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Next Generation Additive Manufacturing of Shrouded Turbine Wheel

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ABSTRACT

Industry is seeing a rise in Additive Manufacturing (AM) for a variety of applications in recent years. Development of new printing technologies is enabling materials to be used and geometries to be manufactured that were not possible or simply cost prohibitive using conventional manufacturing techniques. This paper will review the manufacturing process of an Inconel 718 radial turbine wheel to be operated in a full-scale, short duration test at 705°C for a power generation machine utilizing supercritical CO_2 as the processing fluid. The turbine wheel was built using next generation laser bed powder fusion (LBPF) equipment that allows for significantly less support structure and simplified secondary processing as compared to traditional AM LBPF machines. This paper will review and contrast the required support structure, process monitoring, and secondary-processing of conventional LBPF manufactured parts with the parts produced on next generation machines. Additionally, details of alloy selection, heat treatment, secondary-processing, and material properties verification will be documented and compared with published AM and conventionally manufactured Inconel 718.

INTRODUCTION

The power generation industry utilizes turbomachinery to convert the energy of a moving process fluid into mechanical energy to drive generators. This process fluid often undergoes a series of heating/cooling and compression/expansion steps to induce and enhance this this movement and capture the energy. The energy source for these power plants is typically a form of heat which can originate from a variety of sources such as fossil fuels, solar, geothermal, nuclear, and waste heat from other processes. Analysis shows that utilizing supercritical CO_2 (SCO_2) for a working fluid can improve efficiencies and offer more compact mechanical arrangements than steam, which is currently the most common working fluid in power generation for indirectly transmitted heat sources [1]. The thermodynamic efficiency of power generation cycles is highly dependent on the temperature change achieved in the cycle; therefore, is it advantageous to run the cycle at the highest possible temperature that the machinery will allow. These high temperatures require heat resistant materials and alloys in critical components such as the piping and rotating components.

The turbine discussed in this paper was designed to be part of an expansion stage in an SCO_2 Brayton cycle. The test conditions will have this turbine operating at 705°C and 265 bar. The high temperature and pressure conditions as well as aerodynamic considerations drive the turbine geometry and material selection. The overall geometry of the turbine can be seen in Figure 1. It is generally the form of a covered radial turbine wheel. It has an extended hub to provide for an area of thermal management in the machine. The initial material selection for this turbine was Inconel 738LC due to its desirable mechanical properties and creep resistance at these operating conditions.

Shrouded compressor and expander wheels are typically made using one of three different approaches: Brazing/laser welding a two piece part, machining from a single piece, or casting. First, when manufactured in two parts, a two-piece impeller typically uses a machined, bladed hub and shroud that are attached together using welding or brazing. This reduced strength at this joint typically limits 2-piece impellers to lower-stress applications. Alternatively, the impeller may be able to be machined from a single piece of material. This requires the flow passage to be designed to have access to the full internal surfaces for machining. In this case, the blade design did not allow for access for single piece machining. Additionally, machining Inconel is slow and costly due to the large number of cutting teeth required for small "lollipop" cutting teeth. Finally, the wheel can be precision investment cast, but ensuring the accuracy of the blade profile can be difficult and the cost of a cast wheel can be high for low volume production.

