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Process Capability Study on the Volume Manufacturing of a Complex Rotating Automotive Component in Laser Powder Bed Fusion Additive Manufacturing

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Manufacturing Science Division
Advanced Materials and Manufacturing Technology Office

PROCESS CAPABILITY STUDY ON THE VOLUME MANUFACTURING OF A COMPLEX ROTATING AUTOMOTIVE COMPONENT IN LASER POWDER BED FUSION ADDITIVE MANUFACTURING

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ABSTRACT

Oak Ridge National Lab (ORNL) and Ford Motor Company used an AddUp FormUp 350 to print a turbo wheel geometry to show feasibility of laser powder bed fusion (L-PBF) additive manufacturing (AM) in producing cost-effective components for automotive industries. L-PBF AM has potential to disrupt traditional manufacturing techniques by introducing novel materials and geometries that cannot otherwise be produced. Fundamental challenges associated with L-PBF include limitations on printing overhang geometries and resulting surface finish. In this collaboration, ORNL and Ford partnered with AddUp to show the viability of using L-PBF for an AM design turbine wheel while reducing as-fabricated surface roughness. A cost model associated with mass production was produced to analyze benefits of pursing L-PBF AM compared to investment casting.

1. LASER POWDER BED FUSION ADDITIVE MANUFACTURING OF TURBO WHEEL

This Phase 1 technical collaboration between ORNL and Ford Motor Company began on April 8th, 2022, in which ORNL and Ford used an AddUp FormUp 350 to manufacture a default geometry turbine wheel used in a turbocharger operating at high temperatures and speeds. Upon signing the Phase 1 Technical Collaboration with ORNL, Ford opted to include AddUp Inc given the prior work performed under a cooperative research and development agreement (CRADA) already in place between AddUp and ORNL. AddUp's FormUp 350 has been at ORNL's Manufacturing Demonstration Facility (MDF) since 2019 for research and development in tooling.

L-PBF AM offers design complexity such as shell geometries, conformal cooling channels, and lattice structure geometries that are impossible in conventional metal processing techniques. The AM design was made with a hollow interior for reduced inertia to improve fuel economy and overall engine performance. Initial prototypes were printed using Maraging Steel at ORNL, and final design iterations were printed using Inconel 718 at the AddUp USA headquarters in Cincinnati, OH.

1.1 BACKGROUND

For over a century Ford Motor Company has pioneered the automotive industry and continues to lead advancement initiatives globally. With over 200,000 employees and 62 plants worldwide, Ford's core business includes designing, manufacturing, marketing, and servicing a full line of cars, trucks, and SUVs, as well as Lincoln luxury vehicles.

AddUp Inc. brings the expertise in design, manufacturing, and automation of both Fives and Michelin for development of laser powder bed fusion (L-PBF) technology for large-scale production. Offering advancement in aluminum, titanium, and steels, AddUp has impact in aeronautics, automotive, energy, medical, and defense.

Additive manufacturing (AM) offers design flexibility demanding applications previously unavailable to traditional manufacturing. Internal cavities are designed inherently in AM components which reduce both overall mass and print time. Initial prototypes were printed using maraging steel since the process parameters developed at ORNL were readily available to inform any AM related challenges such as defect formation or design alterations. Finally, Inconel 718 was used to print the turbo wheel to be used for a bench test owing to its excellent high temperature properties such as tensile and creep strength.

1.2 TECHNICAL RESULTS

One of the critical factors for printing parts with excellent surface finish is the use of finer powders. Whereas printing overhangs with extreme angles require a powder bed with high bed density which is achieved by the use of a roller recoating system. The AddUp FormUp 350 offers both features. Table 1 shows the PSD for both maraging steel prints performed at ORNL and Inconel 718 performed at AddUp.

Table 1. PSD metrics for Maraging Steel and Inconel 718.

Powder Chemistry	d_{10}	d_{50}	d_{90}
Maraging Steel	5.00	12.50	21.00
Inconel 718	5.20	10.63	17.25

Primary steps with the CAD model of the turbo wheel were to determine if support structures were necessary to achieve a successful print. Avoiding post-processing steps is critical to minimizing the cost so the print was attempted with no support structures. Figure 1 shows the as-fabricated turbo wheel using Grade-300 maraging steel.

