ATS Land Based Turbine Casting Initiative

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INTRODUCTION

The Advanced Turbine Systems (ATS) program has set goals that include a large-scale utility turbine efficiency that exceeds 60 percent (LHV) using natural gas and 15 percent heat rate improvement for industrial turbine systems. To meet these goals, technological advances developed for aircraft gas turbine engines need to be applied to land based gas turbines. These technological advances include: single crystal castings, alloys tailored to exploit these microstructures, complex internal cooling schemes, and coatings. Equiaxed and directionally solidified castings are employed in current land-based power generation equipment. These castings do not posses the ability to meet the efficiency targets as outlined above. The production use of premium single crystal components with complex internal cooling schemes in the latest generation of low sulfur superalloys is necessary to meet the ATS goals.

While the processes, measurements, and controls are in place for aircraft gas turbine single crystal castings, a re-examination of these practices is necessary primarily because of the 2X to 10X increase in the size of components for land based turbines. As the casting size increases, the total number of defects and variation in properties increase with the surface area and volume of material. These property variations have been shown to impart additional cost and performance penalties. Furthermore, these issues must be addressed in the context of an altered operating scenario in which the long-term, steady state durability is more critical than the number of start-up and shut-down cycles.

OBJECTIVE

The objective of the Land Based Turbine Casting Initiative is to develop and implement technology specifically for land based turbine size components. The technology development will occur in the following areas:

- Enhance the performance of land based turbines through the application of complex cooling geometries, use of low sulfur alloys, and single crystal microstructure castings.
- Develop and implement improved casting and inspection practices.
- Establish grain defect tolerance limits that meet performance standards and maximize casting yields.

APPROACH

The aircraft gas turbine technologies and processes are being extended and applied to develop high efficiency, environmentally superior, and cost competitive gas turbine systems for application in utility and industrial land based power generation equipment. This program scales up aircraft gas turbine casting technology to land based gas turbine size components and is based on four technology thrust areas. The four thrust areas are: low sulfur alloys, casting process development/understanding, post-cast process development/improvement, and establishing casting defect tolerance levels. The program technology thrust areas are shown schematically in Figure 1. These four technology thrust areas, while pursuing different disciplines and discrete innovations, constitute a coherent system that encompasses the entire process.

