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Internally Cooled Turbine Rotor for Small Gas Turbine



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August 28, 2017

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ABSTRACT

In collaboration with Brayton Energy LLC, ORNL worked to develop the necessary processing science for the high-gamma prime Ni-base superalloy CM247 for advanced small turbine applications. Preliminary monotonic testing indicated the behavior of electron beam melted (EBM) CM247 achieved similar properties of the cast counterpart. Brayton has applied these results to both radial and small axial turbine rotor designs. Preliminary results indicate that measurable increases in turbine inlet temperature may be achieved while respecting aerodynamic constraints.

1. INTERNALLY COOLED TURBINE ROTOR FOR SMALL GAS TURBINE

This phase 1 technical collaboration project (MDF-TC-2015-075) was begun on September 16, 2015 and was completed on July 1, 2017. The collaboration partner Brayton Energy LLC is a small business. ORNL and Brayton demonstrated electron beam melting (EBM) additive manufacturing processing conditions to enable EBM deposited Ni-base superalloy CM247 material to achieve mechanical properties similar to conventional cast material.

1.1 BACKGROUND

Across the gas turbine community, there continual need for technological innovations to push the efficiency of gas turbine engines higher. Due to limitations of current materials, component design is becoming the frontier for sustaining increases in gas turbine engine efficiency. In the case of small gas turbine rotors, designs of small gas turbine rotors with internal cooling passages exist, that in theory would lead to an efficiency increase. However, only additive manufacturing technologies have the flexibility to fabricate the geometries. Within this space, Brayton Energy has developed the design, prototyping, and testing expertise for these cutting-edge turbomachinery and gas turbine systems.

The firing temperature of a gas turbine is the primary factor influencing its thermal efficiency. This method allows the gas temperature to be hundreds of degrees above that of the metal surface. Industrial gas turbines over 4 MWe and most aero-derivative engines employ insertable hollow turbine blades with intricate internal cooling passages. The improvements associated with the increased turbine inlet temperature (TIT) are somewhat off-set by the thermodynamic decrement associated with the over-board cooling air flow. Turbine blades made by this method are cost-prohibitive for smaller gas turbines.

However, microturbines and small gas turbines, in the 10 to 2000 kWe range tend to employ a single uncooled cast turbine rotor, either of the radial or axial type. For smaller microturbines employing a recuperator, the higher firing temperature must be accompanied by an increase in pressure ratio to maximize the efficiency gains. Increasing the expansion ratio with the turbine's inlet temperature enables the recuperator inlet temperature to remain at tolerable (economical) levels. However this increases the challenge of meeting the rotor's creep life target. Higher pressure ratios translate to increased turbine tip speed and stress levels. A preliminary evaluation of the cooled radial turbine rotor shows that the blade thicknesses will likely increase to accommodate internal cooling passages. Thicker blades tend to result in higher aerodynamic blockage and consequential losses. Further, thicker blades tend to increase the root stress at the rotor hub. The preceding discussion serves to

emphasize the complex interactions between the system requirements, the turbine design, and the proposed new manufacturing method.

Because the extraneous operational conditions that these advanced component designs will experience, significant advancements in the high temperature alloys currently processable by additive manufacturing (AM) technologies is required. Specifically, the ability to process high-gamma prime containing nickel-base (Ni-base) superalloys is needed. The technical challenge with these alloys is their tendency for cracking upon solidification. The alloy selected for the additive metal process will require high tensile and creep strength at elevated temperatures, in addition to being oxidation resistant. The state-of-the-art microturbine and small blisk employs MarM247 or a similar creep-resistant vacuum melt casting alloy.

1.2 TECHNICAL RESULTS

1.2.1 Material Processing

ORNL fabricated sample coupons from the high-gamma prime Ni-base superalloy CM247 using the Arcam Q10+ electron beam melting (EBM) technology that has been modified for processing of high temperature metals. The Ni-base superalloy CM247 was chosen due to being the low carbon variant of MarM247. The reduced carbon content of the alloy has been shown to lead to a reduction of defects during casting of the alloy. Additionally, in evaluating suitable AM processes to use for fabrication of the material, the EBM process provides the unique capability of heating the powder bed to temperatures in excess of 1000 °C and operating in a vacuum. The heated powder bed provides the benefit of reducing the potential for residual stresses to accumulate within the part, and mitigation of many of the solidification related cracking phenomena in CM247.

Illustrated in Figure 1 is the build layout used in this study for the fabrication of microstructure and tensile coupons. Due to the thin wall nature of the components of interest, the coupons were slim in nature, being 8mm in diameter and 50mm in length. Due to the sensitivity of crack formation to part geometry and build layout to process parameters, several builds were completed to minimize the defects such as porosity and cracks within the material.