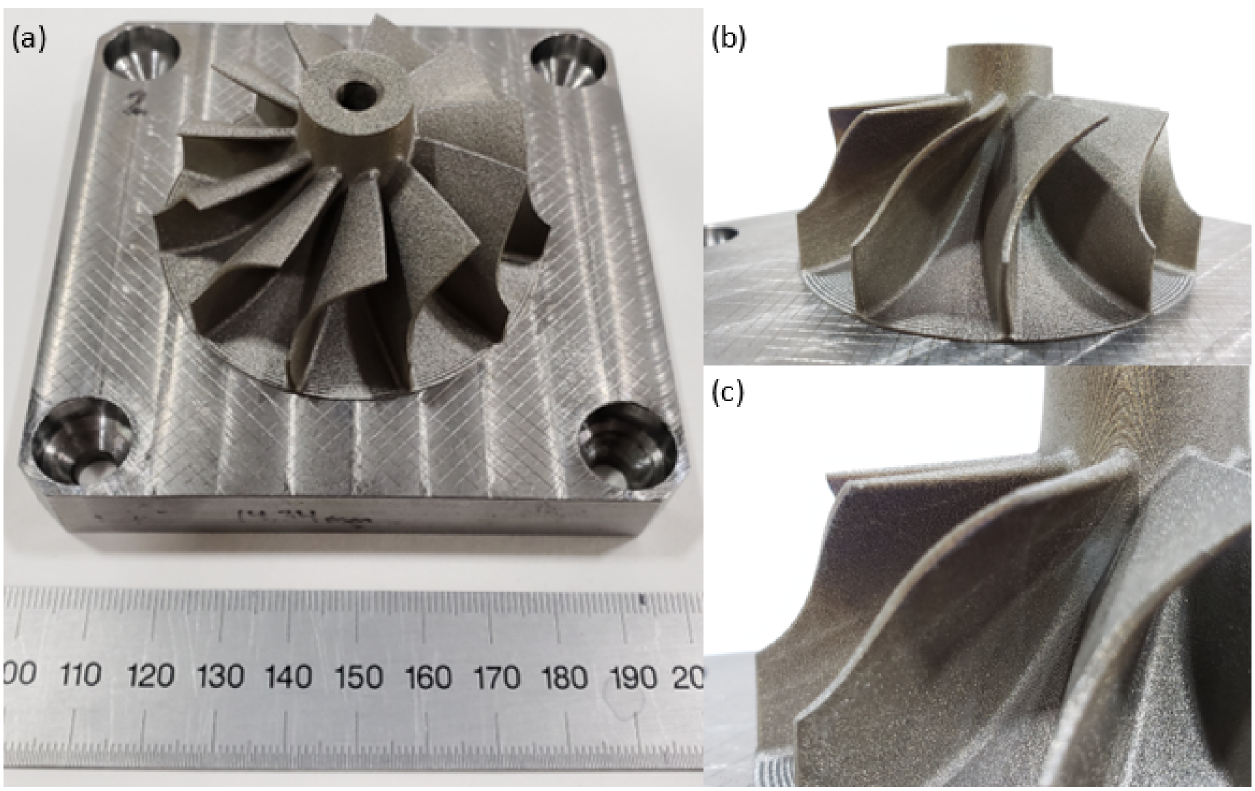

Figure 1. (a) As-fabricated turbo wheel printing from Maraging Steel (b) Isometric view of turbo wheel and (c) Close up showing the downskin surface finish.

Figure 1 shows a successful print that demonstrated the viability of additively manufacturing a complete turbo wheel geometry without the need for supporting low-angled features.

After proving feasibility of printing the geometry shown in Figure 1, the emphasis was placed on optimizing as-fabricated surface finish to reduce the influence of surface-dominated properties such as fatigue. The contour study was designed with goals to improve as-fabricated surface finish and determine the print settings resulting in geometric tolerances in the as-printed condition as close to the CAD model as possible. L-PBF often uses a contour followed by infill melt strategy to obtain parts with superior surface finish as well as desired microstructures. If an insufficient overlap is used between the contour and infill, it can result in porosity at the contour-infill interface thereby making the part susceptible to premature failure under fatigue. Furthermore, since contouring has a crucial role on dictating the surface finish, a contour study was designed to investigate the hatch and contour offset.

