depleted zone. Measurements were made of the maximum depth of penetration and the results of all tests (both uncoated and coated) are shown graphically in Figure 5.

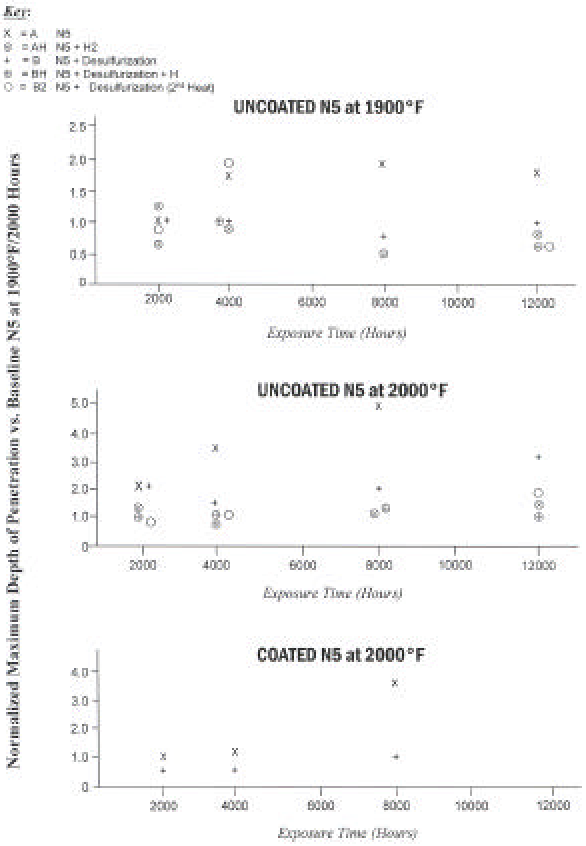


Figure 5 – Burner rig oxidation test results

The results are normalized relative to the deepest attack observed for Baseline N5 (Condition A) exposed 1900°F/2000 hours. This measurement is thus reported as “1” and all other measurements are reported relative to it. These plots of maximum penetration enable direct comparisons to be made between the various conditions for both uncoated and coated material. The data indicated there was scatter and variability in maximum depth of penetration observed for specific temperatures/times. Because of this scatter situation the absolute amount of attack measured in inches is not as meaningful as the overall relative comparison of trends between materials. On this relative basis then, the results are consistent with a general trend that reducing sulfur to levels below 1 ppm improves oxidation resistance for all materials/test conditions.

The results for the 1900° tests indicate little significant improvement in oxidation resistance at the 2000 hour test interval. At 4000 hours and longer, the beneficial effect of desulfurization becomes more apparent with the maximum depth of penetration only approximately 50% of that seen for the baseline material. Data were unavailable for several conditions at 8000 hours but the limited testing which was conducted supports the general observations of the benefits of desulfurization. In addition, there appears to be little significant benefit by applying a hydrogen heat treatment to melt desulfurized material. The beneficial effect of desulfurization can be seen in terms of a thinner surface depletion layer. These results suggest improved resistance to 1900°F oxidation for all conditions where the sulfur level is below 1 ppm.

The results for the 2000°F tests were somewhat different in that a significant benefit was discerned immediately at the shorter 2000 hour exposure time. The beneficial effect became more significant at longer times with maximum depths of penetration less than 50% of that seen for the baseline material. Unfortunately, baseline material was not available for the 12,000 hour test to enable comparisons to be made. Comparisons with hydrogen heat treated baseline, however, indicated the same types of trends. Typical microstructures of oxidation pins exposed at 2000°F/12,000 hours are shown in Figure 6.

Again, the beneficial effect can be manifested by a thinner surface layer. Similar to the 1900°F results, the 2000°F results suggest improved oxidation resistance for all conditions where the sulfur level is below 1 ppm.