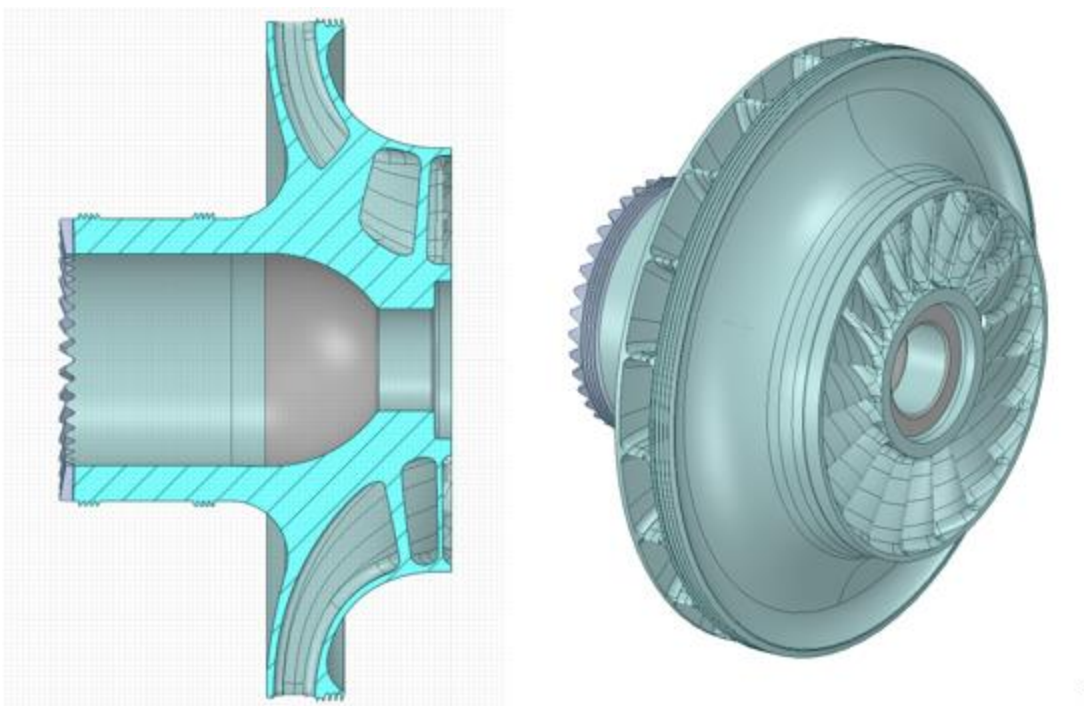

Figure 1 - Turbine Geometry

It was determined that none of the conventional manufacturing methods provided an optimal solution for this application. It was determined that an alternative manufacturing method, additive LBPF process, was the most advantageous method to produce this turbine wheel. The authors have experience manufacturing a variety of radial turbomachinery components utilizing titanium, Inconel, and steel as the base material [3].

There are documented successes using LBPF to produce test samples from Inconel 738LC [4],[5]. An initial attempt to manufacture this turbine blade in Inconel 738LC failed due to significant cracks that were observed following heat treatment. It was determined that there are currently manufacturing limitations on successfully building complex of geometries using Inconel 738LC and that more development would be needed to produce this part. The final turbine wheel discussed in the remainder of this paper was manufactured with Inconel 718 which is a more mature and widely used AM alloy. Inconel 718 has very good elevated temperature properties, but significantly reduced creep properties compared to Inconel 738LC [4]. The planned test campaign for this turbine has short duration, and the reduced creep resistance of Inconel 718 will be sufficient for testing; for a long term commercial product, a material with higher creep resistance will be required.

METHODOLOGY

To evaluate the use of Inconel 718, the creep rupture model that was developed for Inconel 738LC in a previous study was used with but the material properties were changed to reflect Inconel 718[3]. The stress rupture data for Inconel 718 was taken from the Aerospace Structural Metals Handbook [2][1]. This data was collapsed utilizing a modified Larsen Miller Parameter. The previously referenced study showed that the AM Inconel 738LC stress rupture properties were inferior to cast Inconel 738LC. It was not known if Inconel 718 would have a similar drop in material properties so an AM reduction factor was utilized. The allowable design included a general safety factor, an AM reduction factor, and a reduction factor for design relative to rupture for a given design life (This is the same reduction factor that is required in the ASME Boiler and Pressure Vessel Code (Section 8, Division 2) [6]). The allowable design stress versus the design temperature can be seen in Figure 2.

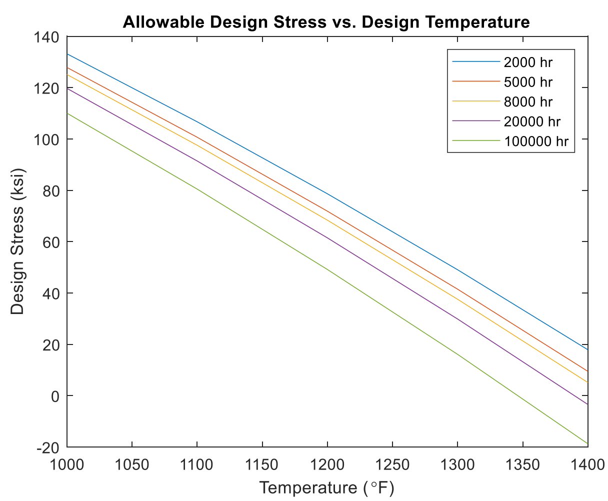

Figure 2. Larsen Miller Parameter Calculated Allowable Stress vs. Temperature at Various Design Lives

Figure 3 shows the resulting elastic-plastic solution for the impeller at 5,000 hours. As observed, this figure shows that the impeller should survive for at least 5,000 hours, which is substantially greater than the expected duration of testing for the impeller.

