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Full Scale Engine Demonstration of Additively Manufactured High Gamma Prime Turbine Blade

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Materials Science and Technology Division
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Full Scale Engine Demonstration of Additively Manufactured High Gamma Prime Turbine Blades

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ABSTRACT

Additive manufacturing (AM), also known as 3D printing, is a rapidly developing technology with tremendous potential in both developmental and production applications. Solar Turbines Incorporated is committed to AM technology development for gas turbine applications. The ability to metal 3D print novel designs of turbine blades capable of actual turbine engine operation would effectively reduce design validation cycle time and allow acquisition of key performance data early in a design campaign. In support of Solar's advanced manufacturing development and ongoing engine efficiency improvement goals, ORNL and Solar conducted a project to 3D print, machine, inspect, and engine test a full set of Mercury™ 50 stage 2 turbine blades. This full-scale, hot-fired engine demonstration has identified both the capabilities and limitations of the current technologies required to produce turbine hot-section AM components.

1. FULL SCALE ENGINE DEMONSTRATION OF ADDITIVELY MANUFACTURED HIGH-GAMMA PRIME NI-BASE SUPERALLOY TURBINE BLADE

This project was begun on March 7, 2019 and was completed on September 7, 2020. The collaboration partner Solar Turbines Incorporated (Solar Turbines) is a large business. Through the development efforts of this program, ORNL and Solar Turbines demonstrated the capability to successfully produce and operate additively manufactured (AM) turbine blades in a hot-fired industrial gas turbine.

1.1 BACKGROUND

The goal of this project is to fabricate prototype additive manufactured (AM) Inconel™ 738 turbine blades and demonstrate suitability for operation in the extreme environment of a hot-fired industrial gas turbine engine. The ability to rapidly fabricate prototype turbine components from a high temperature capable superalloy would allow for significant reductions in the design and validation phases of the product development cycle. Prior Phase 1 work demonstrated capability to AM process Inconel™ 738 and to fabricate a proof of concept AM turbine blade component that displayed minimum viable mechanical properties and component geometries suitable for hot-fire engine testing. With these feasibility results in hand, ORNL and Solar progressed with a project to fabricate a complete set of more than eighty (80) prototype turbine blades for hot-fire testing in a Mercury™ 50 turbine engine.

1.2 TECHNICAL RESULTS

For this program, more than eighty (80) additive manufactured Inconel™ 738 blades were 3D printed on two Arcam EBM machines. Conventional heat treatment and machining processes were then used to meet the final turbine blade surface finish and geometric requirements needed for assembly and hot-fire operation. A combination of in-situ monitoring, Non-Destructive Testing (NDT), and room temperature spin pit proof testing were used to certify the blades for engine operation. The AM blades were hot fire tested in a Mercury™ 50 turbine engine at normal operating speed (100% speed) and under full load, steady state conditions.

1.2.1 Additive Manufacture of Turbine Blade Set

For the additive manufacture of the turbine blades, two Arcam Q10+ electron beam melting (EBM) systems were utilized. The Arcam Q10+ EBM system operates in a controlled chamber vacuum environment of 2x10-3 mBar. Builds were started once a preheat temperature of 1000°C was achieved on a 150x150x10mm 304 stainless steel build plate. A build plate layout of four blades was used to fabricate the oversized turbine blades as shown in Figure 1. For the program, 45 successive builds of 4 blades each were fabricated. Of these 45 builds, only 3 builds failed as a result of machine interruptions which were external events to the Arcam Q10+ printers such as power interruptions. Each build utilized the exact same set of process themes previously developed for Inconel™ 738 during the course of the Phase 1 CRADA with Solar Turbines to evaluate the materials feasibility for this program.

Figure 1: Macro image of a representative build lot of four oversized "as printed" blades produced with the Electron Beam – Powder Bed Fusion (EB-PBF) process. More than 44 builds were produced at ORNL to yield a complete set AM blades required to assemble the Mercury™ 50 bladed turbine disk assembly.