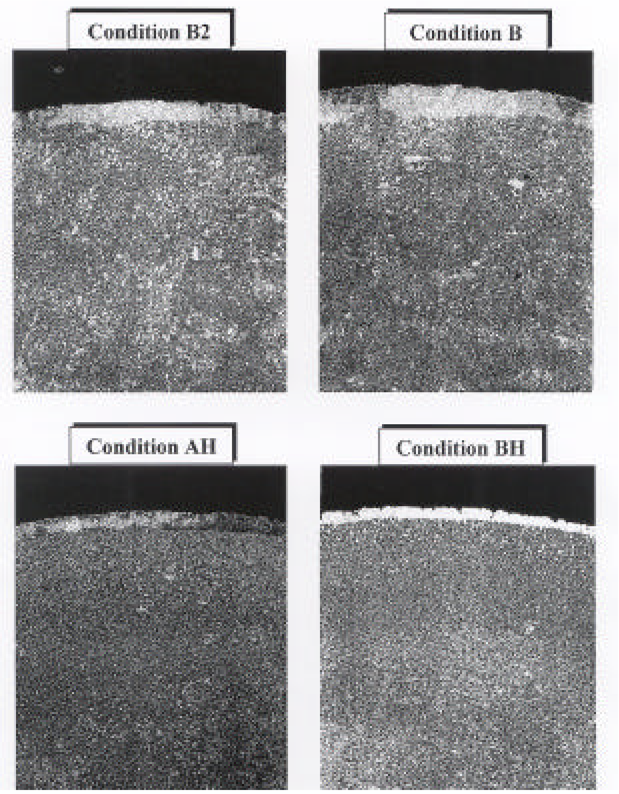


Figure 6 – Typical microstructures of uncoated N5 oxidation pins exposed 2000°F/12000 hours. 200X

Coated Oxidation Results. Both Baseline N5 (Condition A) and melt desulfurized (Condition B) material were subjected to 2000°F oxidation testing out to 8000 hours exposure. For coated materials surface attack consists of formation/spallation of oxide layers on the outer surfaces of the coating as well as general or overall reduction in coating thickness. This is measured by preparation of transverse metallurgical mounts to reveal the test pin in cross section. Measurements of the minimum diameter of the cross section (including the coating layer) unaffected by the attack are then made and compared to the original total diameter of the untested pin. The specimen diameter is thus reduced as a function of either the presence of oxide layers (which are not included in the measurement) or their absence due to spallation during the test.

The results of the measurements of the coated oxidation specimens are shown graphically in Figure 5. Again, these results are normalized relative to the deepest attack observed for uncoated Baseline N5 (Condition A) exposed 1900°F/2000 hours. These results for the coated test pins confirm the beneficial effects of desulfurization observed for uncoated material and are consistent with the previous trend for uncoated material in that melt desulfurization improves oxidation resistance at all exposure times. The benefit of melt desulfurization is evident after only 2000 hours of exposure and is manifested in terms of less overall surface attack. This pattern of improvement in oxidation resistance continues to the longer exposure times and increases in magnitude. At the 8000 hour exposure, for example the depth of attack for desulfurized material is only approximately 30% that of the Baseline N5. Typical microstructures of coated oxidation pins exposed at 2000°F/4000 and 8000 hours are shown in Figure 7. The beneficial effect of desulfurization can be seen in terms of a thinner surface depletion layer.

Viewing these results with a different perspective it can be seen that employing desulfurized material in combination with coating further enhances the effectiveness of the coating itself in providing improved environmental resistance particularly at the longer exposure time. With a more adherent protective alumina formed on the surface of the nickel aluminide, significantly less spallation/reformation of the surface oxide occurs resulting in a more stable structure relative to gamma' decomposition.

Uncoated Corrosion Results. Planned exposures were to reach a 4000 hour maximum but most of the specimens were pulled from the corrosion rigs in shorter times because of the condition of the specimens. The longest times ranged from 3600 - 3800 hours exposure. The