The Orignal Equipment Manufacturer (OEM) standard parameter performs hatching 31µm beyond the CAD boundary and performs the contour pass 39µm inside the CAD boundary. Although this eliminates the possibility of contour-infill interfacial porosity, it was theorized that the hatch lines extending 80µm beyond the contour pass was revealing visible hatch patterning which causes a higher surface roughness. By defining the OEM contour pass position as zero, five unique contour positions were set each with a -25µm offset (extending out from the part) to test the effect of number of contour passes. 25 turbo wheels were deposited on a full-size 350mm x 350mm build plate in the FormUp350 system to test of a range of contour passes and order of contour melting as shown in Figure 2(a).

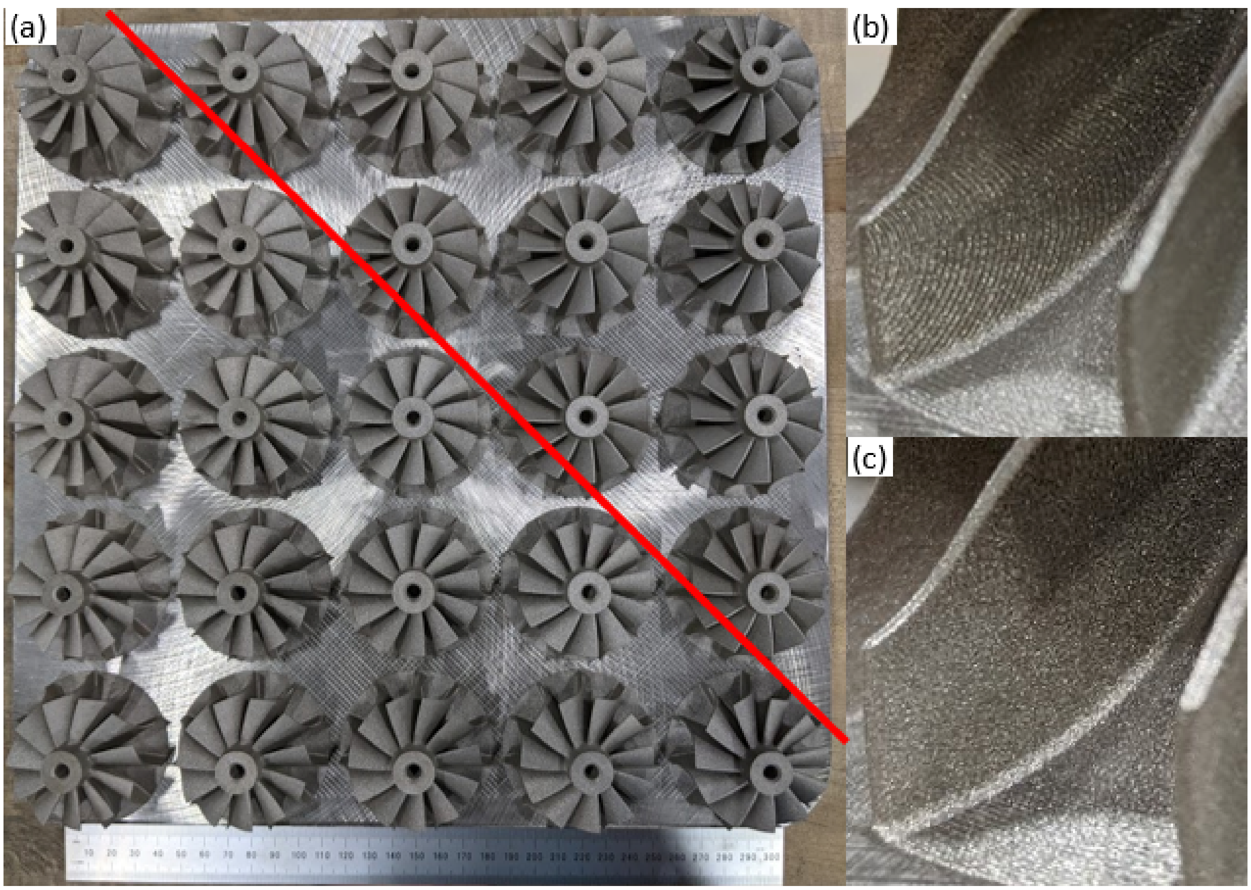

Figure 2. (a) Completed contour study layout, (b) single fin melted using a single contour pass with visible hatch patterning, (c) single fin melted using five contour passes with no visible hatch patterning.