In-situ process monitoring quality check of each build occurred through the collection of layer images using the Q10+ systems built in near infrared (near-IR) cameras. These images were analyzed by an artificial intelligence (AI) algorithm trained by manually annotating cracks and defects of in-situ layer data taken from build of other blade geometries printed and other crack prone nickel materials so as to produce a robustly trained AI. The GUI is shown in Figure 2. Utilizing this AI trained algorithm, all layer images from the 42 successful builds were processed for identifying defect bearing blades and removing them from the population of suitable blades. The cracks identified in the defective blades were associated with the presence of pores or lack of fusion (LOF) defects that impacted the local cooling rates of the surrounding material. A large portion of the pores identified in defective blades were the results of spatter ejecting from the melt pool and landing within the melt area resulting in the appearance of a shallow surface pore when near the surface as in Figure 3 (stereo microscope image) and Figure 4 (CT Radiography).

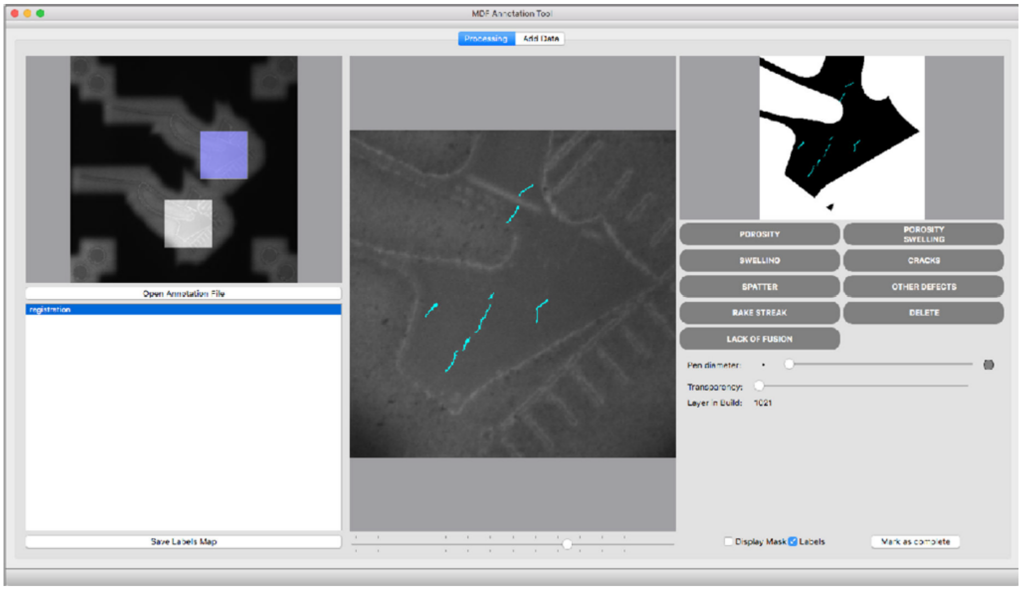

Figure 2: Screenshot of Graphical User Interface (GUI) of annotation tool used at ORNL to evaluate the in-situ process monitoring data. The in-situ data were used to pre-screen AM blade material quality for occurrence of unacceptable cracking and porosity