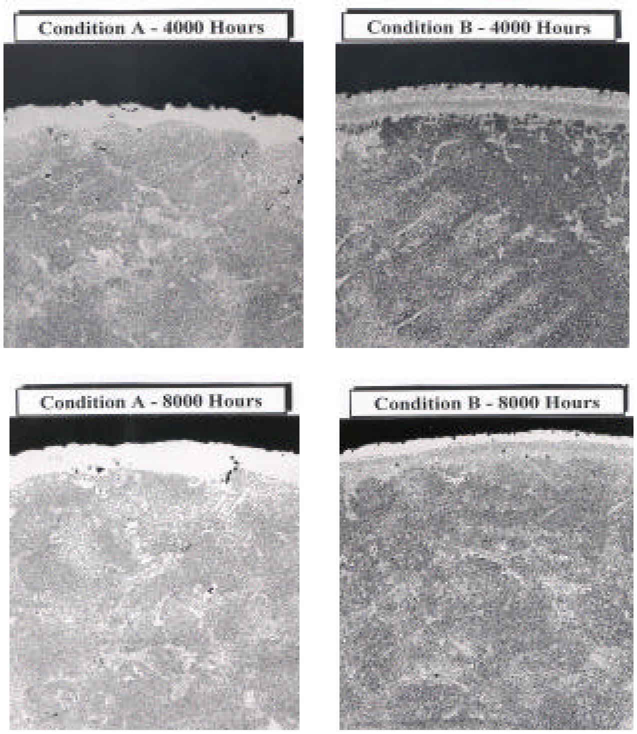


Figure 7 – Typical microstructures of aluminide-coated N5 oxidation pins exposed for 4000/8000 hours.

specimens exhibited a moderate to heavy corrosion attack. Metallographic evaluations were completed and revealed considerable scatter in the attack exhibited by the specimens. Within this scatter in the data, some samples showed significant amounts of attack in only a few hundred hours and others showed relatively little attack after 1000 - 2000 hours exposure. This scatter was common to all sample groups tested, including the non-desulfurized baseline alloy. A relationship, however, was observed between maximum depth of observed penetration attack and material condition and this is shown in Figure 8. Similar to the oxidation situation, desulfurization appears to have a beneficial effect upon corrosion resistance as well.

In spite of this relationship, however, the degree of scatter 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. This situation tends 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.

Test Material Used in Corrosion Tests

		Material Condition	Sulfur content (ppm)
A	-	N5 Baseline (Standard)	2.1
AH	-	Standard + H_2 Anneal	0.7
B	-	Desulfurized	0.8
B_2	-	Desulfurized	0.4
BH	-	Desulfurized + H_2 Anneal	0.3

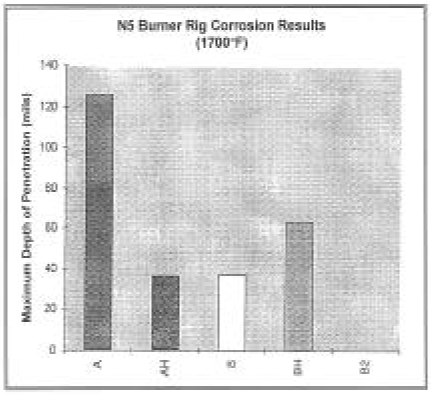


Figure 8 – 1700°F Corrosion Results (Uncoated Specimens)

Summary

Oxidation testing of uncoated and aluminide-coated N5 (without yttrium) test pins at 1900°F and 2000°F has shown that reducing sulfur to levels below 1 ppm results in significantly improved oxidation resistance compared to baseline material (sulfur level of 2.1 ppm). Further, the method of achieving the reduced sulfur was not critical to achieving the improvement in oxidation resistance. Whether desulfurization was accomplished by metal melt practice or by a hydrogen annealing heat treatment did not appear to be significant processing variables. Finally, it was noted that superimposing a hydrogen anneal onto melt practice desulfurization did not result in a significant increment of benefit. Since hydrogen anneals are time-consuming and expensive, the results suggest that melt desulfurization is a more economical method to accomplish the desired sulfur reductions.

Hot-corrosion testing of uncoated N5 (without yttrium) test pins at 1700°F indicated no apparent trend with alloy sulfur content. There was 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 1000-4000 hours exposure. At this point, the results suggest that sulfur level has little influence on the 1700°F hot corrosion resistance of the N5 alloy under these particular conditions.

Task 3 - SX Casting Process

SX casting activity focused on several cored bucket configurations including the GE 7EC, 6FA, and 7FA Stage 1 Buckets and the 7H Stage 1 Nozzle. These are all complex-cooled configurations ranging in size from approximately 10-15 inches which exhibit the general types of features (complex internal cores, overall length and width and complexity of airfoil contours) that anticipate the types of designs planned for the ATS. These were thus considered to be appropriate configurations to expand the capability range for complex-cored SX airfoils for land-based turbine systems.

