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Land-Based Turbine Casting Initiative

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Introduction

The Advanced Turbine Systems (ATS) program has set goals which include a large-scale utility turbine efficiency that exceeds 60 percent (LHV) on natural gas and an industrial turbine system heat rate improvement of 15 percent. 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: directionally solidified and 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 possess 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 alloys is necessary to meet the ATS goals. However, at present, the use of single crystal components with complex internal cooling schemes is restricted to industrial sized or aeroderivative engines, and prototype utility sized components.

Objective

While the processes, measurements and specification of controls are in place for components currently used in aircraft gas turbine engines, a re-examination of the practice is necessary, primarily because of 2X to 3X increase in size of single crystal castings for land based turbines. As the casting size increases, it would seem inevitable that the total number of defects and variation in properties with increasing surface area and volume of material would increase also. These property variations may be expected 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.

Specific developments have been identified which are required to scale aircraft single crystal casting technology up to land based turbine size components. The objective of the proposed program is:

- Develop and implement the technology necessary to scale single crystal aircraft gas turbine investment casting technology up to utility land based turbine sized components.
- Enhance the performance of industrial land based turbines through the application of next generation single crystal superalloys.
- Develop and implement improved casting and inspection practices.

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Approach

The United States aircraft gas turbine industry has developed, implemented, and successfully utilized state-of-the-art crystal growth technologies, such as directional and single crystal solidification, to achieve a world dominant market position. This world dominant market position has contributed significantly to the U.S. balance of trade. The proposed program will extend and apply this technological preeminence to the land based power generation industry to develop high efficiency, environmentally superior, and cost competitive gas turbine systems for application in utility and industrial land based power generation equipment. The proposed program includes all aspects of investment cast hardware for land based power generation equipment including alloy chemistry, investment casting process development and understanding, post-casting processing, and characterizing the detrimental effect of defects common to large directionally solidified or single crystal components. The team assembled to conduct the proposed program includes expertise in the areas of alloy production, investment casting, and OEM end users.

The proposed program to scale aircraft gas turbine casting technology up to land based gas turbine size components is based on four technology thrust areas. These four technology thrust areas, while pursuing different disciplines and discrete innovations, constitute a coherent system which encompasses the entire process to reliably produce high quality, cost effective investment casting for land based gas turbines. 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.

To scale investment casting technology up to land based gas turbine engines will require advances in each of the thrust areas. Within the low sulfur activities, previously developed melt processing treatments which lower the bulk alloy sulfur content will be examined. Casting process activities will focus on developing a fundamental understanding of the relationship between defect formation and cast part geometry, casting process parameters, and mold and core design and materials. The post-cast process improvement efforts will address the need of enhancing mold, core, and gating removal, and heat treatment and HIP cycles to produce optimum properties in large section sized components. In addition, improved nondestructive inspection systems need to be developed for large land based components. The fourth thrust area examines the effect of casting defects; such as freckles, primary misorientation, low angle grain boundaries, and recrystallized grains, on mechanical performance. While improvements in any one of these thrust areas will improve land based turbine performance, by working each of these technologies concurrently, the developments will be coordinated and synergize to produce the highest quality, most cost effective castings.

The proposed program will be conducted by a team comprised of utility and industrial gas turbine OEM's, an investment casting supplier, and an inspection system developer. This team addresses the entire supply chain to produce land based gas turbine castings including: alloy production, investment casting and end users. The team members include:

- ABB: producer of utility power generation gas turbines.
- ARACOR: developer of industrial nondestructive evaluation systems based on computed tomography and digital radiography.
- General Electric: producer of power generation gas turbines, aircraft gas turbines,