From left to right below the red line on Figure 2(a), the first column melts at each contour position once, starting at OEM zero to 100µm. The second column melts the lowest four components with two contour passes, inner to outer, offset by 25µm, varying start position. The third column melts the lowest three components with a 25µm offset from the last, also varying start position. This is continued until the bottom right component is melted at all five contour positions. Only 15 components were required to test this design. Since 25 can fit on a single plate, the melt order was changed on the 10 components that melted more than a single contour. From right to left above the red line, the first column melted four components with two contour passes, outer to inner. This continues until the fourth column shows a single turbo wheel which melted all five contour positions, outer to inner. Figure 2(b) shows a turbo wheel melted with a single contour pass at the OEM zero position and Figure 2(c) shows a turbo wheel melted with all five contour passes. Hatch patterning was removed using multiple contour passes; however it is unclear if defects are being induced as a byproduct. Furthermore, it must be ascertained if this is due to the position of the contour passes.

Ford performed profilometry on component melted with a single contour pass at 50µm from OEM standard contour position and measured a 7.3µm surface finish. A component melted with three contour passes up to 100µm contour position measured on average 8.1µm. However, a component melted with three contour passes up to 75µm contour position measured on average 8.4µm. This evidence support that it is not the number of contour passes but rather the position of the outermost contour pass that most influences as-fabricated surface finish.

ORNL performed standard metallography on components to determine which showed best surface finish. Future work could determine the influence of multiple contour passes on microstructure and microhardness values. Figure 3 shows mounted sectioned turbo wheels.