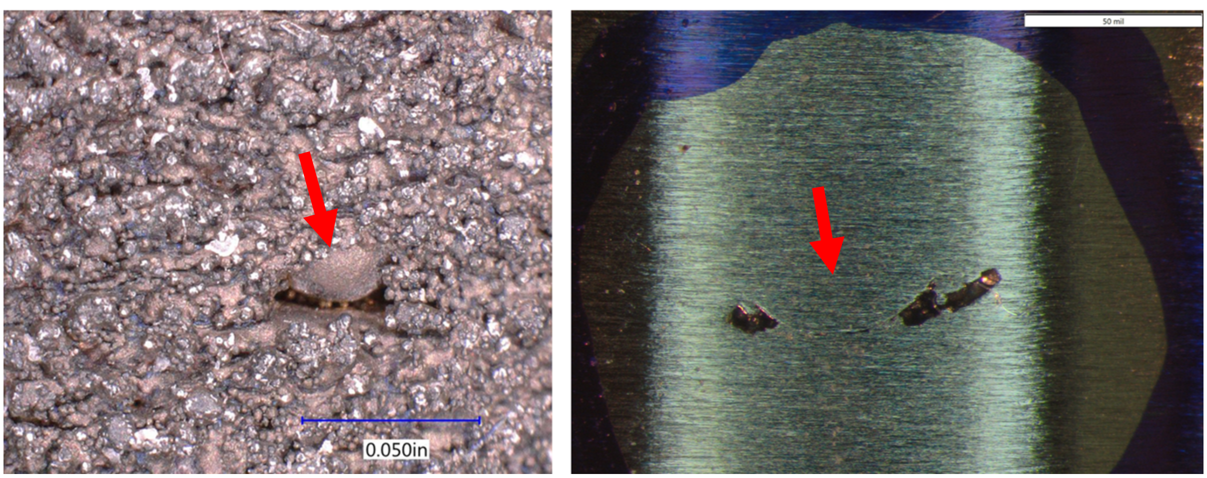

Figure 3: Stereo microscope images of typical AM process induced discontinuities caused by lack of fusion (LOF) in the layers below a relatively large spatter melt ball. The surface connected LOF discontinuities were visually detectable in both the "as printed" (left) and post-machined states.

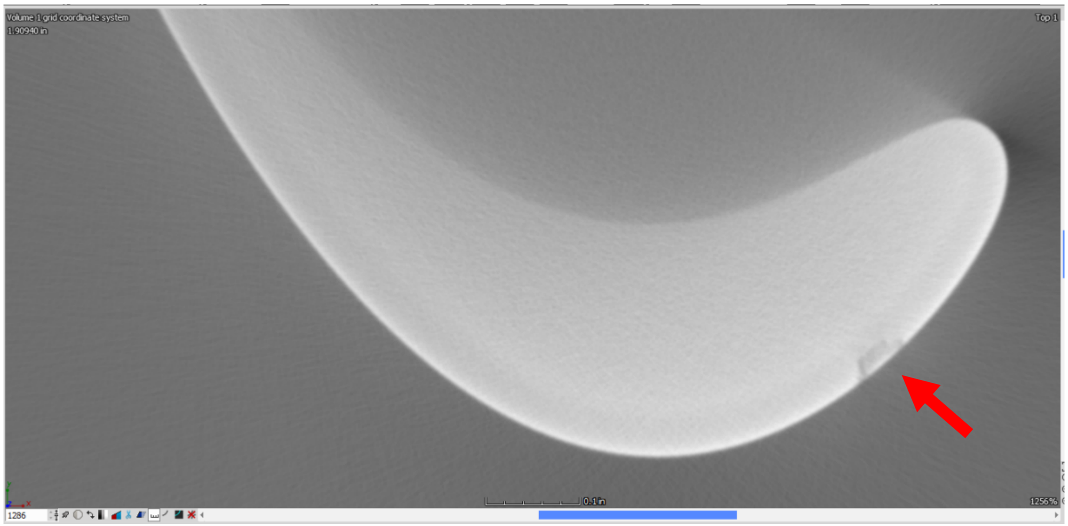

Figure 4: Image of a CT radiography section through a LOF discontinuity showing a semi-circular void corresponding to the lack of fusion that occurred in the layers below a spatter melt balls.

1.2.2 AM Blade Machining and Dimensional Inspection

The hot isostatic pressed (HIP) and heat treated AM blades were finished to the final design intent geometry by means of conventional machining processes. A minimum of 1mm extra stock material was present in the "as printed" geometry to allow for clean up during subsequent finishing. Conventional machining of the airfoil, attachment, and shroud were used to meet both desired surface finish and geometry (Figure 5). More than eighty (80) AM blades were finished machined to support assembly of a complete AM bladed stage 2 disk assembly.

