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DEVELOPMENT OF ADVANCED CORES AND CASTINGS FOR IMPROVED GAS TURBINE PERFORMANCE

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ABSTRACT

Perhaps the most significant design challenge in a modern gas turbine is maintaining adequate life of the high-temperature blades without sacrificing performance through excessive cooling air. This optimization requires tight integration between the mechanical, aerodynamic, and thermal design of the blade and the manufacturing constraints of the ceramic core and superalloy investment casting process. One turbine manufacturer has recently completed a facility to develop and manufacture advanced, high-performance ceramic cores, validate these cores in the casting process, produce cores at scale, and produce castings at pilot scale.

This paper describes the three-dimensional, complex design features of low-flow ceramic cores and discusses some of the related manufacturing implications for the cores and castings. An overview of the production facility will be given, including ceramic core processing, methods to adapt single crystal investment casting to these complex geometries, and new inspection techniques involving high-powered computed tomography. Lastly, examples will be shown of the techniques and advantages to cycle and yield of modeling, including grain growth, microstructure, core shift, and residual stresses.

INTRODUCTION

As gas turbine efficiency increases significantly with turbine inlet temperature, design requirements of the first stage turbine blade have become increasingly challenging. Turbine inlet temperatures in the newest machines are several hundred degrees higher than the melting point of nickel-based superalloys from which the hot gas path components are cast. These components operate with a three year service interval and achieve that design life through single crystal, creep-resistant metallurgy, dense vertically-cracked thermal barrier coatings, shaped-hole film cooling, and internal turbulated cooling passages (Figure 1). Cooling air used inside the blade does not produce useful work in that turbine row and therefore significantly reduces turbine output and efficiency. Designers are constantly seeking to decrease the amount and increase the effectiveness of that cooling air.

Figure 1. Finished gas turbine blade manufactured as an investment casting with a ceramic core to form internal cooling channels.

CERAMIC CORES FOR ADVANCED BLADE COOLING

The ceramic cores used in the investment casting process to create internal cooling passages are themselves subject to design and manufacturing constraints. These cores are conventionally produced by injection of a ceramic slurry into a hard-tooled metal die, with subsequent firing and finishing processes. The die design requirement of a single pull plane or a reasonable number of slides restricts the design options for the internal cooling passages, typically resulting in a fairly simple internal structure similar to that shown in Figure 2. While this configuration will pass a significant amount of air through the blade, it is evident that a limited fraction of the cooling air is directly against the hot surface of the metal, and much of the air is wasted passing through the interior of the blade, despite the mitigating strategy of serpentine passages, with flow up one passage and down another.

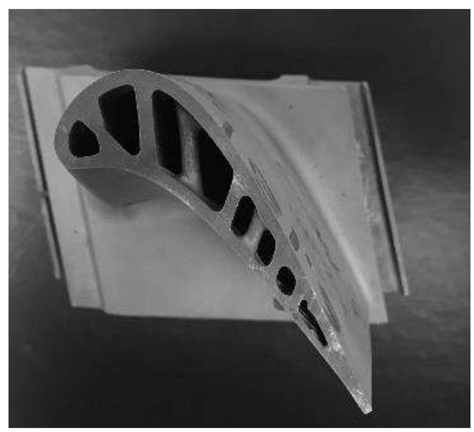

Figure 2. Cross section of gas turbine blade with conventional internal cooling.

Designers have long envisioned more complex internal structures such as that

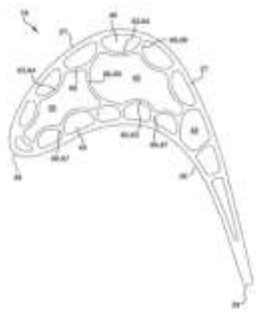

Figure 3. Schematic of cross section showing Advanced Blade Cooling.

shown in Figure 3[1], where the lowest temperature cooling air can be restricted to the hottest internal surfaces of the blade, and leave the center of the blade stagnant or for the return of spent air. In such a manner, the same blade temperature can be achieved with lower cooling air flow, a cooler blade can be achieved with the same flow, or a higher gas path temperature can be achieved with the same flow and the same blade temperature. In any of these applications of Advanced Blade Cooling (ABC), there is a significant benefit to overall machine performance. The gas turbine industry has spent significant effort attempting to develop the design and manufacturing technology needed to produce the ABC ceramic cores required to cast these complex shapes.[2 3 4]