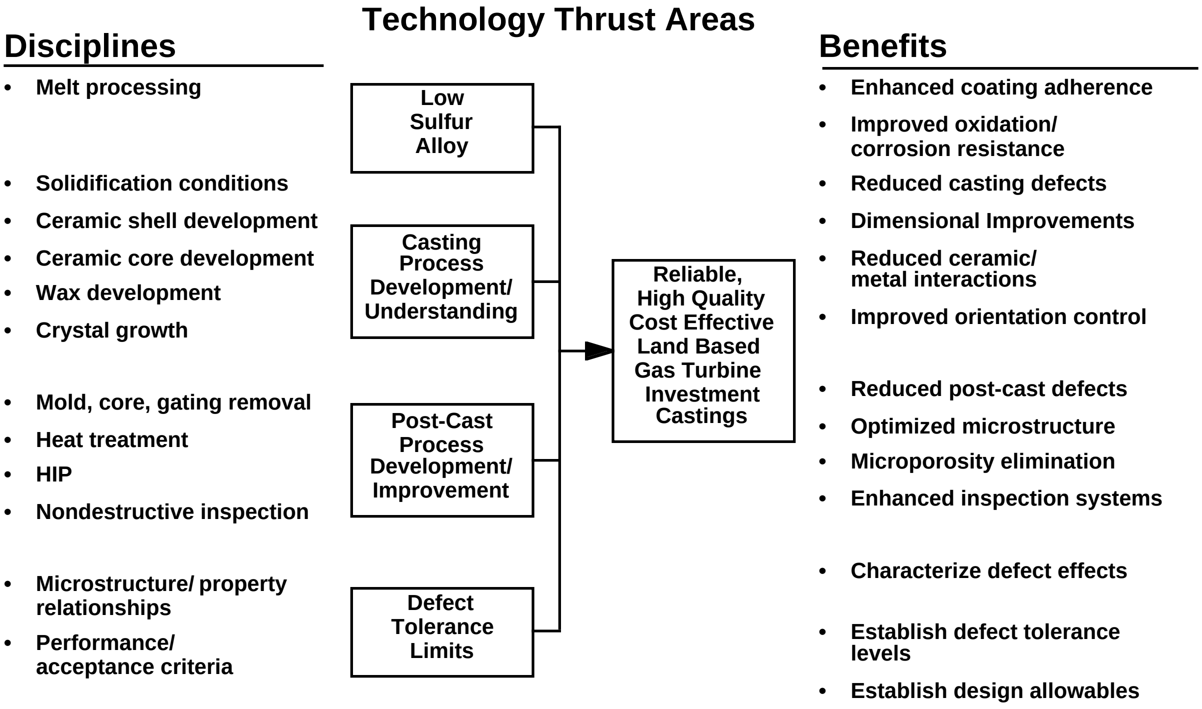

Figure 1: Howmet Corporation ATS Land Based Turbine Casting Initiative Technology Thrust Areas

To accomplish the technology development, and ensure the technology advances are transitioned to the industry in a timely manner, Howmet is teamed with utility and industrial gas turbine OEM’s. This team addresses the entire enterprise to produce land based gas turbine castings including: alloy producers, investment casters, engine builders, and an inspection system developer. The team includes: ABB, ARACOR, General Electric Corporate Research and Development, Howmet Corporation, Pratt & Whitney, Solar, and Westinghouse.

PROJECT DESCRIPTION

The technical activities that occur in each of the four technology thrust areas are briefly described below.

Low Sulfur Alloy Castings

An objective of the proposed program is to produce nickel-based superalloy castings with superior environmental resistance through the use of low sulfur alloys. Low-sulfur alloy, in the range of less than 1.0 wppm sulfur, has been produced in small, laboratory sized heats at Howmet. For this program, special low-sulfur heats of GTD 111, PWA 1484 and Rene' N5 were prepared. The target sulfur level for these heats was less than 1.0 wppm. Howmet has continued to improve its low sulfur melt capabilities beyond the limits currently attained and scaled the heat sizes from development to production sizes. In addition, production blends and virgin CMSX-4 and CMSX-10 heats were purchased from Cannon-Muskegon. Possible differences in the sulfur levels attained in the various alloys were characterized and compared against the level typical of current production processes of these alloys.

Solid test panels, 0.080" thick, were cast in the above alloys and cyclic oxidation benchmark testing of the panels using the low and current production sulfur levels is being conducted to assess the beneficial effect of low sulfur. Oxidation testing is being completed on bare metal and coated samples.

Casting Process Development / Understanding

Designed experiments were conducted to generate the process knowledge necessary to assure process improvement on large land based single crystal blade configurations. The designed experiments were conducted on current second generation single crystal alloy compositions, Rene’ N5 and CMSX-4; and a third generation single crystal alloy, CMSX-10. These experiments examined the effects of casting parameters on metallurgical and dimensional quality. The objective of these experiments was to identify the critical factors affecting quality and the interactions between different factors. With this knowledge, it will be possible to optimize the most critical factors identified in the designed experiments. The knowledge gained from this series of designed experiments will be captured in process models so that it can be transferred and applied to other component geometries and alloys.

The responses of current mold systems were benchmarked, and explored in the casting parameter designed experiments. To quantify the capability of current mold systems, thermo-mechanical and thermo-physical properties were measured on molds produced over a 3 month period. The results of these tests have been compared to dimensional data on production wax patterns, molds, and castings collected over the related period of time. The results of the benchmarking and designed experiments provided input for the mold development activities. In addition to examining mold performance, the behavior of the pattern waxes is also being investigated. The results of current programs to develop new wax systems for aircraft turbine engine hardware are being examined for application to large utility sized blades. These evaluations assess the dimensional performance of new waxes, their compatibility with the mold materials, and the resultant casting surface quality.

The response of current core systems has also been benchmarked, and explored in the casting parameter designed experiments. To quantify the capability of current core systems, current production data was analyzed to assess the defects attributed to cores. Cores systems currently being developed are being examined for large, utility turbine size blades. The cores are being evaluated for dimensional, mechanical and visual quality; then will be integrated into casting portions of the program to evaluate applicability.