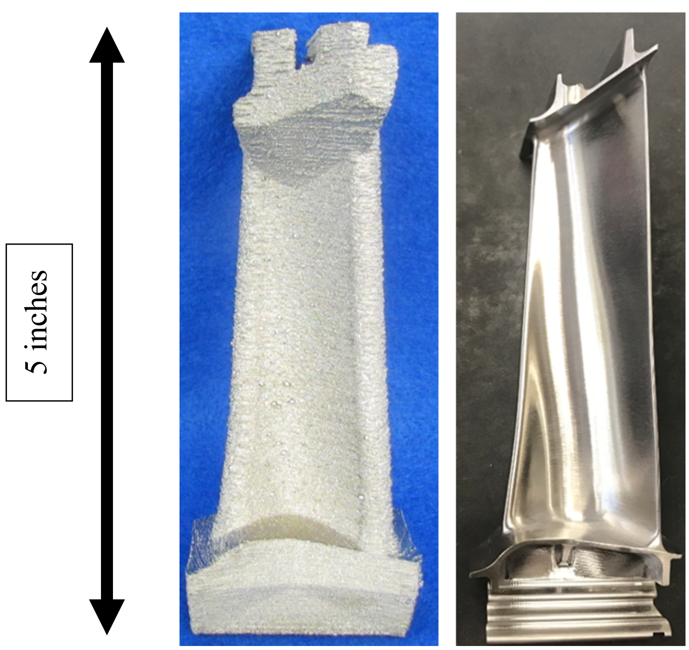

Figure 5: Macro image of oversized "as printed" blades produced with the Electron Beam – Powder Bed Fusion (EB-PBF) process (left) and the finished machined AM turbine blade (right) showing the overall size and shape of the AM turbine blade before and after machining.

Three-dimensional non-contact light scanning of the blades was used to ensure the machined AM blades met the final design intent geometry prior to assembly and operation in the turbine engine. See Figure 6 for a typical 3D scan result showing a dimensional deviation from -0.0021" to +0.0033" from the nominal design intent of the airfoil region. An assessment of the airfoil thickness at a critical section location near the shroud revealed the average thickness of the 80+ blade population was 0.001" thicker than design intent (Figure 7). The total range in airfoil thickness at the selected location ranged from -0.003 to +0.009" relative to nominal design intent. Based on these dimensional evaluations the machined AM blade geometries were deemed acceptable for hot fire testing in the turbine engine.

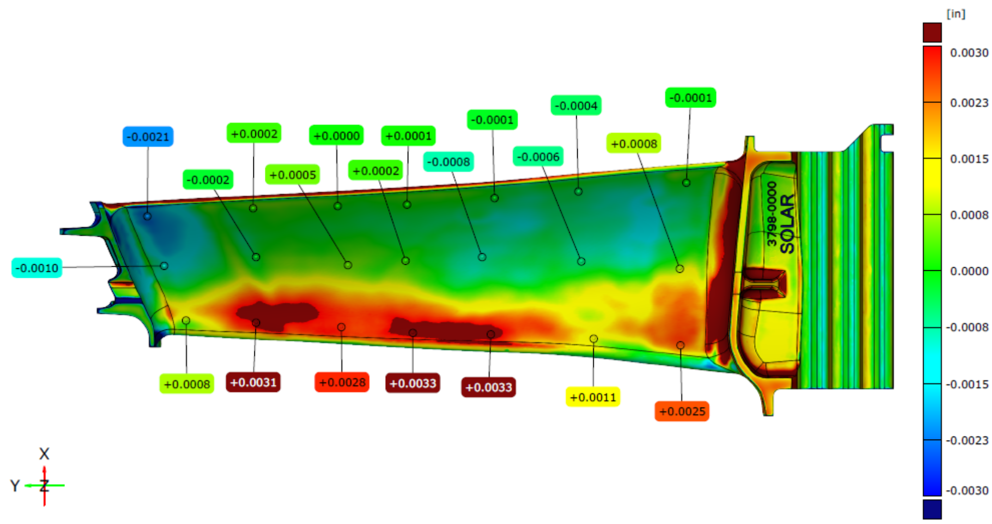

Figure 6: Rendering of 3D scan results of a representative finish machined AM blade airfoil compared to the design intent model showing deviations on the airfoil ranging between -0.0021 and +0.0033".