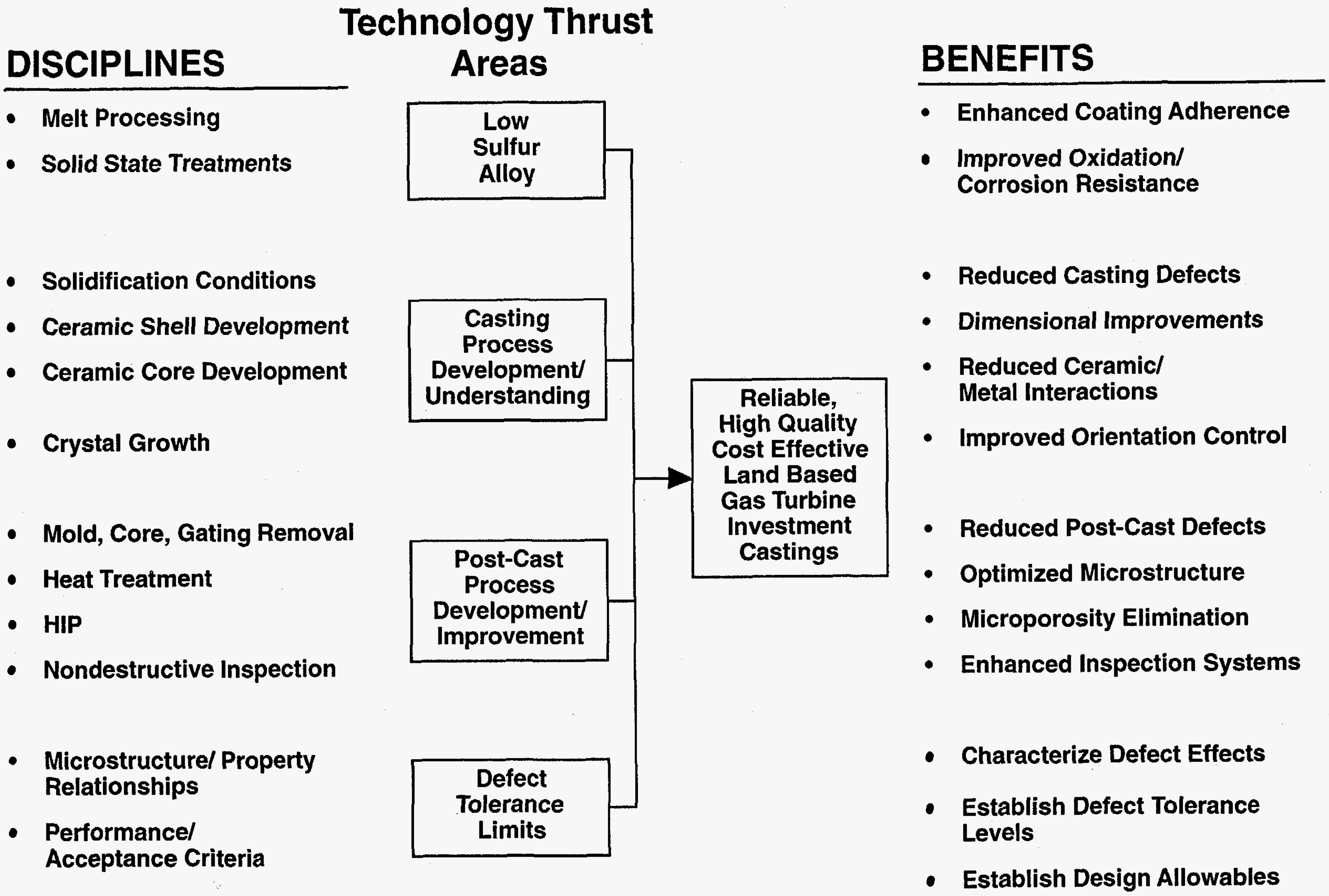

Figure 1. Land-Based Turbine Casting Initiative Technology Thrust Areas

and power generation and aircraft gas turbine superalloy developer.

- Howmet: superalloy supplier and superalloy investment casting company.
- Pratt & Whitney: producer of aeroderivative power generation gas turbines, and a superalloy developer for aircraft and power generation gas turbine applications.
- Solar: producer of industrial power generation gas turbines.
- Westinghouse: producer of utility power generation gas turbines.

Project Description

The program to develop and implement the technology necessary to cast large single crystal components was initiated in June, 1995. The detailed program planning phase has been completed. Technical efforts began in September, 1995. The discussion that follows overviews the program plan and highlights the technical activities to be conducted during the course of this program.