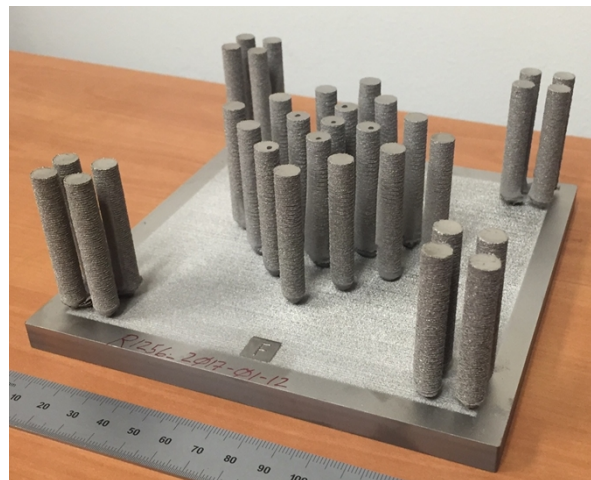


Figure 1: Example CM247 build of microstructure and tensile coupons.

1.2.2 Microstructure Characterization

In the as-fabricated state, the EBM deposited CM247 exhibited elongated grains aligned to the build direction as illustrated by the grain orientation map in Figure 2. In most instances, the grains are on the order of 1mm in length which is the thickness of 20 layers on average and have widths in the 100 micron range. Microstructurally, the gamma prime size and volume fraction is z-height sensitive in the as-fabricated state. This is the result of the time at temperature of the different layers of the build.

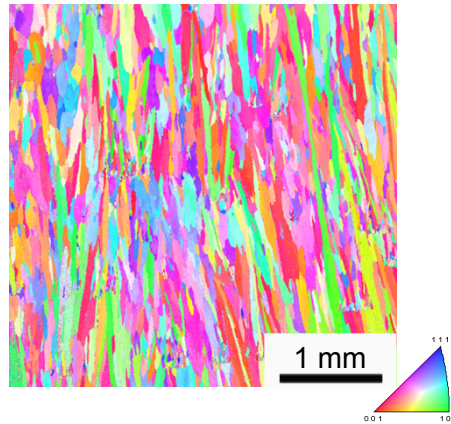


Figure 2: Representative SEM grain orientation map of as-fabricated CM247 indicating a columnar grain structure aligned with the build direction.

To homogenize the material, the material was given a hot isostatic press (HIP) and aging treatment. Shown in Figure 3 is the resultant microstructure that indicates the gamma prime precipitates are uniform in size and distribution. It should be noted though, that during the HIP step, the grain structure did undergo recrystallization as evidenced in the grain orientation map in Figure 4 by the random grain size and breakdown in the columnar structure.

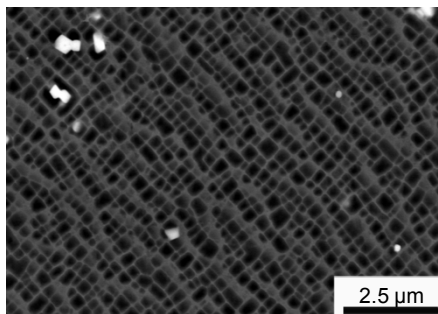


Figure 3: Post-processed gamma prime precipitate structure depicting a uniform size and shape.

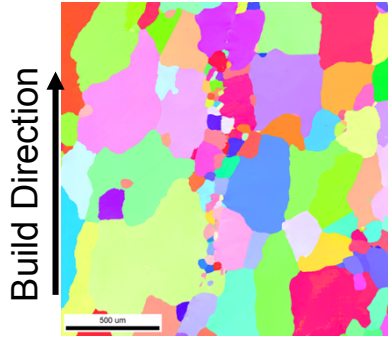


Figure 4: Recrystallized grain structure in the post-processed CM247 material.

1.2.3 Preliminary Tensile Properties

Preliminary monotonic testing of fully post-processed CM247 material fabricated through the EBM process was conducted at 850, 900, and 950 °C. These temperatures are most relevant due to these being representative of the operational temperature of the components. Summarized in Table 1 are the elastic and plastic properties as a function of temperature. Comparing the yield and ultimate stress of the EBM fabricated material, these values are similar to those obtained in cast CM247 at identical temperatures. Interestingly though, the elongation at failure is observed to decline with temperature which is inverse to what is typically observed in the cast material. This trend can largely be attributed to the sensitivity of Ni-base superalloy properties to grain size, dendrite arm spacing, and solute segregation.