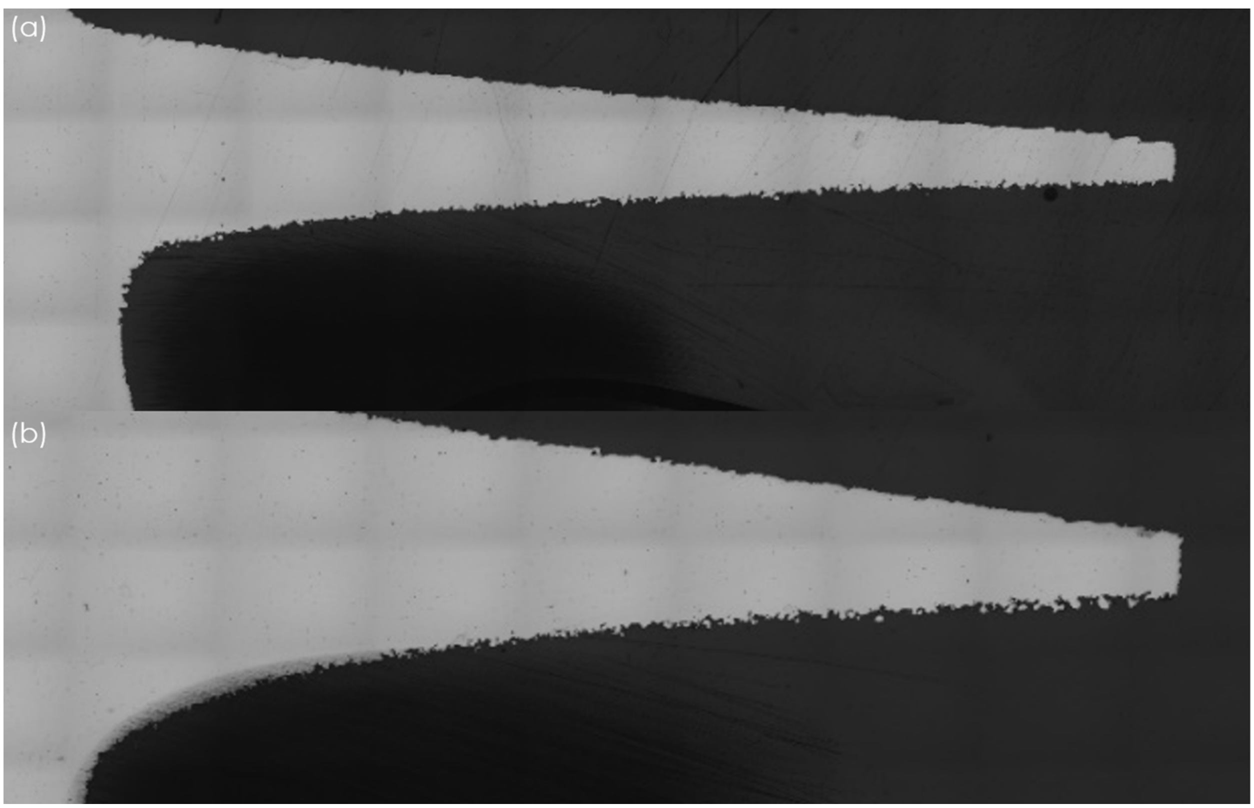

Figure 3. (a) Optical micrograph of single contour pass downskin and (b) Optical micrograph of downkin using five contour passes. Although more contour passes may be useful, the position of the outermost contour drives surface finish as shown by partially melted particles clinging to the surface in (b).

Figure 3(a) was melted with a single contour pass at the OEM zero contour position while Figure 3(b) melted at all five contour positions. Gaps are noted near the tip of the fin in Figure 3(b) indicating that melting 100µm beyond the OEM contour pass induced porosity. Thus, a single contour pass is sufficient given a position beyond the hatch lines to remove hatch patterning, so long as its position is correct.

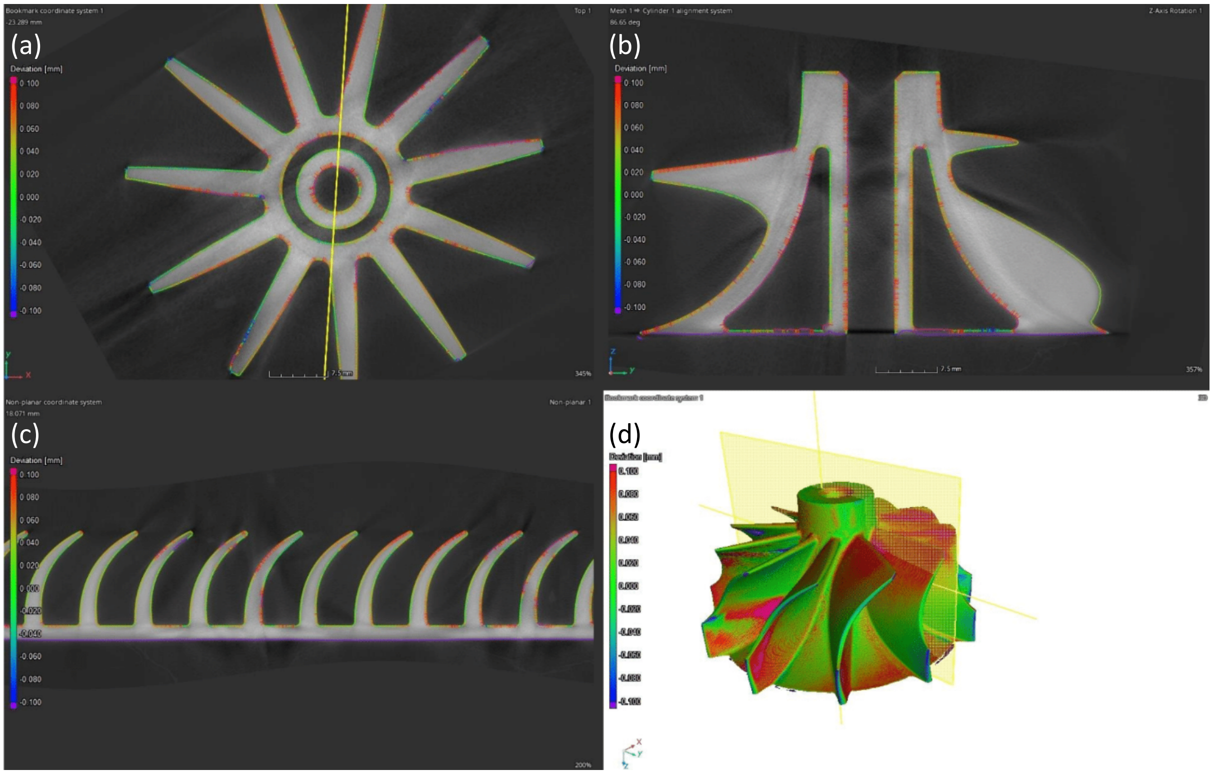

Figure 4. Geometric tolerances measured from x-ray computed tomography (X-CT) of a turbo wheel melted with three contour passes showing edge calculations compared to CAD of (a) a slice in XY, (b) a slice in XZ (c) the fins viewed in parametric space, and (d) surface tolerancing of the entire geometry.