Casting Trials. Each mold was constructed to yield 1-7 castings depending upon the specific configuration. 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 minimize/avoid mold cracking. The castings were processed through the production routing including the various NDT characterizations.

7EC Stage 1 Prototype Bucket

The series of five casting trials involved with the 7EC Prototype Bucket configuration identified acceptable mold temperature, metal temperature and withdrawal rates. The casting parameters resulted in no randomly-nucleated equiaxed grains nucleating from the solidification process. This indicated the casting process itself offered reasonable consistency. Additionally, with these parameters and optimized baffling configurations, freckles were eliminated from the casting surfaces. Localized grain defects have been observed, however, and platform corners and overhangs appear to be particularly sensitive to nucleation in these areas. It was established that grain feeds are preferred to insulation wrapping to eliminate separately nucleated grains in these areas but optimization, however, is required to establish exact placement of the feeds. One other type of grain problem was noted and that was isolated nucleation in the grain selector ramp areas. Using alternative types of support rods in the ramp area reduced the number of these nucleations but they were not completely eliminated. Finally, the trials have resulted in castings free of FPI or X-Ray detectable defects such as dross or porosity. All of this supports the belief that the SX process can be successfully scaled-up to produce 7EC Stage 1 Bucket types of configurations.

It was assessed, however, that because of certain limitations, other configurations would be more suitable to complete the casting process work. These limitations were associated with the fact that the 7EC tooling was prototype in nature. As a prototype, the core die tooling was never a finalized tool. As a consequence, satisfactory core production was somewhat limited and at times subject to core ejection difficulties. In addition, there were trailing edge core break and core stability concerns and it would be difficult to firmly establish dimensional success. Since hard production tooling became available for two other configurations and because of the 7EC limitations, a decision was made to terminate activity with this configuration. The two alternative configurations are the GE 6FA and 7FA Stage 1 Buckets. The 6FA (approximately 10 inches long) and the 7FA (approximately 14 inches long) are both representative of the class of large land-based turbine components anticipated for ATS applications.

6FA Stage 1 Bucket

Casting activity for the 6FA Prototype Bucket was designated as Trial 6 and involved a total of four molds. Two of the molds were configured to yield 7 castings while the other two were to yield 5 castings for a total of 24 casting for this trial. In addition to cluster size, the other variable included in this trial was baffle design in which a cluster of each size was produced with both the standard baffle configuration and a modified finger design minimizing the average distance between the mold and the baffle. Four of the castings were short-cast, the result of incomplete fill, in that metal ran out of a crack in the mold. The results of the grain evaluation indicated five castings would be acceptable as per current aircraft grain reject criteria. This represented an overall yield of 25%. Three of the defect-free casting came from a 7-piece mold made with the standard baffle. The remaining castings exhibited different types of surface grain defects with a number exhibiting more than one type of defect.

Confirming the previous results for the 7EC configuration, there were no instances of root-face freckle chain formation. As a generalized observation for this castings, most of the grains were nucleated or located not on shank or airfoil surfaces, but on convex platforms, grain feed bars and airfoil trailing edges. Ramp nucleation (two instances) was much less prevalent in Trial 6 than in the two previous trials for the 7EC configuration. It is believed that alternate ceramic mold support rods reduced flash at mold/rod junctions and carefully controlled mold preparation/drying conditions reduced flash at ramp surfaces, both of which contributed to reduced grain nucleation at these sites. It was unusual to note that for the first time slivers were observed as part of defect occurrence. These are relatively short and narrow grains which have nucleated on the casting surface generally in shank areas. The name derives from the long/narrow shape which results when the nucleated grain is crowded out by the growth of the main crystal which nucleated in the starter.

7FA Stage 1 Bucket

The series of three casting trials involved with the 7FA Prototype Bucket configuration identified casting parameters and mold construction details which produced an overall grain yield of 23%. The production of defect-free castings supports the conclusion that the SX process can be successfully scaled-up to produce these types of large configurations for land-based turbine applications.

Employment of the improved LCS shell system reduced the incidence of mold cracking and metal run-out. Optimized baffle configurations eliminated freckle grain defects from root surfaces and combined feed bar and mold wrap positioning schemes eliminated grain nucleation at platform corners, overhangs and feed areas. Additionally, the trials have resulted in castings free of FPI or X-Ray detectable defects such as dross or microshrinkage.