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. Since it is well established that lower sulfur content in castings results in improved oxidation performance, Howmet has developed a process to reduce sulfur content in the master alloy. Low sulfur alloy, in the range of less than 1.0 wppm sulfur, has been produced at Howmet. For this program, special low sulfur heats of GTD 111, PWA 1484 and Rene' N5 will be prepared. The target sulfur level for these heats will be less than 1.0 wppm. Throughout the course of this program, Howmet will continue to improve its low sulfur melt capabilities beyond the limits currently attained and will work to scale the heat sizes from development to production sizes. Cannon-Muskegon will produce low sulfur CMSX-4 and CMSX-10 heats. Possible differences in the sulfur levels attained in the various alloys will be characterized.

Low sulfur components will be cast. One goal during casting is to prevent the bulk pickup of sulfur. The sulfur content of the ingot will be compared to that of the cast components. Low sulfur solid test panels will be cast to provide test material for process scale-up. Flat panels (0.080" thick) will be cast in CMSX-4, PWA 1484, GTD 111 and Rene' N5 current production and low sulfur materials. Cyclic oxidation benchmark testing of the panels with low and current production sulfur levels will be conducted to assess the beneficial effect of low sulfur.

Production scale-up of the low sulfur alloy formulation process will be guided by measurement of residual sulfur contents, cyclic oxidation testing and microstructure characterization. Sulfur analysis will be performed using a LECO model 444-LS sulfur and carbon analyzer. This instrument can measure sulfur contents as low as 0.1 wppm in an inexpensive and timely fashion. Results of experimental work will be used to provide direction in the identification of beneficial process modifications.

DS/SC Casting Parameter Development

Most DS/SC casting processes originated with aircraft applications and evolved to other configurations. Some process attributes can be scaled up or down based on configuration. Other process attributes cannot be readily scaled due to size limitations. This task will examine the effect of scaling casting parameters on both metallurgical and dimensional casting quality.

The current DS/SC process for land based turbines will be benchmarked relative to aircraft blade and vane DS/SC processes. Benchmarking will include: alloy, application (stage and/or configuration), part sophistication (machined or as-cast features), and sophistication of cooling (solid, radial hole impingement, film). The benchmarking includes documenting shrinkage, dross, inclusion, dimensional distortion, wall deviations, and single crystal grain defects. The different types of single crystal grain defects include: primary misorientation, bicrystals, low angle boundaries (LAB), slivers, freckles, and zebras. The grain defects are shown schematically in Figure 2.

Based on the benchmark analysis, designed experiments will be conducted to generate the process knowledge necessary to make true process improvement on large land based single crystal blade configurations. The designed experiments will be conducted on current generation single crystal alloy compositions, Rene N5' and CMSX-4, and a third generation single crystal alloy, CMSX-10. These experiments will examine not only the effects of geometry, alloy composition, and casting parameters on metallurgical and dimensional quality; but also will include mold and core factors as well. The objective of these experiments is to identify the critical factors affecting quality and 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.

Mold Materials and Design

The mold must fulfill the dual role of maintaining casting shape while allowing for adequate heat transfer. These requirements are often conflicting in that a thicker shell improves dimensional repeatability, but reduces heat transfer which can increase the likelihood of metallurgical grain defects. The response of current mold systems and designs will be benchmarked, and explored in the casting parameter designed experiments. Based on the results of the benchmarking and designed experiments, mold development activities will be conducted.

To quantify the capability of current mold systems, statistical data on thermophysical properties will be determined as a function of temperature on molds produced over a 3 month period. The results of these tests will be compared to dimensional data on production wax patterns, molds, and castings collected over the related period of time. Also, the test results will be compared to grain inspection results on castings produced over the related period of time. Where technically justified, the data will be examined for correlations between shell properties and shell performance through casting. Key relationships between shell properties and casting quality will be noted.

Mold development will be conducted to evaluate new concepts to improve those aspects of mold performance identified as most in need of improvement. Such concepts could include use of advanced forms of slurry powders, binders, stuccos, and reinforcements, and various processing modifications. These changes will be evaluated on test specimens and compared to the benchmarking results. Modifications showing promise will be evaluated in integrated casting experiments.