One such ceramic core resulting from that research is shown in Figure 4 and the corresponding blade in Figure 5. Volume production of these components is part of the GE 7HA.02 product line.[5] While details of the specific manufacturing technologies involved are not relevant to this summary of its impact on investment casting development and application, the process is not constrained by conventional dies and hard tooling, thereby improving the designer's ability to optimize performance. Overcoming the technical issues created by removing these limitations, however, has taken nearly a decade of research and development.

Figure 4. ABC ceramic core.

Figure 5. Single crystal blade cast with an ABC core.

DESIGN AND APPLICATION CONSIDERATIONS

The development of these cores necessitated close integration with the design process for air-cooled gas turbine blades. External aerodynamics are unaffected by the advanced cores, as this was an early design constraint. In some cases, existing analysis tools for internal flow and heat transfer were modified to account for new flow geometries, including turbulators, pins, flow splits, and film cooling hole inlet conditions. Mechanical design is affected through the impact of the internal shape on response frequencies and magnitudes, as well as the complexity of managing fatigue and life of the internal metal structure under transient conditions.

Considerable effort was required to engineer a ceramic that is capable of being precisely formed to these complex shapes, but that is also compatible with subsequent ceramic firing and finishing and with the casting process itself. The complex geometry and large variations in characteristic dimensions require shrinkage rates, composition, and firing cycle to be optimized to minimize cracking while maintaining dimensions and strength, a design challenge assisted by drawing from the depth of the manufacturer's expertise in ceramics processing and ceramic matrix composites. The ceramic composition, firing stages, and fixture strategy acting together create a system that produces a repeatable and dimensionally-stable process.

A further development objective was to minimize the need for changes to the single crystal casting process, and to adapt the advanced core design to make subsequent casting and post-cast process comparable for blades with either conventional cores or advanced cores, as demonstrated through casting trials. The core material is slightly stronger than conventional serpentine cores and thus has good yield through wax pattern injection but is not so strong that it causes internal stresses that lead to recrystallization. Thermal expansion characteristics at casting temperature are similar to conventional cores, and thus the material can be used with the same shelling system and slip techniques familiar in the industry today. Some consideration had to be given to internal core supports, pinning locations, core bonding, reducing porosity at

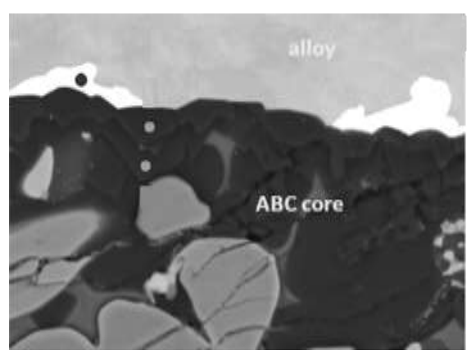

Figure 6. Micrograph of interface between core and cast alloy.

turnarounds, managing residual stress, and leaching. Detailed micrography has confirmed that the interaction between the core and the alloy is similar to that expected for a high silica core (Figure 6).

The resultant ABC core has characteristics similar enough to conventional serpentine cores used today that it can be cast and leached via conventional processes, leaving behind the complex cooling channels in the airfoil. Internal and external casting trials have validated the ceramic core technology is mature to the point where it can be cast across multiple foundries with minimal changes to existing casting processes.

DIAGNOSTIC TECHNIQUES

An additional significant consideration in the application of these three-dimensional, multi-wall cores is inspectability. Borescope access to every internal region of the blade can no longer be assured, and internal wall dimensions cannot be nondestructively evaluated with conventional ultrasonic techniques. While conventional digital radiography is useful in some sections of the blade, internal features in the complex blade cannot always be clearly seen and inspected, as illustrated in Figure 7.