It is believed that improved grain yields can be achieved by elimination of the isolated cases of columnar grain initiating in either the ramp area or the core support windows at the casting tips. The key to improved yields here involves minimizing the numbers of flash sites (by eliminating mold cracking) which have previously been shown to reduce grain nucleation in these areas. Macrophotos of one of the defect-free castings are shown in Figure 9.

Figure 9 – Photos of defect-free 7FA Stage 1 Bucket casting.

7HA Stage 1 Nozzle

All activity for this 10-inch 1ong cored part was focused on Trial 1 – Mold Structural Integrity. Because of the size and geometry of the 7H Stage 1 Nozzle, the Trial 1 molds were configured to yield a single casting per mold. A total of four molds were constructed for Trial 1. For these molds, the nozzle wax patterns were positioned and gated such that the SX starter would feed into the inner and outer shrouds at the leading edge corners.

The results for the four Trial 1 molds highlighted the fact that significant problems were associated with producing this nozzle component. The most significant problems were related to mold structural integrity in that of the our molds, only one survived the mold-build process for casting. The other three all exhibited serious evidence of handling damage. It was assessed that the extent of this handling damage was such that localized patching, replacement or repair could not salvage the molds. It was clear that a more robust mold design relative to the shell thickness and mold support rods were needed to withstand the stresses generated during the mold-dipping/slurry-draining movements experienced in mold build.

The mold that survived assembly and build was cast successfully without any run-out. Grain etch revealed the presence of a number of equiaxed grains in the outer shroud area nearest the leading edge and the fillet between the leading edge and the outer shroud. It was reasoned that this nucleation took place relatively late in the solidification process because the equiaxed grains did not subsequently grow in a columnar manner along the body of the airfoil portion of the nozzle. These results highlight the need to incorporate grain feeds in this area to avoid this spurious nucleation.

Summary

The Task 3 SX Casting Process activity demonstrated that SX casting technology can be successfully applied to complex-cored airfoil castings for land-based power generation applications. Casting efforts were focused on several cored bucket configurations, including the GE 7EC, 6FA, and 7FA Stage 1 Buckets and the 7H Stage 1 Nozzle. Their size (approximately 10-15 inches long) and complexity were considered appropriate to demonstrate expanding the capability range for complex-cored SX airfoils for land-based turbine systems.

The cored buckets employed tooling being used to produce DS-columnar grained components. As such, features had to be added to the tooling to enable SX versions to be produced.

Thermal simulation modeling was used to help determine the feasibility of developing a sound casting process for these large components. First, three-dimensional models of the envisioned molds were constructed and simulations were then conducted of the casting processes. The results highlighted certain areas in the casting configurations where grain nucleations could occur. This formed the framework for the placement of grain feed bars and mold insulating wrap to eliminate these nucleations.

Through an iterative series of casting trials which incorporated modeling results as well as the results from previous trials, an acceptable combination of mold temperature, metal temperature and withdrawal rates was established for the cored bucket castings. These casting parameters resulted in no randomly nucleated equiaxed grains nucleating from the solidification process. Localized grain defects occurring in generally the same regions of the castings were observed throughout the trials. The successful incorporation of furnace and mold configuration features eliminated many of these grain defects. Baffle configurations eliminated freckle-chain grains on root surfaces and optimized grain feed bars/mold insulation wrapping eliminated grain nucleations on platform corners, overhangs and feed areas. Overall grain yields of 25% and 23% were achieved for the 6FA and 7FA cored buckets, respectively. Isolated grain nucleations were observed, however, in either the ramp areas or the core support windows at the casting tips. The key to improved grain yields in these instances involves minimizing the numbers of metal flash sites (these result when molten metal penetrates very small cracks in the mold surface layers) which can act as grain nucleation sites.

Employment of the improved LCS shell system reduced the incidence of mold cracking and metal run-out. Additionally, the trials consistently resulted in castings free of FPI or X-Ray detectable defects such as dross or microshrinkage.