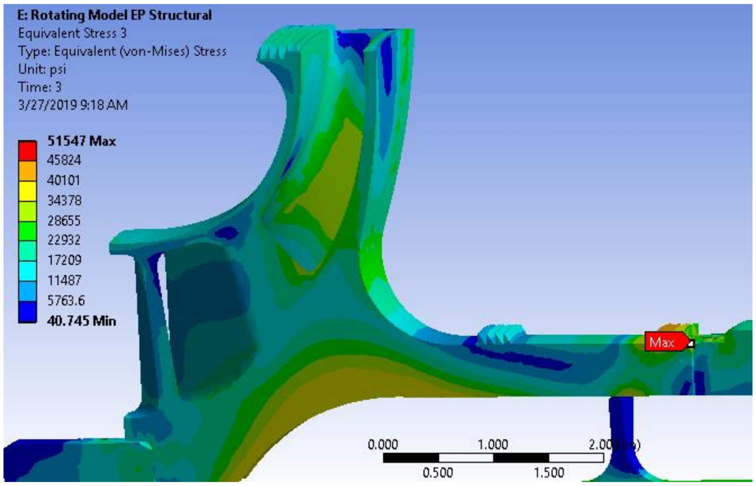

Figure 3. Stress Field in the Elastic-Plastic Solution

In order to determine if the AM reduction factor was sufficient or even necessary coupons were printed with the turbine and tested at conditions that could be directly compared to existing published data.

The manufacturing process of this turbine wheel was quite involved and required a significant amount of secondary-processing and inspection after additively manufacturing the part. The following is a high level overview of the process:

- Design and layout build with support structure
- AM Build
- Stress relieve
- Hot Isostatic Press, HIP
- Solution & Age Heat Treat
- Media blast
- Materials properties testing
- X-Ray, CT Scan
- Machine
- Abrasive Flow Machining
- Florescent Penetrant Inspection, FPI
- Balance
- Spin Test
- FPI
- Final QC and dimensional inspection

The build process of this turbine was completed on a Velo3D Sapphire system. This system is considered a next generation LBPF build platform. It utilizes a similar overall process to conventional LBPF by of using precision lasers to selectively melt 2D cross sections of a 3D part in layers of powder metal. The next generation features of the Sapphire system are considered to be its novel CAD workflow, automated calibration ability, onboard process monitoring capabilities and non-contact re-coater system. Lastly the process sets developed by Velo3D allow users to build more complex geometries than traditional LPBF systems.

CAD Workflow

The Sapphire system uses a specific proprietary software developed by Velo3D to setup and configure additive builds. This software is called VeloFlow. It eliminates the requirement for users to convert solid models into STL files and the need to use a generic file prep and an equipment specific build layout software. STL files are tessellated surface files without any meta data. With VeloFlow all metadata is retained, and the file prep and build layout is performed in one interface. This reduces risk of file corruption and increases the robustness of build layout.

Automated Calibration

Prior to each build it is imperative to demonstrate the machine is calibrated. Traditionally this is executed during routine preventative maintenance and requires an equipment supplier field service engineer to present to execute. With the Sapphire system calibration is automated. It is a machine operation executed by the additive machine user simply by pressing a button. If the machine is out of specification the error is recognized by the machine and it adjusts the settings. This calibration is performed for the beam size across the build plane, multi-laser overlay accuracy, powder bed health, and sensor readings.

Onboard Process monitoring

Process monitoring in traditional LBPF is limited largely to the environment that is required to safely melt and consolidate metal powder. This includes O_2 concentration and Ar laminar flow across the build plane. However, no feedback or monitoring is performed on the melting process. Along with the traditional process monitoring the Sapphire system has two next generation process monitoring features. They are called height mapper and the part quality metric. Height mapper is feature that evaluates the powder bed and scanned part with each layer. It first images the powder bed prior to the scan and evaluates the topology of the recoated layer. After the scan another series of images is taken to calculate the topology of the part. If the powder bed or part are out of spec the system will either try to recoat to fix powder bed erosion or pause the build in anticipation of part re-coater interference. The part quality metric is derived for each laser and layer. The metric is a unit filtered from the coaxial sensors of each laser. It has been shown this metric correlates with the deposited material’s density [7].