Post Cast Process Development / Improvement

The current ceramic mold and core removal systems, which were derived from those used on aircraft turbine castings, were benchmarked for applicability on large, land based turbine castings. Based on the benchmarking analysis, deficiencies in mold and core removal procedures are being assessed, and new procedures developed and tested to evaluate their effect on part quality and cost. The current systems used to remove the gating and clean the airfoils were also benchmarked to determine the levels of scrap or rework caused by the current procedures, and to assess the relative cost of the current procedures. Based on the results of the benchmarking analysis, new techniques are being developed and evaluated.

The heat treatment and hot isostatic pressing (HIP) operations developed for aircraft turbine size components are being tested on large land based components. The focus of these studies is to develop solution heat treatment cycles for CMSX-4, CMSX-10, and Rene’ N5 that ensure required solutioning levels for IGT sized components, but which can be accomplished in reduced times. For the CMSX-10 alloy, these studies are especially critical since the solution times can extend up to 45 hours.

Investment casting designs, particularly high performance turbine blades and vanes, are rapidly evolving in complexity. A new approach to dimensional control of castings based on X-ray metrology has been developed called 2.5D reconstruction. The approach uses multiple 2D X-ray views of the casting to reconstruct the 3D geometry of selected features. This inspection technique is being scaled from aircraft sized castings, to the cross sections and path lengths typical of land based castings.

Defect Tolerance Limits

The complete elimination of single crystal grain defects is very difficult in large component sizes for some alloy compositions. This activity will assess the performance loss associated with having defects present so that proper defect tolerance levels are specified which ensure adequate performance and maximize casting yields. Test material with different primary orientations, crystal boundaries, freckles and recrystallized grains was cast, heat treated, and machined for mechanical testing. To evaluate the effect of low angle boundary (LAB) misorientation, seeded bicrystal slabs with varying LAB misorientation were cast. LAB's in these slabs were characterized by visual macroetch and X-ray Laue techniques. Specimen were machined with the LAB normal to the stress axis or located in a highly stressed notch area. The types of testing being conducted include: creep, fatigue, and tension testing.

RESULTS

The technical effort of this ATS program to develop and implement the technology necessary to cast large single crystal components began in September 1995. The discussion that follows highlights the technical activities conducted to date.

Low Sulfur Alloy

Heats of PWA 1484 and Rene’ N5 have been successfully produced using a Howmet developed low sulfur refining process. Howmet Alloy Dover (HAD) has been able to produce 5,000 lb. production heats of PWA 1484 and Rene’ N5 with sulfur levels at 0.3 ppm and 0.8 ppm respectfully. These master heats have been cast and are undergoing evaluation.

Samples from all alloys in the low sulfur effort have been measured for sulfur content by the Leco 444LS analyzer at Howmet Research Center (HRC), as well as Glow Discharge Mass Spectrometry (GDMS) at Northern Analytical. Figure 2 shows the average result of 2 analyses performed at different times. The N5 production casting sulfur level is a result of one GDMS measurement. As can be seen, the Howmet Low Sulfur process does reduce the bulk sulfur levels in the master alloys. A comparison to Howmet's High Sensitivity Low Sulfur measurement technique is underway.