Mechanical property tests, including tensile and stress rupture characterizations were conducted on thin-sheet specimens machined from 7EC buckets and compared to data available in the literature for N5 SX alloy. The tensile results indicated lower strength and ductility values compared to published data. Microshrinkage and carbide formations present on the fracture surfaces may have contributed to this situation. The fact that the cross sectional area of the sheet specimens was approximately 1/9 that of test bars usually used for aircraft component testing may also have had an effect here. The stress rupture results, on the other hand, exhibited equivalent or superior performance compared to published data. This suggests that stress rupture performance was not as sensitive to factors such as microshrinkage, carbide formations, and specimen configuration as the tensile properties.

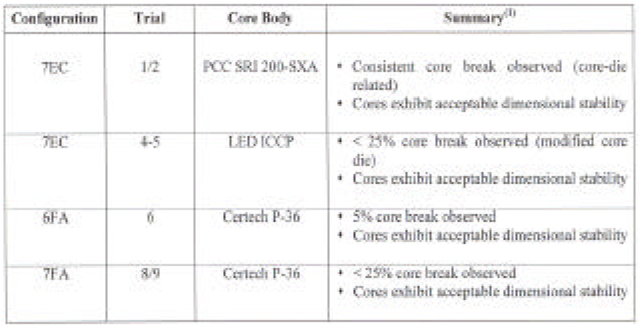
The casting results for the 7H Stage 1 Nozzle highlighted the need to optimize mold build procedures to eliminate mold cracking and metal run-out. The grain results highlighted the requirement to optimize grain feed in order to eliminate instances of spurious grain nucleation in shroud areas.

Task 4 - Core Materials & Design

The Task 4 Core Material activity demonstrated that a number of silica-based core bodies are available to produce complex serpentine cores for SX castings intended for use in land-base turbine engine applications. The core efforts were focused on evaluating both low and high pressure core manufacturing processes for the production of cores for the GE 7EC, 6FA, and 7FA Stage 1 Bucket configurations. The core configurations and complexity were considered appropriate to demonstrate extending the capability range of cores for land-based turbine system components.

An iterative series of casting trials were conducted in which the configurations were produced employing a number of silica-based core bodies including the PCC SRI 200-SXA low pressure silica core body, the LED ICCP low pressure silica/zircon core body and the Certech P-36 high pressure silica/zircon/alumina core body. The core evaluation results for all of the bucket casting trials are listed in Table 4. Included in the table are the configurations cast, the trial number, the core body used and summary comments relative to core performance. In all cases, the cores were able to be leached using standard caustic core removal cycles. In all cases, there was no evidence of unusual core/metal interaction products. Finally, in all cases the core stability assessments indicated results comparable to the production measurements of columnar-grain castings currently being produced with the tooling. The findings all indicated that tool rework would not be needed to produce dimensionally acceptable castings.

Table 4 – Core Performance Summary



Configuration	Trial	Core Body	Summary[1]
7EC	1/2	PCC SRI 200-SXA	• Consistent core break observed (core-die related) • Cores exhibit acceptable dimensional stability
7EC	4-5	LED ICCP	• < 25% core break observed (modified core die) • Cores exhibit acceptable dimensional stability
6FA	6	Certech P-36	• 5% core break observed • Cores exhibit acceptable dimensional stability
7FA	8/9	Certech P-36	• < 25% core break observed • Cores exhibit acceptable dimensional stability

(1)*Cores removed with standard caustic leach cycles with no unusual core/metal reaction products observed.*

The major issue addressed during this task involved core break and this was found to be a function of the specific core die used. For the 7EC castings, prototype core die tooling was used initially and this resulted in considerable core break as revealed by FPI and X-Ray inspection operations. Selective die modifications and core strengthening rods were able to significantly reduce the incidents of core break. For the 6FA and 7FA castings, hard production-ready core die tooling was available which also resulted in significantly reduced incidents of core break. It was thus assessed that core break was not so much a function of the particular type of core body used but, in fact, more a function of the available core die tooling.