Figure 4 – Velo3D Sapphire Build Platform

Non-contact re-coater system

Traditional LBPF use scrapers or rollers that apply a new coat of powdered material on the build platform to start each build layer. These traditional methods require the recoating mechanism to be positioned the exact distance from the powder bed as the desired thickness of the powder layer being distributed. Layers are often on the order of 0.030µm to 0.090µm. Some geometries can undergo significant distortions due to thermal stresses which cause the part to grow in the vertical direction which can lead to interference issues during the re-coating process and subsequent build failures. A roller when contacting a component would experience a compacting force while a scraper would exert a shearing force. The part being contacted must be able to structurally withstand the re-coating process. This limits the aspect ratio that can be printed and will not allow large overhangs or free-floating parts. The Sapphire's proprietary non-contact re-coater feature allows for geometries with significantly more overhung features to be created without issues common to conventional LBPF.

Design Freedom

Support structure on any area that has an overhang of 45° or more are required on any traditional LBPF machines while the next generation machines can build parts with overhangs as low as 5° without support structure. This support structure provides structural integrity during the build, but must be removed and discarded after completion of the build. The traditional machine support structure for this turbine wheel can be seen in Figure 5a., the support structure is shaded red. The traditional machine used for this build setup was an EOS M290 utilizing Magics to generate the support structure. The next generation machine can be seen in Figure 5b, the required support structure is shaded blue. The part volume for the turbine part minus any supports was 1702 cm^3. The support structure volume for the traditional machine was 686 cm^3 while the next generation machine required only 69 cm^3.

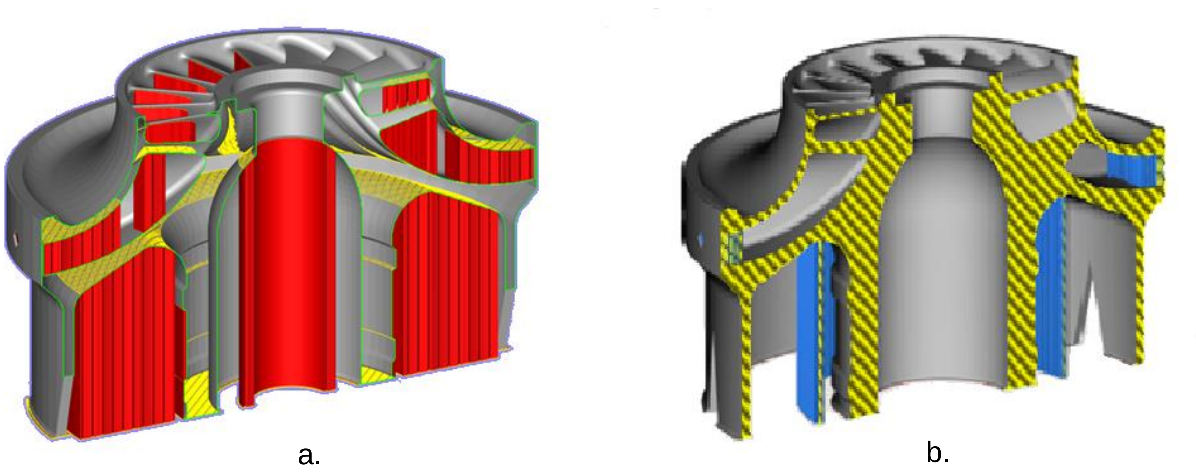

Figure 5 - Comparison of Support Structure from Conventional to Next Generation Build

For this geometry this was a 90% reduction in required support structure which significantly reduced the required print time, improved material utilization, and reduced amount of manual secondary-processing time required to create a finished part. Figure 6 shows the turbine wheel attached to the build plate built with the reduced support structure.

After the part was built it went through stress relief, HIP, solution treatment, and aging heat treatment processes.

Figure 6 - Turbine Wheel and Test Coupons after Build

Then the external features of the part were machined to a near finished shape. The internal features that were created during building were not smooth enough for the desired aerodynamic properties and the part was extrude honed to improve the flow path surface finish. The turbine wheel was examined using several non-destructive techniques florescent penetrant inspection (FPI), CT-scan, and digital x-ray. The part was then balanced and over-speed spin tested. After the spin test the part was again checked for cracks using FPI.

RESULT AND DISCUSSION

The finished turbine wheel can be seen in Figure 7. The processing required to finish this wheel was extensive and several quality assurance checks had to be passed in order to utilize this wheel on the SCO_2 turbomachinery. The material properties had to be reviewed to ensure the expected strength and creep requirements would be met using the AM process. Non-destructive testing techniques were utilized to verify that the part was did not have any critical defects. Additionally, the part was checked for dimensional accuracy compared to the design.