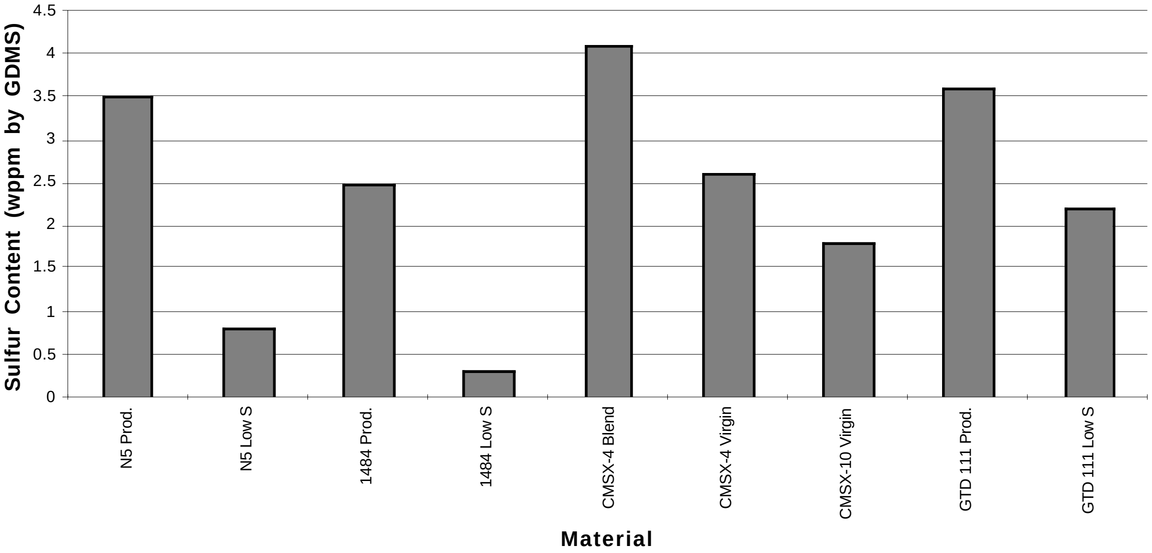

Figure 2: Sulfur Content of Ingot Material Measured by GDMS.

Coupons have been prepared from panels cast in each of the alloys. Four coupons of each alloy are being tested. The alloy materials currently in oxidation testing are:

Low Sulfur	Production
N5	N5
PWA 1484	PWA 1484
GTD-111	GTD-111
CMSX-4 Virgin	CMSX-4
CMSX-10 Virgin	

Currently, oxidation testing at 2150°F (1177°C) for uncoated and coated coupons is underway. The test cycle is 50 minutes at 2150°F and 10 minutes of cooling. Figure 3 shows the weight change versus time for each uncoated alloy system at 950 cycles. Each curve represents the average weight change for four coupons per alloy at each inspection interval. The legend indicates the systems in order of the least amount of weight change from top to bottom. Due to space limitations in the test rig, the GTD 111 low sulfur and production alloys were not included in the 2150°F uncoated testing. The coatings selected for oxidation testing are LDC-2E, a packed aluminide process; MDC 150, a Howmet developed Platinum Aluminide coating; and MDC 150L, a Howmet developed low-sulfur Platinum Aluminide coating. The oxidation testing of the coated samples has not progressed to the point where significant trends can be observed. These results will be reported at a later date.

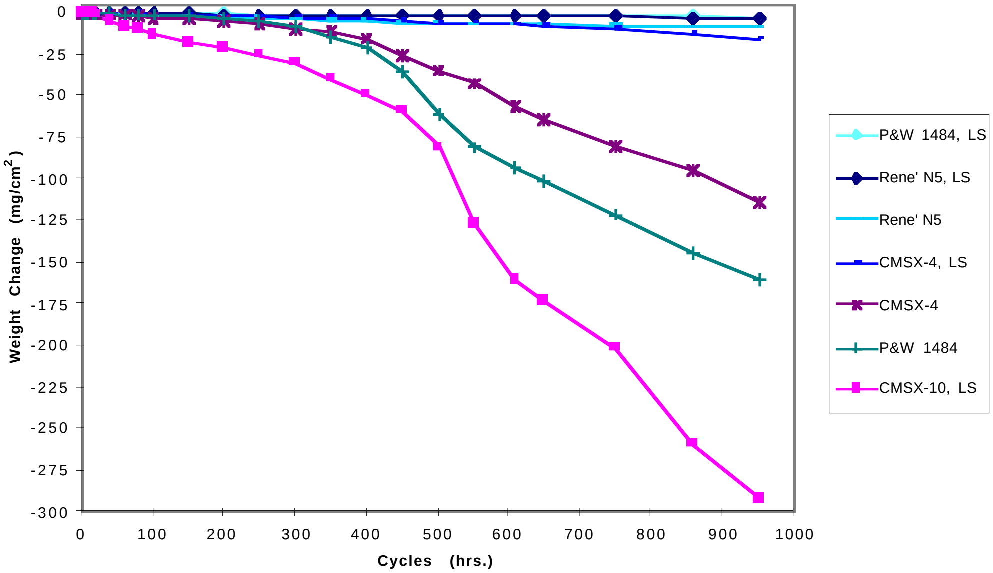

Figure 3: Cyclic Oxidation at 2150°F (1177°C) of Uncoated Production and Low Sulfur Systems.