In addition to examining mold performance, the behavior of the waxes that form the patterns will also be investigated. The results of the current program to develop new wax systems for aircraft turbine engine hardware will be examined for application to large utility sized blades. These evaluations will assess the dimensional performance of the new waxes, their compatibility with the mold materials, and the resultant casting surface quality.

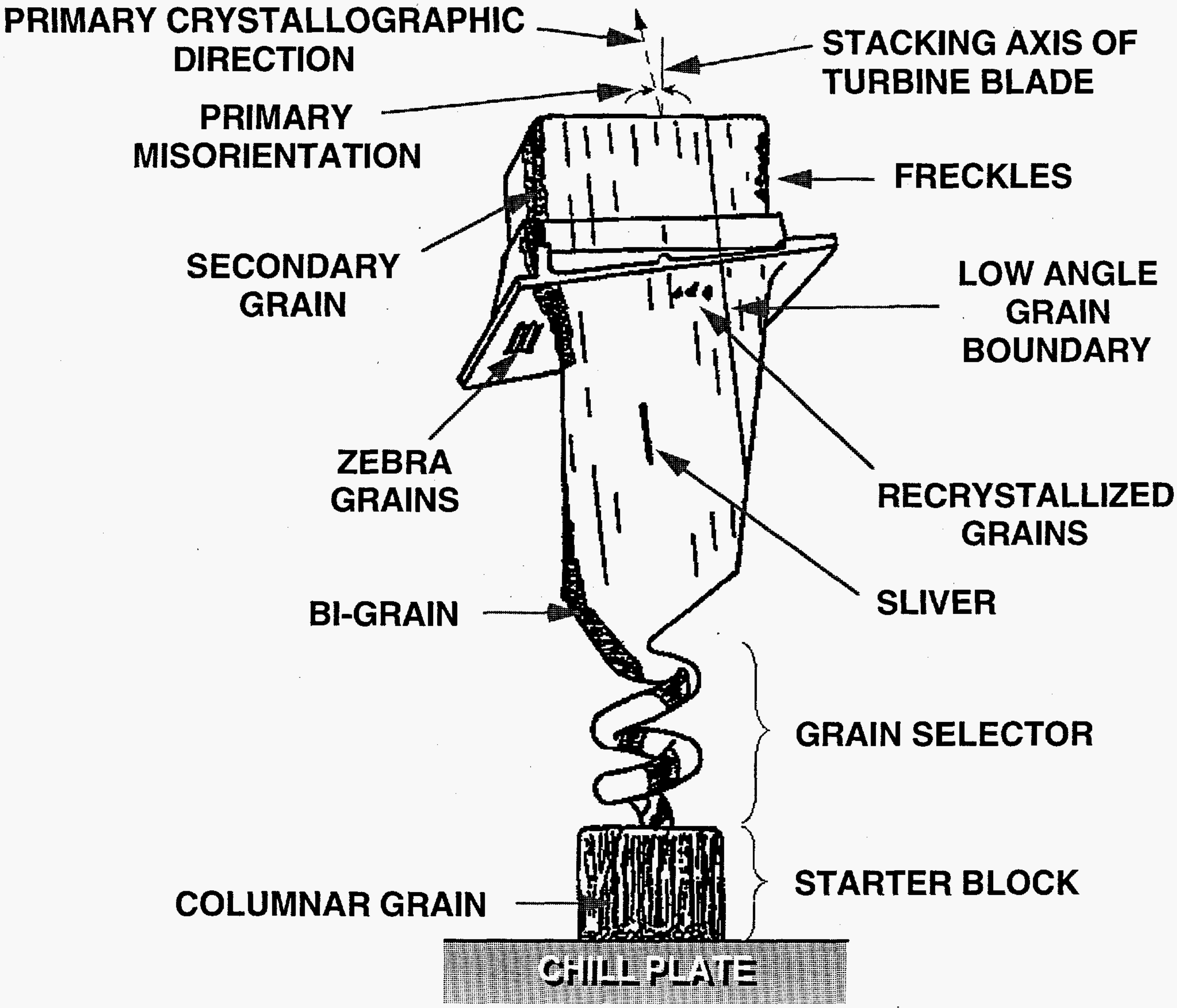

Figure 2. Grain Defects in Single Crystal Turbine Blades

Core Materials and Design

The core produces the internal passages in cooled blades and vanes. As such, the core must be dimensionally stable, not react with the molten metal, but yet needs to be removed from the casting without degrading casting quality. The response of current core systems and designs will be benchmarked, and explored in the casting parameter designed experiments. Based on the results of the benchmarking and designed experiments, core development activities will be conducted.

To quantify the capability of current core systems, current production data will be analyzed to assess the defects attributed to cores. These defects will be related to specific core thermophysical and thermomechanical properties. In addition, alternative core positioning techniques will be investigated for dimensional and microstructural casting effects within the casting parameter designed experiments.

Alternate cores are currently being developed for DS/SC aircraft turbine investment castings to reduce cost and improve core and casting quality. Small trials have indicated that these new cores have potential for the production of the large cores required for utility turbines. This task will extend and modify current developments to examine their feasibility for blade and vane cores. The cores will be evaluated for dimensional, mechanical and visual quality and then integrated into casting portions of the program to evaluate applicability.

Grain Orientation Control

Single crystal castings are used to exploit the anisotropy in superalloy mechanical properties with different crystallographic orientations. As such, control about the desired orientation becomes critical. In this task the procedures for controlling orientation, which were developed on aircraft turbine size components, will be evaluated for applicability to land based sized components. In addition, the phenomena of splaying, the fanning out and rotation of orientations as the crystal grows, will be investigated.