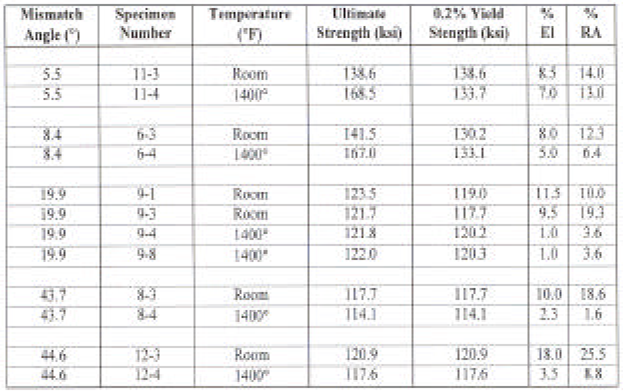
Task 5 - Grain Orientation Control

The Task 5 Grain Orientation Control activity was focused on mechanical property testing of Rene N5 specimens exhibiting a range of defects including grain boundary mismatch angle and freckles. Testing included tensile, stress rupture, and LCF tests conducted at various temperatures and conditions.

Tensile tests conducted at room temperature and 1400°F and stress rupture tests at 1600°F/80 ksi and 1800°F/40 ksi were conducted on specimens machined from double-seed slab castings exhibiting grain boundary mismatch angles ranging from approximately 5-45 degrees. The results of these tests are listed in Table 5 and Table 6. Tensile results indicated strength properties were sensitive to mismatch, particularly at the higher angles with reductions of 30% at mismatch angles above 20 degrees. Room temperature ductilities exhibited little degradation with mismatch while the 1400°F ductilities were only slightly degraded at mismatch angles above 20 degrees. The stress rupture lives at both test temperatures were extremely sensitive to mismatch in that 90% reductions were observed at mismatch angles greater than 8 degrees.

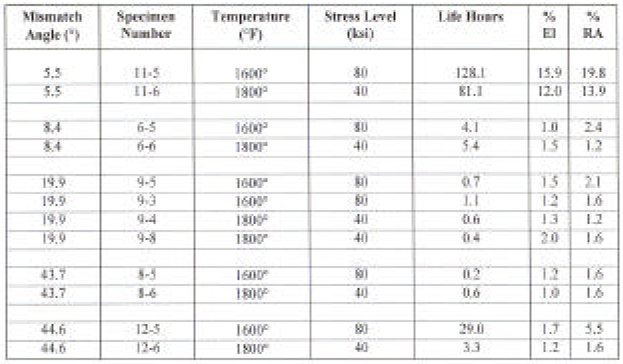
LCF testing also indicated a sensitivity to mismatch angle. At higher test temperatures, for example, a 35% life reduction was observed by increasing mismatch angle from 11 degrees to 21 degrees, and 65% reduction going from 21 degrees, and 65% reduction going from 21 degrees to 31 degrees (Figure 10). Based on limited data, LCF life for 0.06 inch-sized freckles appeared to be comparable to that for nominally defect-free material.

Table 5 – Double-Seed Test Slab Tensile Test Results



Mismatch Angle (°)	Specimen Number	Temperature (°F)	Ultimate Strength (ksi)	0.2% Yield Stength (ksi)	% El	% RA
5.5	11-3	Room	138.6	138.6	8.5	14.0
5.5	11-4	1400°	168.5	133.7	7.0	13.0
8.4	6-3	Room	141.5	130.2	8.0	12.3
8.4	6-4	1400°	167.0	133.1	5.0	6.4
19.9	9-1	Room	123.5	119.0	11.5	10.0
19.9	9-3	Room	121.7	117.7	9.5	19.3
19.9	9-4	1400°	121.8	120.2	1.0	3.6
19.9	9-8	1400°	122.0	120.3	1.0	3.6
43.7	8-3	Room	117.7	117.7	10.0	18.6
43.7	8-4	1400°	114.1	114.1	2.3	1.6
44.6	12-3	Room	120.9	120.9	18.0	25.5
44.6	12-4	1400°	117.6	117.6	3.5	8.8

Table 6 – Double-Seed Test Slab Stress Rupture Results



Mismatch Angle (°)	Specimen Number	Temperature (°F)	Stress Level (ksi)	Life Hours	% El	% RA
5.5	11-5	1600°	80	128.1	15.9	19.8
5.5	11-6	1800°	40	81.1	12.0	13.9
8.4	6-5	1600°	80	4.1	1.0	2.4
8.4	6-6	1800°	40	5.4	1.5	1.2
19.9	9-5	1600°	80	0.7	1.5	2.1
19.9	9-3	1600°	80	1.1	1.2	1.6
19.9	9-4	1800°	40	0.6	1.3	1.2
19.9	9-8	1800°	40	0.4	2.0	1.6
43.7	8-5	1600°	80	0.2	1.2	1.6
43.7	8-6	1800°	40	0.6	1.0	1.6
44.6	12-5	1600°	80	29.0	1.7	5.5
44.6	12-6	1800°	40	3.3	1.2	1.6