Also, oxidation testing is in progress at 2000°F (1093°C) for uncoated coupons. In this case, the exposure cycle has been modified to be 100 hours of hot time and cool to room temperature for weight change measurements. All ten alloy systems were included in this test. Figure 4 below shows the results for 900 hours of oxidation testing. The legend indicates the systems in order of the least amount of weight change from top to bottom.

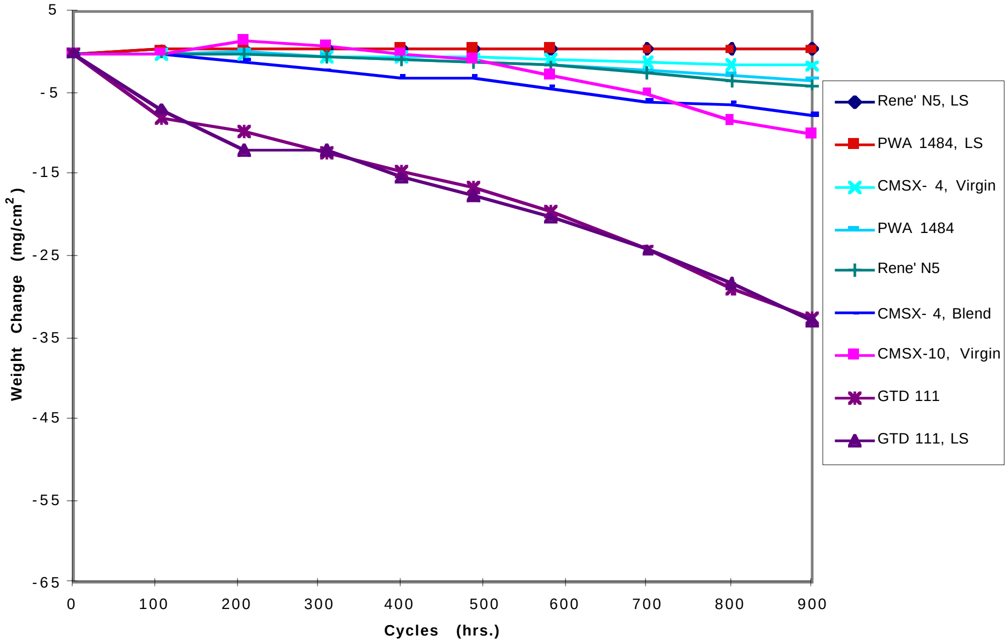

Figure 4: Cyclic Oxidation at 2000°F (1093°C) of Uncoated Production and Low Sulfur Systems.

Casting Process Development / Understanding

Currently, defects in large single crystal utility sized castings are primarily dimensional or grain related. These defects are directly related to the significantly larger surface area and part volume associated with IGT-sized components as compared to the aero-sized components. As grain and dimensional defects are reduced, other defects may surface as leading scrap causes. The experiments conducted include variables that should improve both the dimensional quality and reduce grain and crystal defects.

Howmet Hampton Casting (HHC) has completed their first casting experiment using the General Electric 9H first stage blade. This blade was part of a designed experiment that investigated: core placement enhancements, shell structural modifications, different starter types, and changes in casting withdrawal rates. Casting inspection included grain mapping, wax and metal airfoil wall thickness measurements, and external airfoil profile measurements. One of the processing factor combinations chosen for this experiment produced very good casting quality. The grain quality was good except for a very few freckle chains located in the blade platform and root sections. This effort, along with efforts sponsored by GE, allowed HHC to begin pre-production deliveries of the 9H blade for subsequent test engine builds. Due to production component commitments, further experimental efforts on the 9H first stage blade will be completed at HRC with HHC providing guidance. Following the casting experiments, all information and results will be transitioned back to HHC for inclusion into the production processes.

Howmet Dover Casting (HDC) used the Westinghouse 501F first stage blade for their casting experiment. The 501F blade is currently produced as an equiaxed component. The wax patterns were modified and the casting process changed to produce a single crystal component. The completed Taguchi L12 casting experiment investigated factors in the following areas: mold assembly, casting process parameters, and mold configuration. A review of the blades and grain maps showed a range of grain defects. As was the intent of the designed experiment, some blades exhibited relatively few defects, while others had significant grain defects throughout the airfoil and root sections. An evaluation of the blades was completed for the following quality characteristics: starter defects; airfoil grain boundaries; airfoil, root, and ramp freckle indications; core indications in the airfoil; misoriented grains in the platform area; airfoil recrystallized grains; x-ray indications; primary crystal orientation; and ultrasound wall thickness. Based on this evaluation, the mold configuration factors exhibited the most significant impact. Most of the remaining experiment factors had a minor impact on blade quality. This may be due to the relatively small range used for the experiment factors and the significant and severity of core breakouts on the surface. In fact, 18 of the 36 parts cast had indications where the core protruded through the airfoil wall.