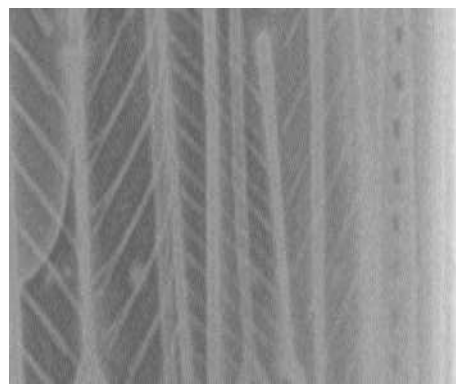

Figure 7. DR of portion of a blade with advanced cooling.

Consequently, the introduction of advanced cores into castings required the development of high-powered computed tomography equipment and techniques for this application. Such a CT system was developed, validated, and installed in the foundry specifically for this purpose. Edge detection software was leveraged from the manufacturer’s medical imaging technology to automatically detect and calculate for the entire blade or any cross section exterior dimensions, exterior wall thicknesses, interior wall thicknesses, radial heights, and cooling flow passage diameters. To date, the system has been determined to be more accurate than UT inspection. It is also capable of detecting residual core, finning or flashing, kiss out, and other casting defects. As shown in Figure 8, blades can be inspected prior to shelling and leaching if desired and molds can be inspected prior to casting. The inspection time is sufficiently fast to allow for 100% inspection of every blade, if desired.

Figure 8. One slice from a CT image of a conventional blade, with core and shell.

A separate commercially available CT system is used to inspect quality and dimensions of wax patterns and cores prior to casting, which again can be 100% inspected. This overall capability has proven to be invaluable as a development and diagnostic tool, and has the potential to significantly affect future part inspection and qualification strategies in the industry.

CORE REPAIR

A secondary benefit of this advanced core development (but one that is very relevant for the manufacture of a highly engineered, high value add component) is the apparent improved repairability of the ceramic material. One example of this is shown in Figure 9. During trials, cracks are occasionally found in regions of the trailing edge pin bank, as evident in the closeup showing the visual image (top). The cracks were repaired with a method specifically developed for this type of defect, primarily a surface repair. The internal crack is still easily visible in the CT/radiography image of the core and pattern prior to shelling and casting (middle). After casting however, no evidence of finning or flashing can be seen in the CT/radiography image for that location (bottom).

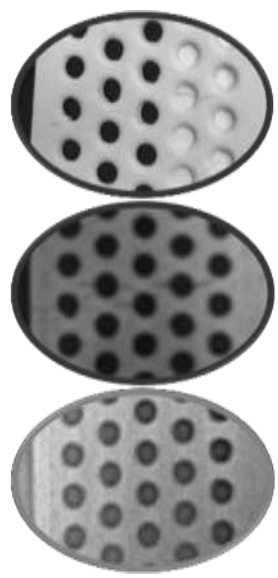

Figure 9. Representative repair and resulting casting of an advanced core.

Other comparable repairs have been developed for other indications and validated through casting trials. Collectively this has significantly improved yields and suggests engineered ceramics can be more thoroughly repaired for casting applications than was perhaps previously thought.

RAPID PROTOTYPING AND SHORT CYCLE PRODUCTION

A further benefit is the ability to make ceramic cores in a compressed development cycle. Without the need for fixed tooling, the often-significant core die design and manufacturing cycle can be eliminated, and prototype ceramic cores can be available on a relatively short cycle for further process development. Two examples are shown here. The first (Figure 10) is a tip shroud core produced to final dimensional and finishing standards and available for casting within 39 days of design conception. The second (Figure 11) is a ceramic core for a legacy gas turbine stage 1 blade, where the core was produced for rapid prototype wax patterns and conventional shelling before directionally solidified casting, with a 5 month total cycle from design to casting qualification.

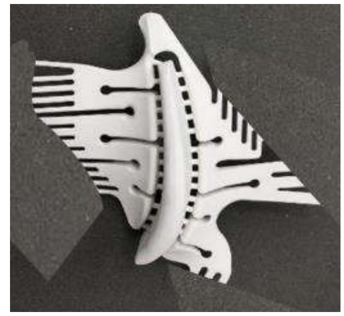

Figure 10. Rapid prototype tip shroud core.