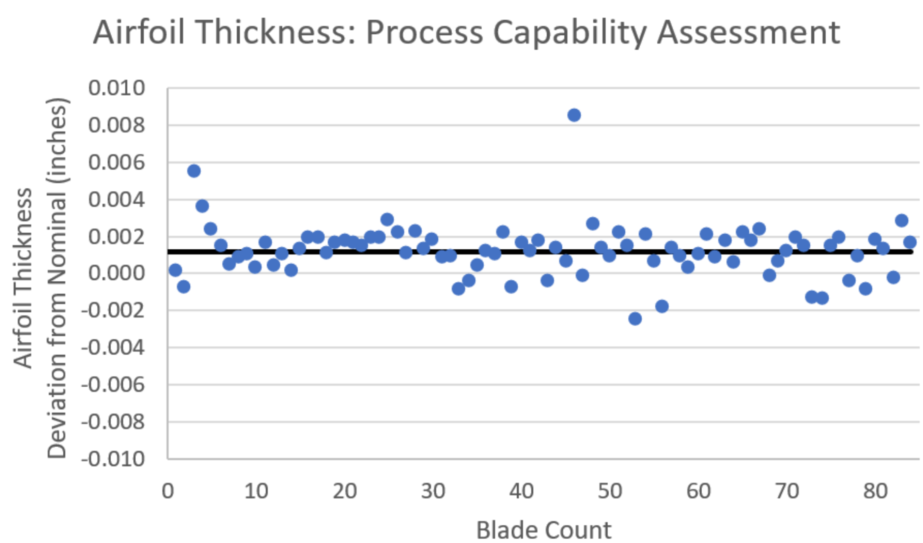

Figure 7: Graph of machined AM blade airfoil thickness results (blue circles) from an outer-span section of 3D scan data showing the average airfoil thickness (solid black line) was approximately 0.001 inch thicker than nominal design intent. The airfoil thickness values of the machined AM blade population ranged between -0.003 and +0.009" from nominal design intent.

1.2.3 AM Bladed Disk Assembly and Spin Pit Test

The machined AM blades were installed into a Mercury™ 50 Stage 2 turbine disk using standard production techniques and tooling. Upon completion of assembly, the AM bladed disk assembly was balance checked and found to be at 0.132 of the standard production maximum imbalance limit. No additional balance corrections of the disk assembly were required.

To ensure mechanical integrity of the assembled AM blade population, a mechanical proof spin pit test was conducted at room temperature. The AM bladed disk assembly was spun at a speed in excess of 15,000 RPM for 10 minutes minimum (Figure 8). After completion of this mechanical proof test, visual and dimensional inspection of the AM bladed disk assembly revealed no evidence of plastic deformation or damage (Figure 9).

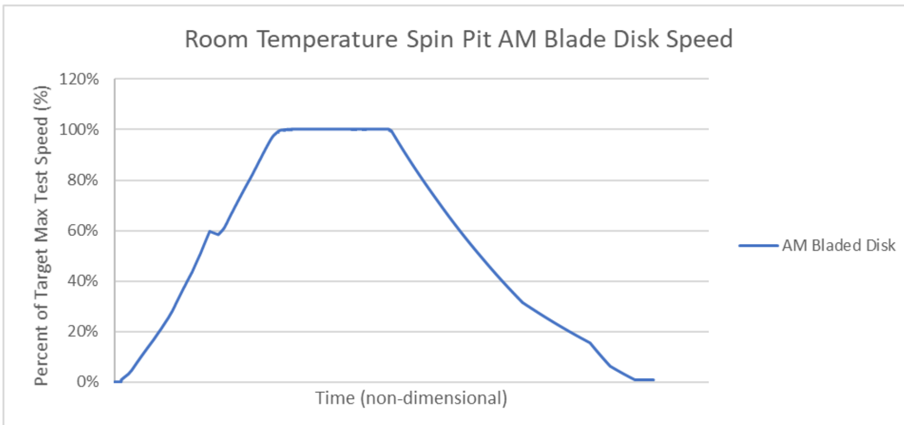

Figure 8: Graph of rotational speed data from AM Bladed disk assembly room temperature spin pit test showing the targeted proof test speed and duration were achieved.