The follow-on utility sized designed experiment will concentrate on improving the casting yields and throughput of the 9H first stage blade. These efforts focus on new core and shell materials to improve dimensional control, and casting parameter adjustments to reduce root freckle defects. To complete the second casting experiment, the 9H prototype core and wax dies have been made available to HRC for producing the experiment cores and wax patterns. The second experiment will include control factors such as: wax type, core type, shell structure, mold configuration, and casting parameter adjustment. The effort will also investigate the transition of a new core material to a production capable process for IGT sized components.

Howmet Whitehall Casting (HWC) has defined their experimental approach, and decided to continue casting development on the Solar Mars first stage blade, cast in CMSX-10. Casting variables that impact the formation of recrystallized grains (RX) and low angle boundaries will be investigated in the designed experiment. In addition, several blades will be microprobe inspected for elemental distribution after casting. The experimental layout has been determined and the patterns have been cast . They are awaiting solution heat treatment. Many of the blades cast in the experiment will be used to perform additional microstructure evaluations. HRC will address the solution heat treatment processing and dimensional issues related to high temperature solution heat treatment exposure. Additional efforts concerning the transition of CMSX-10 to production include the impact of subsequent thermal cycling (coating, hole plugging, and tip brazing) on final material properties. Howmet has initiated discussions with Cannon-Muskegon and Solar Turbines to address the CMSX-10 material specifications. Part of this effort will include a metallurgical evaluation of as-cast, solutioned, and fully heat treated material for elemental gradients, phase determination, and microstructure. The material specifications will include solution heat treatment cycle parameters such as ramp rates, temperatures, and hold times. Since formation of gamma prime is driven by temperature and cooling rates, a minimum cool down rate is usually specified. To determine the minimum cool down rate that meets Cannon-Muskegon's published properties, several solution heat treatment cycles were run with different controlled cool down rates. Four out of the five controlled cool down rate cycles have been completed. Following the last run, samples will be microprobe inspected and a metallurgical evaluation completed.

Shell test bar wax assemblies were prepared at HRC and then sent to HHC for subsequent shell investment. The molds were invested at the rate of one a week, for the purpose of determining the variability of the process over time. Nine molds have been invested and returned to HRC for testing. Porosity, density, and creep measurements have been completed and the data is being analyzed. Analyses of test results and wax-to-cast dimensional data were completed and compared to a similar Equiax cast blade. A comparison to a similar DS/SC blade is underway. Shells for an L16 Taguchi follow-on shell development experiment have been fabricated and are currently in test. Factors in the trial are: reinforcement composition, slurry composition, stucco composition and particle size, and slurry drying. Creep, room temperature green shell modulus of rupture, and green and fired density and porosity testing have been completed. High temperature modulus of rupture and dilatometry testing are in process. A short confirmation trial will be conducted on factors that indicate improved performance.

Two development wax compounds are being investigated for suitability to fabricate large IGT patterns. Benchmark analyses of the new formulations, including dimensional stability, surface finish, physical properties, and mold compatibility are being investigated. A generic core design was selected to test these formulations and cores have been ordered. To aid in understanding the flow of wax into the die cavity, die cavity temperature and pressure sensor equipment have been procured and will be employed in these studies. There has been no additional effort in the past reporting period due to difficulties in obtaining test cores. Additional efforts will commence when cores can be procured.

Core development activities are proceeding with baseline core material property testing complete. Based on the benchmarking efforts and core developments efforts underway at

Howmet, a modified core material that demonstrates improved strength and dimensional properties has been formulated. Physical property testing completed during this period indicate a 3X to 6X improvement in high temperature (>2730°F) creep resistance over the baseline material, as well as a small improvement in room temperature strength. Additional testing is continuing.