Figure 7 - Finished Turbine Wheel

Mechanical properties of the turbine wheel are extremely important for the test program. The wheel will be rotating at greater than 14,000 RPM during testing and will be in a high temperature environment. Therefor it is critical that the material properties of the turbine are well understood. Test samples were printed and heat treated with the turbine for testing tensile and stress rupture properties.

ASTM F3055-14, provided a general specification for LBPF Inconel 718 and provides required tensile properties for AM produced samples. The measured tensile and required tensile properties can be seen in Table 1 and Figure 8. The measured tensile results all exceeded the ASTM F3055 minimum requirements.

Table 1 - Tensile Test Results and Minimum Requirements per ASTM F3055-14

Sample Number	Min UTS, MPa	UTS, MPa	Min YS, MPa	YS, MPa	Min El%	El%	RA%
H1	1240	1340	940	1070	12	17	28
H2	1240	1340	940	1080	12	18	30
V1	1240	1280	920	1050	12	13	14
V2	1240	1280	920	1010	12	15	22

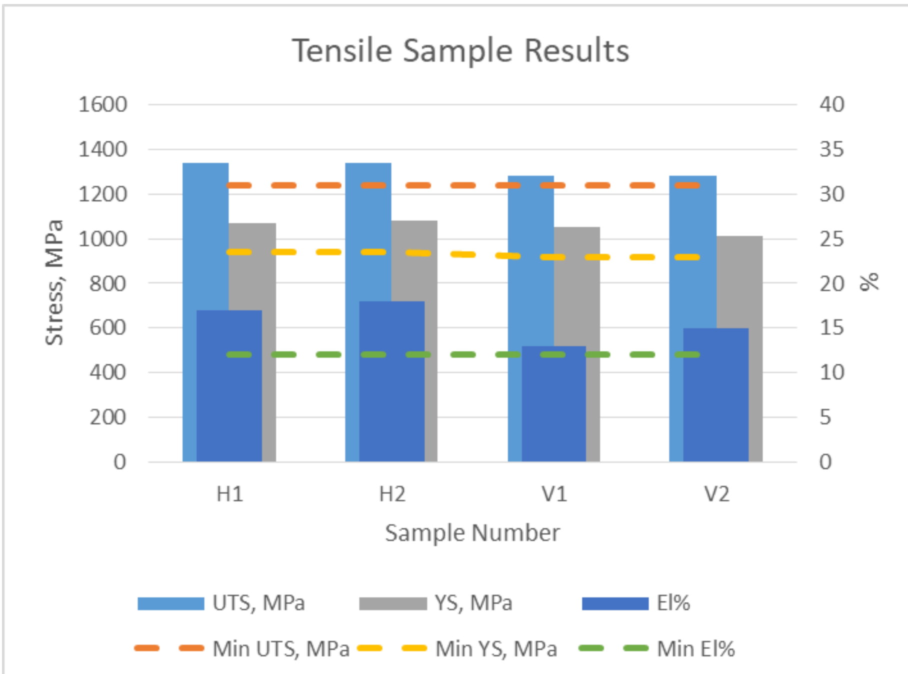

Figure 8 - Tensile Test Results and Minimum Requirements per ASTM F3055-14

The chemical composition of the test samples were also reviewed and met the ASTM requirements. The results can be seen in Table 2.

Table 2 - Chemical Composition

Elements	Min. %	Max. %	Results %
Nickel	50	55	52.8
Chromium	17	21	18.8
Manganese	---	0.35	0.04
Silicon	---	0.35	0.06
Carbon	---	0.08	0.04
Sulfur	---	0.015	0.001
Phosphorus	---	0.015	0.005
Iron	---	---	REM
Aluminum	0.2	0.8	0.46
Titanium	0.65	1.15	0.98
Molybdenum	2.8	3.3	3.04
Cobalt	---	1	0.13
Copper	---	0.3	0.03
Niobium + Tantalum	4.75	5.5	5.16
Boron	---	0.006	0.002

Additionally high temperature creep rupture tests were performed with test samples built and heat treated with the turbine wheel. Due to limited budget and time a single test point was chosen to perform the stress rupture testing. The stress rupture test was performed at 704.4°C (1300°F) and 517 MPa (75 ksi). The results can be seen in Table 3. Figure 9 shows how the stress rupture data compares with published data for Inconel 718 from the Aerospace Structural Metals Handbook. Based on this single testing point the LBPF samples show to have better stress rupture properties than projected and thus the life is expected to exceed the duration of the test.