The current orientation control procedures will be benchmarked through visual inspections, X-ray, Laue orientation determinations, and limited investigation of sub-structure using techniques such as electron channeling patterns (ECP). Components cast with several combinations of alloy, component design, mold design and other casting parameters will be characterized to identify the problems associated with scale up of single crystal casting technology. A principle activity in the benchmarking will be to define the extent of orientation splaying. Splaying will be assessed using Laue techniques and ECP at different locations along and normal to the primary axis of the casting.

Based on the results of the benchmarking analysis, new procedures to achieve better orientation control or to reduce splaying will be evaluated. Factors to be considered include different starter configurations, different selector configurations, and modified casting parameters. Modifications showing promise will be evaluated in integrated casting experiments.

Mold and Core Removal

After casting, the ceramic mold and core must be removed from the casting without degrading the casting quality. The current ceramic mold and core removal systems, which were derived from those used on aircraft turbine castings, will be benchmarked for applicability on large, land based turbine castings. Specifically, the benchmarking will examine the levels of scrap or rework caused by poor procedures. The benchmarking will also examine the time required for core removal in large components, and determine its impact on overall casting cost.

Based on the benchmarking analysis, deficiencies in mold and core removal procedures will be assessed, and new procedures developed and tested to evaluated their effect on part quality and cost.

Airfoil Cleanup Techniques

Gating removal and airfoil cleanup techniques may be very different for land based components as compared to aircraft turbine components due to their very different sizes. For example, aircraft turbine components are typical small enough to handle manually. For land based turbine components, manual handling may not be acceptable. The current systems used to remove the gating and clean the airfoils will be 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 will be developed and evaluated.

Post Cast Processing

Post cast processing operations include heat treatment, HIP and quality inspections. The current heat treatment and HIP operations, which have been developed for aircraft turbine size components and limited section sizes, will be benchmarked for applicability to large land based components which may exhibit coarser dendritic structures, and more severe levels of macrosegregation and porosity formation. New techniques will be developed and tested based on the results of the benchmarking analysis.