To assist in the transition of a new wax formulation and core material to IGT components, the 9H prototype wax and core dies were made available to HRC for producing the experiment wax patterns and cores. The core die has been shipped to Howmet Morristown Casting Support to begin core trials. Initial delivery of five cores in the new core material was completed. These cores will be used in the second 9H casting experiment at HRC. Efforts expected to support the casting experiment include CMM inspection of all cores and documentation of resulting quality. The wax die has been shipped to HRC to begin development trials. Preliminary wax injection of three patterns has been completed. After additional cores are procured, wax injection efforts to support the integrated casting experiments will begin.

Large single crystal castings are known to exhibit a phenomenon termed "Splaying", which is the fanning or spreading of the primary dendrites during solidification. Splaying is not a problem in aircraft components because of their much smaller size. However, in large IGT components, the effect is much more pronounced. Large single crystal samples were cast under conditions to exaggerate and suppress splaying. The castings included the Seimens V84.4 first stage turbine blade for evaluation by P&W, and large slabs for evaluation by HRC. Two molds of the Seimens V84.4 blade in both PWA 1483 and PWA 1484 have been cast at HDC. The casting parameters were adjusted to induce splaying and the results will be measured for effect. The blades have been delivered to Pratt & Whitney for further evaluation. HRC has completed casting four molds of slabs to investigate splaying effects. The slabs were 4” wide by 10” tall, with thicknesses of 0.5” and 1.0”. The slabs were oriented on the mold in such a way as to induce different thermal gradients and crystal orientations during solidification. The molds were then cast with varying process parameters. After post-cast processing, the slabs will be evaluated to characterize the extent of dendrite fanning and splaying. The results will be compared to predictions from thermal and fluid model solutions.

Post-Cast Process Development

In order to investigate the potential effect of aero-engine size gating, mold, and core removal processes on large IGT single crystal castings, the current production methods and procedures were benchmarked. To aid in the understanding and comparison of smaller aero-size to larger IGT components, the benchmarking effort included three Howmet manufacturing facilities. For aero-size components HWC was investigated, and for larger IGT components HHC and HDC were included in the benchmarking effort. From discussions with manufacturing and engineering personnel at each facility, the primary cause of scrap from mold and gating removal for single crystal castings was the occurrence of RX from improper handling. Since the processes are primarily manual, occasional scrap does occur due to heat checking, excessive grinding, or improper handling. Based on the above benchmarking efforts, an automated process for handling and gating removal is being investigated. The process will eliminate, or significantly reduce, manual handling as well as provide CNC programmable gate removal. The process will also eliminate heat checking since no heat is generated during the cutting process.

Because of the difference in size between aero and IGT components, different heat treatment cycles and processes are often used. Single crystal slabs, 6” x 6” x 1” thick, cast in CMSX-4 and Rene’ N5, were subjected to the current production IGT solution and age cycles. Test bars were then extracted from the material and submitted for various mechanical testing. Based on current specifications for both alloys, mechanical test parameters were established. The tests include room and elevated temperature tensile, creep rupture, and low cycle fatigue tests. Table VI summarizes the test efforts for this task.

Table VI. Baseline Mechanical Test Matrix For Rene’ N5 and CMSX-4

Alloy	Test Type	Test Condition	Number of Tests
N5	Tensile	70°F	8
		1200°F	5
		1600°F	5
	Creep Rupture	1600°F/70ksi	1
		1600°F/75ksi	4
		1600°F/85ksi	1
		1600°F/95ksi	1
		1800°F/43ksi	4
	Low Cycle Fatigue	1400°F/0.75-1.0s	7
CMSX-4	Tensile	70°F	8
		1200°F	5
		1650°F	5
	Creep Rupture	1400°F/110ksi	4
		1400°F/115ksi	4
		1400°F/120ksi	4
		1400°F/130ksi	1
		1600°F/88ksi	4
	Low Cycle Fatigue	1400°F/0.70-0.9s	7

The higher temperature tests are generally based on conditions in each alloy specification for typical aero-size components. In order to achieve the much longer component lives necessary in the IGT-sized components, the operating temperature is usually lower than typically seen in aero-sized engines. Since much of the published information for both N5 and CMSX-4 is in the 1700°F and higher range, this effort also performed testing in the lower temperature range in order to expand the mechanical properties database. Thus, the lower temperature creep rupture parameters are based on test conditions about 200°F lower than the material specifications.