In overall summary, the results suggested some potential for relaxation of freckle defect rejection criteria, but it is believed more testing is required to characterize a wider range of (1) temperature response, (2) freckle-size distributions, and (3) the effects of freckles on other mechanical properties such as tensile, stress rupture and high cycle fatigue (HCF) response. There appeared, however, to be little potential for relaxation of LAB/HAB rejection criteria. Significant stress rupture life reductions were observed at mismatch angles above 8 degrees and significant LCF life reductions were observed at mismatch angles above 11 degrees.

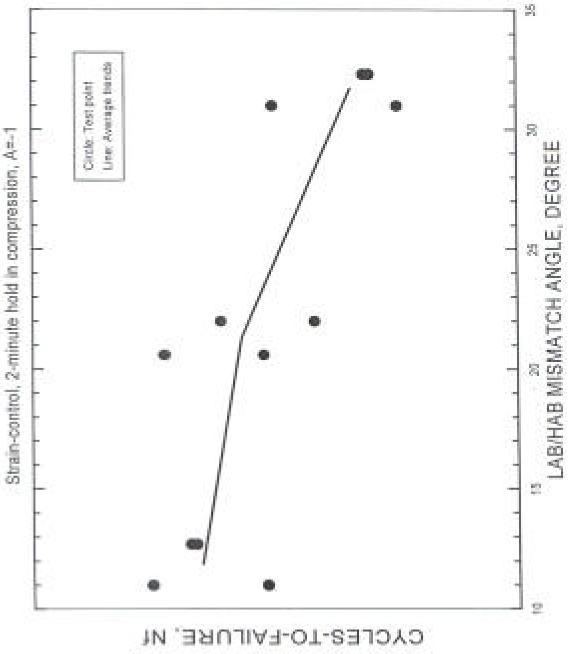


Figure 10 LCF life vs. mismatch angle of LAB/HAB specimens at Level 2-test temperature.

SUMMARY/CONCLUSIONS

The Turbine Airfoil Manufacturing Technology program was conducted to allow aircraft single crystal (SX) casting technology to be applied to land-based power generation applications. The approach involved scale-up of available manufacturing procedures to produce large-size airfoil components. A number of technical issues were addressed including alloy melt practice to reduce sulfur in nickel-base superalloys, modifications/improvements of the SX process, core materials and grain orientation control. The objectives/conclusions relative to the specific issues included the following:

Alloy Melt Practice – Reduce sulfur in N5 Alloy (without yttrium).

- Desulfurization can be accomplished during alloy melting operations resulting in sulfur levels below 1.0 - 0.5 ppm in superalloy N5.
- Desulfurization to sulfur levels below 1 ppm results in enhanced resistance to high temperature oxidation (1900/2000°F) for both coated and uncoated superalloy N5.
- The method of desulfurization is not critical to achieving improvement in oxidation resistance. Melt desulfurization and hydrogen-annealing treatments offer equivalent improvements in oxidation resistance.
- Superimposing a hydrogen anneal onto melt desulfurization did not result in any significant additional benefits.
- Desulfurization had little positive influence on 1700°F hot corrosion resistance.

SX Casting Process – Define methods for casting cored SX airfoils for land-based power generation applications.

- Aircraft SX casting technology can be applied to large-sized airfoil components.
- Castings can be produced free of dross and microshrinkage defects.
- Grain defects are generally confined to specific locations including the SX starter ramps and casting tips.
- Eliminating mold cracks (which act to produce metal flash/fin sites) can minimize grain nucleations at SX starter ramps and casting tips.

Core Materials – Provide stable cores to produce large SX airfoil castings.

- Silica cores are available to produce large SX airfoil castings
- Silica cores can be removed with standard caustic leach cycles.
- No unusual core/metal reaction products are formed during casting operations.
- Satisfactory core dimensional stability has been demonstrated.

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 the 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 cost for industry and electrical cost for consumers. The improvement in oxidation resistance was also observed for coated specimens. 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.