Table 1. Summary of Tensile Properties of EBM CM247

Temperature [°C]	Elastic Modulus [GPa]	Yield Strength [MPa]	Ultimate Strength [MPa]	Elongation at Failure [%]
850	145	750	897	5.9
900	165	750	819	5.25
950	116	550	630	4.4

1.2.4 Preliminary Component Design

After preliminary examination of small axial and radial turbines designed and tested by Brayton, it was decided to focus initially on radial turbines. In approaching the problem, Brayton created a baseline uncooled radial turbine for a relatively high expansion ratio of 6.0. This reference design is illustrated in Figure 5. The most notable feature of this design is that it contains a full backface. While this is not fundamental to the approach, the back-face offers aerodynamic and mechanical efficiency benefits.

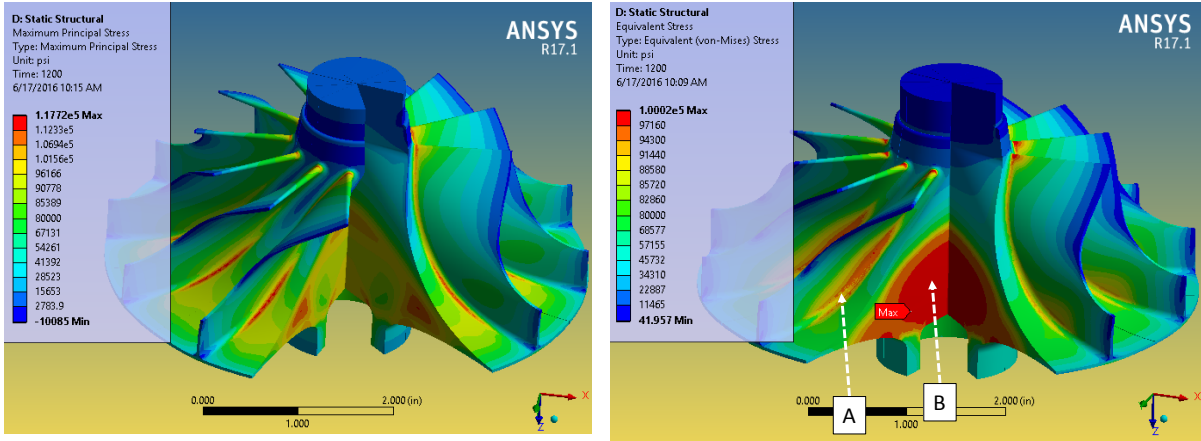


Figure 5 – Principal and Von Mises stresses for reference radial inflow turbine design.

In the reference rotor, location A (figure 5) indicates the zone where temperature and stress combine for the maximum creep rate. The rotor bore, “B” has the highest stress. A series of thermal mechanical design studies were performed to evaluate the impact of locating a cooling passage located under each of the 12 blades. The challenge in the design is to lower the temperature in the creep limiting region without disproportionately increasing stress. The theory of a pure radial hole, running just under the blade, in the thickened back-plate showed promise towards this goal. The challenge is to connect this port to a practical region of the shaft which can facilitate cool air injection. For the purposes of this study, the air was to be injected into the rotor between seals on the shaft. As shown in Figure 6, the route from inlet port to the radial cooling conduit under the blade must pass through the bore, thereby raising stresses in effected regions of the rotor. Figure 6A illustrates a path wherein the cooling is brought close to the creep-limiting region of the blade root. This was shown to raise stresses excessively, off-setting the cooling gains. Figure 6B indicates a more conservative path which results in lower stress levels.