Table 3 - Stress Rupture Test Results at 704.4°C (1300°F) and 517MPa (75ksi)

Sample	Rupture Time, hours
H3	55.9
H4	50.1
V3	98.7
V4	83.7

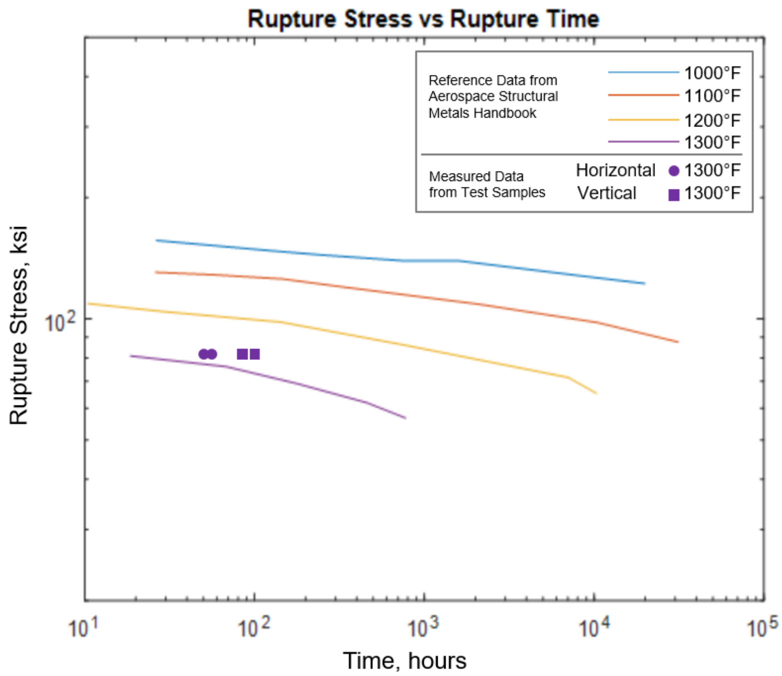

Figure 9 - Stress Rupture Data for Inconel 718 with Test Values

Additionally, the part was subjected to review using both digital X-Ray, CT-Scanning, and FPI. No measurable defects were detected. The turbine was then balanced and spin tested at speeds exceeding the design conditions and rechecked for surface cracks using FPI.

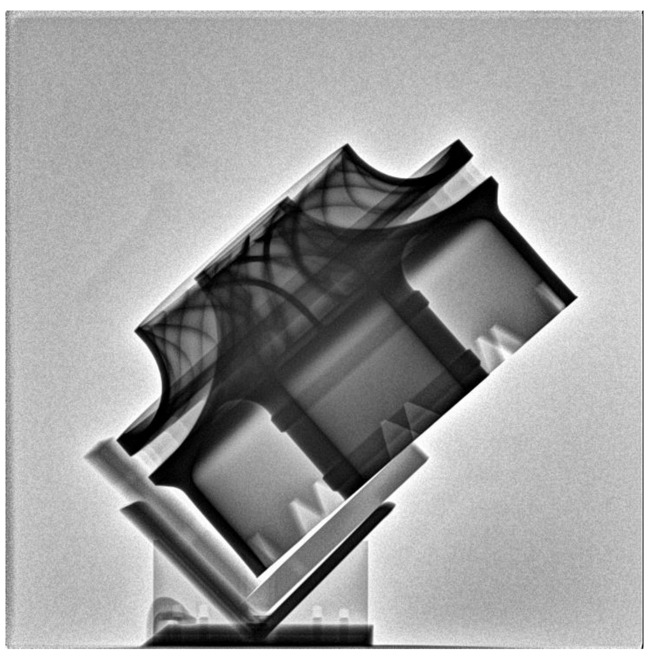

Figure 10 - Digital X-Ray of Turbine Wheel

CONCLUSION

Next generation AM technologies that allow complex geometries to be built with reduced support structures were utilized to build an Inconel 718 radial turbine wheel. The turbine wheel is to be used in a high-temperature, high-pressure, full scale, short duration equipment test with SCO_2 as the working fluid. The turbine was successfully printed with 90% less support structure than traditional LBPF machines which resulted in a reduced build time, higher utilization of material, and less manual secondary-processing required for support removal. Material properties of samples built with the turbine wheel exceeded ASTM 3055-14 requirements for tensile properties and chemistry. Stress rupture testing on samples printed and heat treated with the turbine wheel show that for a single test point the AM life exceeded published values for wrought bar Inconel 718.

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