Figure 9: Image of the AM bladed disk assembly after successful completion of the spin pit over-speed mechanical integrity proof test.

1.2.4 AM Blade Engine Test

Upon completion of the room temperature spin pit proof test, the AM bladed disk assembly was installed into a Mercury™ 50 engine at the Solar Turbines manufacturing facility in San Diego (Figure 10). Established development engine tooling and techniques were employed for the assembly. The engine was then installed in the engine test cell at Solar Turbines (Figure 11) and hot fire engine tested.

The AM blades were operated at 100% speed under full-load, steady-state (thermally soaked) conditions for over four (4) hours (sufficient time to conduct a standard performance evaluation). At this full speed condition, the AM turbine blades spun in excess of 14,000 RPM. The engine operated within normal production limits with no alarms triggered (Figure 12) and was shut down normally to conclude the test.

The geometry of the hot-fired AM turbine blades was an experimental geometry for which no production casting tooling existed. During steady state operation, the performance data points were acquired at various ambient conditions to assess the effect of the experimental blade design.

Figure 10: Image of the Mercury ™ 50 industrial gas turbine after installation of the AM bladed disk assembly into the engine.

Figure 11: Image of a Mercury ™ 50 industrial gas turbine installed in the engine test cell used for the AM blade hot-fire engine test.

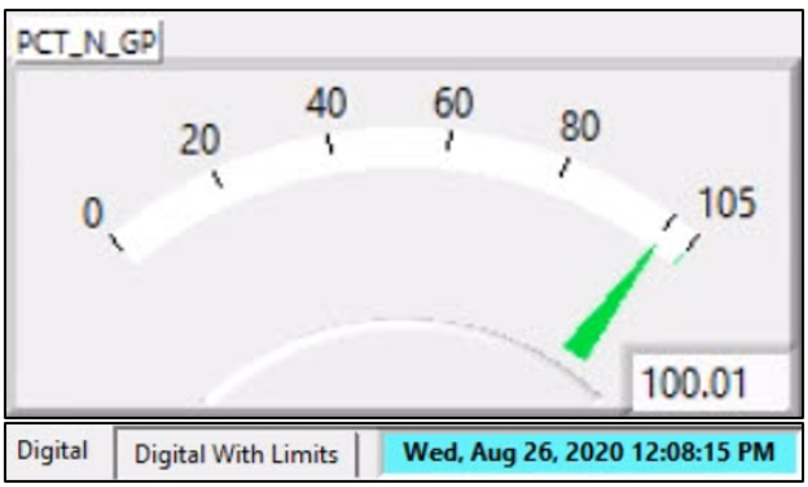

Figure 12: Screenshots of the turbine engine test cell control room data acquisition readout of percent turbine speed upon achieving full load – steady state engine conditions with the AM bladed disk assembly. The engine operated within normal production limits with no alarms triggered.

1.3 IMPACTS

For more than 70 years, since the first development of the cast superalloy turbine blades in the 1950's, investment casting has been the primary manufacturing process suitable for producing turbine blades with adequate properties and geometric precision needed to both survive and perform in the hot section of a gas turbine engine. However, the superior performance of castings comes at the cost of long lead times, high price, and inflexibility to design changes. In response to these constraints, academia and industry have invested heavily in the research, development, and industrial deployment of AM processes capable of producing superalloy turbine blades.

It is widely recognized that expertise in AM processes will yield significant competitive advantage and financial benefit to manufacturers. Product development cycle times can be reduced and product quality improved due to the rapid iterative design and manufacturing capability that AM technology provides. Within the last decade, there are numerous AM component success stories, but the widespread application of these AM benefits to turbine blades had so far been minimal.