In both of these instances, the design of the core was such that conventional manufacturing processes could have been employed. The motivation was a shorter product introduction cycle. The ability to manufacture high quality, complex ceramic cores for precision castings will be a significant advancement for the investment casting industry when more broadly available.

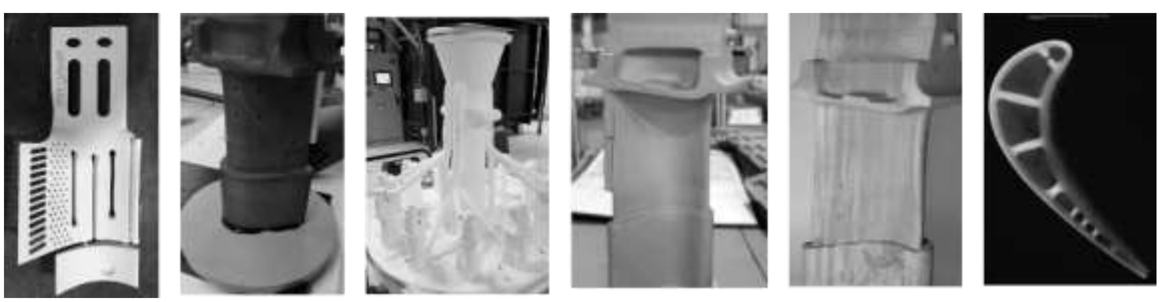

Figure 11. Rapid prototype core, pattern, and resulting production of DS blades.

CASTING DEVELOPMENT FACILITY

A key lesson learned from the introduction of this type of ceramic core is the tight integration required between the core and the casting design processes and the core and casting manufacturing processes. Initial attempts to design and manufacture cores internally for external casting were not as effective at this integration, and significantly delayed the development cycle. This trend is expected to continue as gas turbine blade design concepts become increasingly complex. Consequently, in addition to an internal production facility with the capacity to meet the manufacturer's entire projected demand for Advanced Blade Cooling ceramic cores (the bulk of which will be used for casting in the existing external investment casting supplier base), an internal pilot-scale investment casting development facility was also built.

The primary purpose of the casting facility is to validate ceramic core designs in castings and thereby reduce the risk of technical issues or delays when they are used in full scale casting production at external suppliers. While the development foundry has broad casting capability, it has limited capacity, and at this small scale is not well suited for high volume production. It is intended for development, engine test production, product launch, and small volume specialty jobs. Its scope is limited to single crystal and directionally solidified castings.

Most of the equipment in the foundry is of conventional design and is drawn from existing single crystal investment casting suppliers. Some of this equipment is shown in Figure 12. Ceramic core manufacturing equipment includes a slurry mixer and tower, a

Figure 12. Representative photos from equipment in casting development casting facility.

shuttle kiln operating in batch mode for various stages of firing, and multiple finishing stations for manual touch up and repair. Cores are 100% inspected for dimensions using blue light and CT systems. Bonding of multi-part cores, e.g. separate main body and trailing edge, is done in the wax room.

A 50-ton press is used for wax injection of patterns and chills, with again, characterization of injected patterns by CT and blue light methods. Patterns are assembled into trees both in-house and with external vendors. A development shell system allows for shells to be manufactured with a wide range of slurry and stucco materials prior to de-wax, sintering, and mold preparation using standard equipment. The vacuum induction melting single crystal casting furnace is sized to allow casting of the current largest industrial gas turbine parts, with some allowance for future growth. Most post cast processes, including grit blast, leach, etch, FPI inspection, etc. are performed internally, primarily to reduce development cycle time. As mentioned, all blades are subject to a CT scan to assess internal dimensions, cleanliness, and part quality.

Figure 13. Completed ABC cast blade, meeting required specifications.

MODELING AND NUMERIC SIMULATION

Accelerating the introduction of a new casting design, and in many cases the successes of the introduction itself, increasingly requires numerical simulation to guide the design, reduce unproductive casting iterations, and give physical insight into the relevant physical processes. Significant advancements have been made in the accuracy and usefulness of such design tools, including both proprietary codes developed by individual manufacturers and industry-wide commercial codes. This section highlights those advancements most relevant to the development of the multi-wall cores described above.