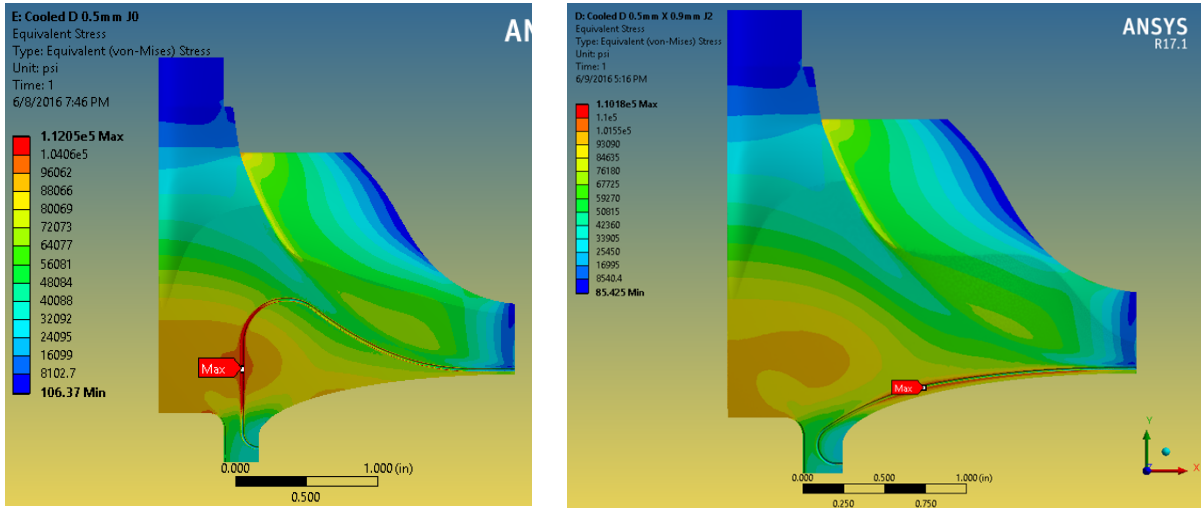


Figure 6. Reference rotor showing two possible routes of the cooling passage, emanating from the shaft, and delivering the cooling air to the blade tip.

A series of trades involving the cooling path, port diameter, and cooling air flow and pressure are underway. Preliminary analysis indicates that optimization of these parameters will lead to measurable improvement in creep life and firing temperature.

1.3 IMPACTS

Improved efficiency is naturally a goal of all gas turbine engines. Brayton is evaluating the potential benefits of a high firing temperature turbine in the broader context of gas turbine economics. Two primary cost factors will be quantified in the final cost analysis. First, the Additively Manufactured (AM)-produced part cost will be compared against the cost of today's competing investment castings. Secondly, higher firing temperature is also accompanied by increased specific power. That is, the effect of raising turbine inlet temp and pressure should result in increased power, without proportional system cost increase. For example, expensive subsystems such as the combustor and the recuperator show strong sensitivity to specific power. Success in this program will be measured against both efficiency and product cost metrics. For this reason, it is likely that both efficiency and product cost improvements will be realized with a successful project. The overall levelized cost or electricity will use to measure the progress of the project.

The findings of this program have the ability to affect a number of current programs ongoing at Brayton. The improvements expected from this project would enhance the selling proposition for these formative business ventures.

1) 12 kWe gas turbine designed for remote tele-com power stations in Asia and Africa. This engine, delivered to an affiliate of the TATA Group, shows the potential for improved reliability and lower emissions in remote areas. Driven by the growing cell phone market, industry specialists predict that the developing world could utilize over 100,000 such units each year. With improvements in efficiency, this engine is also being considered for small series-electric passenger cars.

2) Range extenders for series-electric vehicles. Brayton is developing advanced 60 and 80 kWe microturbines for class 5-7 delivery trucks. These microturbines achieve emission levels well below that set by the California Air Resources Board (CARB), without the need for after-treatment.

3) An advanced 350 kW intercooler-recuperated gas turbine for class-8 trucks and stationary power. This new engine is currently installed in a Kenworth truck. A stationary version of the engine is entering field testing in 2017.

4) A 1 MWe biomass-fired gas turbine. This engine produces electricity from residual cellulosic materials with greater efficiency, lower cost, and less maintenance than competing steam turbines.

These programs, which represent a cross-section of the distributive power generation, transportation, renewable energy, and defense industries hold promise of reduced consumption of fossil fuels and lower emissions.

1.4 CONCLUSIONS

During the course of this project, the high temperature Ni-base superalloy CM247 was successfully processed through the Arcam EBM process. Due to the fabrication conditions and the precipitation strengthening nature of the material, post-process heat-treatments are required to homogenize the material and provide an optimal precipitate structure. Preliminary monotonic tensile properties at high temperature demonstrate the ability of the EBM fabricated material to achieve cast-like properties. To further proof the material for the application, creep testing is required to provide additional design guidelines to the component engineers. Meanwhile, Brayton is continuing to optimize the reference radial turbine design for elevated temperature. This design shows great promise in two applications; vehicular range extenders and turb-prop unmanned aircraft. A twin axial turbine, capable of higher expansion ratio of 7 to 9 will also be evaluated in the coming months.

2. BRAYTON ENERGY, LLC BACKGROUND

Brayton Energy, LLC is an engineering firm specializing in the design, fabrication, and testing of advanced gas turbines and specialized components for the power generation industry. Brayton's 43-person staff includes specialists in turbomachinery aerodynamics, structural analysis, high temperature heat exchangers, combustion, turbomachinery manufacturing and testing. Research and development projects include advanced microturbines, ceramics for gas turbine hot sections, concentrated solar power, supercritical CO₂, closed cycle gas turbines for nuclear power, gas turbine vehicles, and small turbomachinery for unmanned aerial vehicles.