Two principal aspects of post cast processing of large single crystal castings will be evaluated; these relate to gamma prime morphology and secondary microstructural features. With reference to the gamma prime morphology, the focus will be on cooling rates attainable from the solution heat treatment temperature in large single crystal components. The study of secondary features will address the presence of casting porosity and microstructural inhomogeneity, and the feasibility of their reduction via homogenization heat treatment and HIP. To address heat treatment and HIP of large land based components, test bars will cast and used to simulate casting and cooling rate conditions attained in large components. Using the specimens with intentionally simulated microstructures, mechanical properties such as creep and fatigue will be evaluated. For power generation operation, long time creep behavior is most relevant and it is important to establish if this is altered by the starting gamma prime size, given that gamma prime coarsens during long-term service operation. In addition, the thick root sections of large components will be evaluated for segregation and porosity, and then given heat treatment and HIP cycle to verify the above results. The goal here will be to establish the sensitivity of different alloys to gamma prime size variations and to determine if the HIP response in land based turbine components is similar to aircraft turbine hardware.

Based on the results of the above analyses, alterations in the heat treatment and HIP procedures developed for aircraft sized components will be evaluated. These investigations will most likely include gradient bar tests to establish the solutioning and incipient melting behavior of materials with different levels of segregation. These analyses may indicate the need to slow the solutioning heat up rates or extend the solution temperature hold times. The heat treatment studies will also be coupled with HIP studies to ensure closure of microporosity. The objective will be to define optimized processes to produce the appropriate microstructure.

Defect Tolerance Limits

The complete elimination of single crystal grain defects may be very difficult in large component sizes for some alloy compositions. This subtask will assess the performance loss associated with having defects present. Test material with freckles and recrystallized grains will be cast, heat treated, and machined for mechanical testing. To evaluate the effect of LAB misorientation, seeded bicrystal slabs with varying LAB misorientation will be cast. LAB's in these slabs will be characterized by visual macroetch and X-ray Laue techniques. Specimens will be machined with the LAB normal to the stress axis or located in a highly stressed notch area. The types of testing to be conducted include: creep, fatigue, and tensile testing.

Primary orientation control within the specification range defined for aircraft turbine engine components may be difficult for land based components due to the increased size. This effort will assess the performance loss as a function of primary axis misorientation. Creep and fatigue data will be generated as a function of primary misorientation, so that primary grain orientation control specifications can be better defined.

Inspection System Development

Investment casting designs, particularly high performance turbine blades and vanes, are rapidly evolving in complexity. In order to reduce the development cycle for a new design, it is necessary to monitor and control the critical dimensions of the casting and associated cores and molds. In addition, detailed knowledge of the casting geometry is necessary to plan the drilling of cooling holes during airfoil manufacturing. A new approach to dimensional control of castings and casting machining operations 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.

The complete reconstruction of an electronic data file requires three major steps. First, the accurate position and shape of 2D features in each view is determined by model-directed image feature extraction. The model is a deformable template based on the CAD file of the component. The template adapts to the local X-ray intensity pattern of the feature and is able to locate the feature to sub-pixel accuracy. The use of a deformable model also provides the necessary integration to achieve accurate geometry in the presence of high quantum and sensor noise levels. This last point is particularly important in the case of power generation turbine castings since these castings can exhibit long X-ray path lengths which results in poor contrast images and a low signal-to-noise ratio.

Next, a set of correspondences is established between feature projections in each X-ray image where the features are visible or relatively unoccluded by other internal geometric boundaries. From two or more correspondences the 3D geometry of a feature can be reconstructed by stereo triangulation. The accuracy of the 3D reconstruction is directly related to the accuracy by which the position and shape of the feature in each 2D X-ray image projection can be determined. In this phase of computation, the reconstructed 3D geometry is reprojected into each X-ray image and a global optimization is performed to minimize the error of reconstruction. Also in this phase, the identification of secondary features such as porosity occurs.

Thirdly, it is necessary to correlate the measurement of the external dimensions of the part with the internal feature geometry. This integration of data provides a uniform description of the part dimensions and can improve the accuracy of the X-ray dimensional measurements by providing local coordinate datum refinement. This refinement requires an optimum global solution which minimizes the difference between feature position and shape, as determined by 2.5D reconstruction, and determined by external gauging.

Future Activities

The activities described, as contained in the detailed program plan, will be executed over the next 30 months. The activities have just commenced and will be reported in future meetings.

Acknowledgment

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