The three-dimensional nature of the ABC core with internal ligaments and multiple separate flow tubes complicates analysis of the relative motion of the core during sintering, preheating, casting, and solidification. Solid motion, rotation, and deformation of the core and shell were modeled to understand these phenomena (Figure 14) and after validation in casting trials, this information was used to determine the intentional mean shift of the cores (main body and trailing edge) in the wax pattern required to ensure proper wall thicknesses at each cross section. Process capability and positioning of exterior and interior wall thicknesses were held to approximately 0.010”.

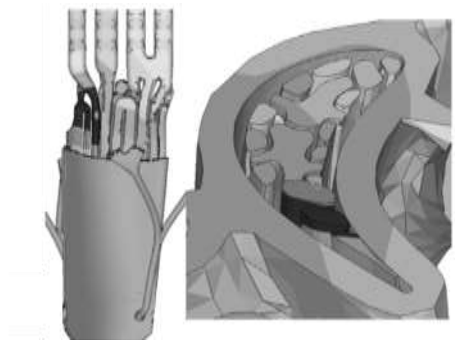

Figure 14. Prediction of core relative motion during casting process.

A further complication of the ABC core is the extent of internal walls in the casting and the increased possibility of residual creep and plastic deformation that could result in residual stress upon cooling and recrystallization or grain nucleation in subsequent processing. This design challenge is confounded by the simultaneous constraint of achieving adequate creep and low cycle fatigue life in the operating blade and required successive design iterations to achieve design targets with a corresponding low probability of internal grain issues. A representative analysis is shown in Figure 15. Prediction of location of residual stress during castingFigure 15.

Figure 15. Prediction of location of residual stress during casting

Figure 16. Prediction of wax flow and core stresses during injection.

During early stages of development prior to engineering of the eventual ceramic slurry composition there was concern about increased risk of core breakage during pattern injection. Modeling and simulation were used to assess that risk (Figure 16) and tune injection parameters as required, as well as to ensure complete fill. In general, however, injection of the ABC core has not been more difficult than a conventional core, as some standard cores also have finely detailed features such as trailing edge slots.

Lastly, and perhaps most importantly, the complexity of the core implies a more torturous path for crystal growth from initiation at the tip (for a tip down configuration) through the core to the platform and root, creating multiple opportunities for grain initiation or increased porosity on the core surface. These risks were analyzed through the combination of a commercially available code for the thermal and solidification front modeling and an in-house code for metallurgy, microstructure, grain nucleation, and freckling. The latter code is a stochastic model, owing to the probabilistic nature of nucleation.

One intermediate result is shown in Figure 17, where the rise and propagation of stray external grains are shown. Reducing the probability of such stray grains, whether at the inner or exterior surface, was obviously a key benefit and objective of the numerical analysis. The microstructure modeling, though computationally intensive, was critical in guiding core design to reduce the probability of defects. The solidification analysis was also critical to designing the initial gating, support mechanisms, and continuators.

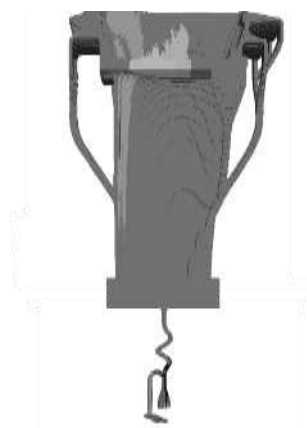

Figure 17. Prediction of grain structure and metallurgy.

CONCLUSION

The development of three-dimensional, multi-wall, precision ceramic cores for volume production has enabled a new generation of reduced cooling flow, high performance superalloy casting used for gas turbines blades. This success follows the introduction of a new suite of simulation tools for cores and castings, and completion of a development casting facility for experimental validation and pilot lot production.

Beyond this, however, the effort has led to complementary benefits, including a stronger and more repairable ceramic core material, accelerated cycle development, processes for manufacturing complex cores without fixed tooling, and new CT-based diagnostic techniques, further demonstrating the potential for ongoing significant improvements in the precision investment casting industry.

ACKNOWLEDGEMENTS

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