All baseline tensile, creep rupture, and low cycle fatigue testing has been completed. The tensile and LCF test results met available specifications or historical data for properties. The test results for the creep rupture properties were very consistent for the higher temperature, but both alloys showed significant standard deviations in the lower temperature test results. Tables VII and VIII below are a summary of the baseline mechanical properties tests.

Table VII: Tensile Summary for Baseline Heat Treatment of CMSX-4 and Rene' N5

Tensile Results (Average)					
Material	**Temperature (°F)**	**UTS (ksi)**	**YS (ksi)**	**EL (%)**	**RoA (%)**
CMSX-4	70	135.0	126.1	22.6	23.6
Typical Minimum		130.0	120.0	6.0	6.0
	1200	142.4	127.4	17.9	28.8
	1650	132.7	109.5	24.2	32.6
Typical Minimum		115.0	108.0	10.0	12.0
Rene' N5	70	150.5	122.0	19.3	20.8
	1200	154.0	122.2	12.2	14.6
	1600	145.0	115.7	18.8	21.7
Typical Minimum		110.0	100.0		12.0

Table VIII: Creep Rupture Summary for Baseline Heat Treatment of CMSX-4 and Rene' N5

Creep Rupture Results (Average)						
Material	**Temperature (°F)**	**Stress Level (ksi)**	**Life (hr)**	**Life St. Dev (hr)**	**EL (%)**	**RoA (%)**
CMSX-4	1400	110.0	235.9	*	24.1	26.7
		115.0	130.4	79.1	20.9	20.3
		120.0	36.5	29.6	22.9	27.3
		130.0	10.3	*	23.1	33.4
	1600	88.0	101.5	17.2	20.8	19.7
Rene' N5	1600	70	213.1	*	30.0	32.1
		75	161.5	22.3	21.2	33.2
		85	12.8	12.8	18.3	16.8
		95	22.3	*	18.8	23.8
	1800	43	57.1	2.8	30.8	41.9

The test material to investigate improved heat treatment processes has been processed through a standard aero component HIP cycle. The material was heat treated using the current IGT production cycles for Rene' N5 and CMSX-4 (solution and age). Test bars were extracted from the slabs. Each bar was Laue inspected to determine crystal orientation. The test bars are scheduled to begin testing shortly.

Defect Tolerance Limit Establishment

An understanding of how much crystal defects detract from the baseline mechanical properties will allow the specifications for the crystal defects to be set at values that ensure performance standards are met while maximizing crystal yield. Howmet has produced sample configurations that contain defect free baseline test material and samples with freckles, low angle grain boundaries (LAB's), recrystallized grains (Rx), and different levels of off primary axis orientation. Most of the test material has been sent to the OEM's for testing. The test sample casting matrix and casting status is shown in Table IX.

Table IX: Test material casting matrix and status

OEM	Alloy	Test Material Type	Status
ABB	CMSX-4	Baseline	Shipped to OEM
		Freckle	Shipped to OEM
		Off Orientation	HRC - Final Evaluation
		Recrystallized Grain	Shipped to OEM
Pratt & Whitney	PWA 1483	Baseline	Shipped to OEM
	PWA 1483	Low Angle Boundary	Shipped to OEM
	PWA 1483	Off Orientation	Shipped to OEM
	PWA 1483	Splaying	Shipped to OEM
	PWA 1484	Splaying	Shipped to OEM
	PWA 1483	Solution Heat Treatment	Shipped to OEM
	PWA 1484	Solution Heat Treatment	Shipped to OEM
Solar	CMSX-10	Baseline	Shipped to OEM
		Off Orientation	HRC - Final Evaluation
		Low Angle Boundary	Shipped to OEM
Westinghouse	CMSX-4	Baseline	Shipped to OEM
		Freckle	Shipped to OEM
		Low Angle Boundary	Shipped to OEM
		Off Orientation	Shipped to OEM
		Solution Heat Treatment	Shipped to OEM

Future Activities

The activities defined above will continue through 1997 and into 1998. In the remaining year of technical effort on the program, the focus will be on productionizing the core, mold, and wax developments for dimensional improvements; and optimizing casting process parameters to reduce or eliminate grain defects. Other priority activities include completing the low sulfur efforts, defining optimized solution heat treatment cycles, and establishing data based defect tolerance level.

Acknowledgment

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