In the industrial gas turbine (IGT) sector, Solar Turbines has previously gained expertise in additive manufacturing of Ni-based solid solution strengthened metallic materials suitable for low-stress, combustion system components. However, the application of this AM experience to historically investment cast and higher-value / higher-risk turbine hot-section components (blades, nozzles) has been limited. A significant barrier to successful AM processing of these high value components has been the severe cracking susceptibility of Ni-based gamma prime strengthened superalloys during AM processing.

In the prior Phase 1 project, the feasibility of AM processing Ni-based gamma prime strengthened materials (Inconel™ 738) was demonstrated: (1) AM Inconel™ 738 microstructures and mechanical properties suitable for survival in a turbine engine hot-section were produced, and (2) A complex airfoil geometry capable of yielding a Mercury™ 50 solid turbine blade was produced. In this Phase 2 project, the ability to fabricate a complete set of AM turbine blades capable of surviving an engine performance test has been demonstrated.

The engine performance test is a critical step in bringing a turbine engine to market and for implementation of product improvements. By removing the need for investment casting tooling from a project schedule critical path, the time and cost to achieve first engine to test can be reduced significantly. The cost of investment cast tooling (typically ranging from $100k to $500k) may be deferred. Additionally, this deferment of locking in the design of an investment casting tool can identify opportunities for additional design improvements that are revealed by the AM produced test articles.

This capability to AM process Ni-base superalloys will accelerate the validation of advanced component design concepts, enabling more rapid implementation of turbine improvements. The combination of AM processable high temperature alloys and AM enabled advanced cooling architectures are key elements for development of new designs able to meet increasingly stringent customer and regulatory efficiency and emissions requirements.

1.3.1 SUBJECT INVENTIONS

This section is not applicable to this program.

1.4 CONCLUSIONS

Prior Phase 1 work to develop the processing science and conduct mechanical testing demonstrated the feasibility of the electron beam additive manufactured (AM) Inconel™ 738 material to be used for prototype turbine blade applications. To continue increasing the TRL level of this technology, the current phase 2 work built off this capability to fabricate more than 80 AM turbine blades needed to build up a full stage 2 Mercury™ 50 turbine disk assembly. After printing, the AM blades were machined to the final required geometry. A combination of in-situ and ex-situ inspections and a room temperature spin pit overspeed test were completed to ensure suitability for operating in the turbine engine environment. In August 2020 the AM bladed stage 2 disk assembly was installed into the Mercury™ 50 industrial gas turbine and hot-fire tested to 100% speed.

With this full-scale engine test accomplished, the Process TRL level of electron beam AM Inconel™ 738 has been further increased to 7, demonstrating the capability of AM materials to serve in functions for critical rotating components for high temperature gas turbine environments.

2. PARTNER BACKGROUND

Solar Turbines Incorporated, a wholly owned subsidiary of Caterpillar since 1981, headquartered in San Diego, California, employs more than 8,000 employees, many of which are located at the headquarters in San Diego, California. Solar Turbines is a leading industrial gas turbine OEM, offering a range of gas turbines and turbomachinery equipment in the 1- 23 MW range for oil & gas exploration and transmission, and for power generation and cogeneration. Solar Turbines' state-of-the-art gas turbines are complemented by a line of compressors that can be matched with Solar Turbines equipment, or that of other OEMs. More than 16,000 Solar units are installed in more than 100 countries accounting for more than 3 billion fleet operating hours.

Solar Turbines has over 50 years of experience with the design, development and commercialization of industrial gas turbines and turbomachinery products. Solar Turbines has a long record of development of gas turbine technologies from internally funded and government programs. An example of a successful government-industry partnership was the DOE-Solar Advanced Turbine Systems (ATS) program, which resulted in the development of the 4.6 MW Mercury™ 50 recuperated gas turbine. Solar Turbines has also been involved in the development of gas turbine products for renewable energy including bio-gas and solar energy.