Figure 4 shows an as-fabricated turbo wheel melted with three contour passes extending to -50µm registered against the default CAD geometry. Bounds show discrepancies of ±100µm which is roughly 5X the D_{90} PSD. Possible explanations for resulting values of this order are performing these measurements in the as-fabricated condition without the benefit of fully relaxing residual stresses from a stress relief anneal cycle. Contributing factors include partially melted powder clinging to downward-facing surfaces, the exclusion of a downskin parameter setting, and registration misalignment. From these maraging steel results, the focus was set on carrying out studies in Inconel 718.

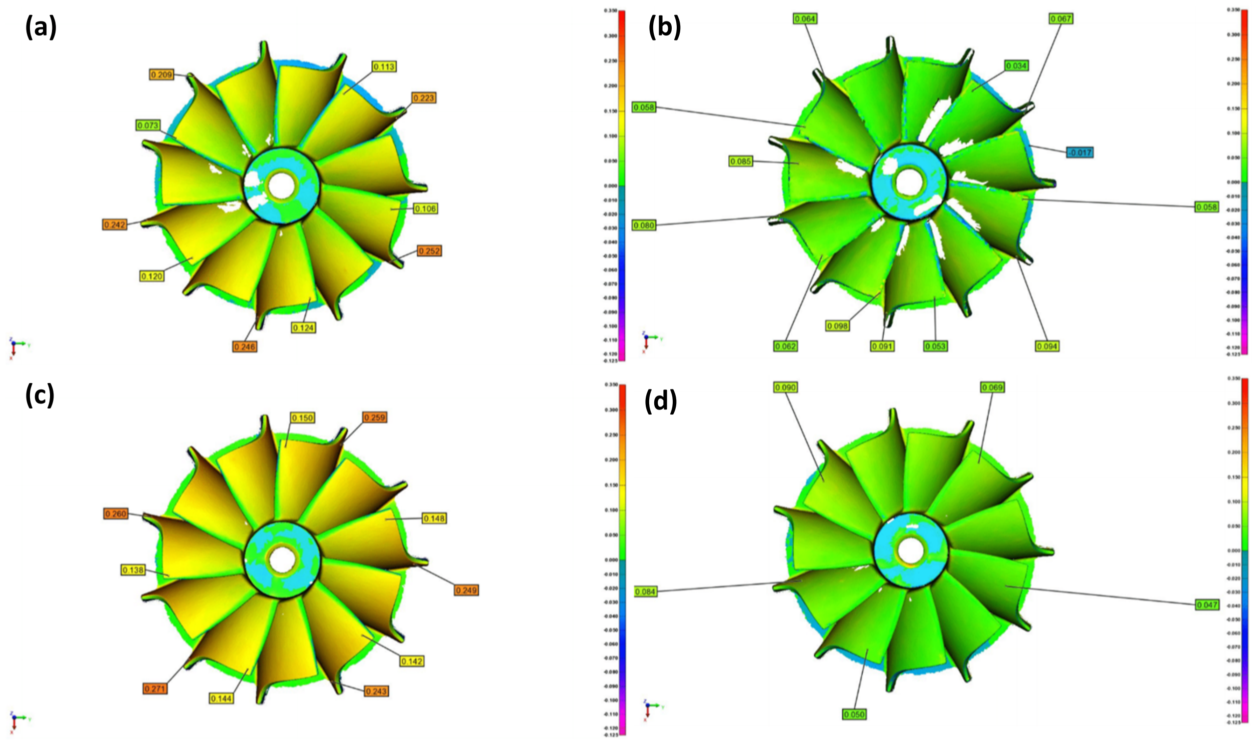

Figure 5. Geometric tolerances measured from light-sanning of turbo wheels with the outer contour extending the following distance beyond CAD boundary: (a) #08 at 36µm, (b) #11 at 11µm, (c) #13 at 61µm and (d) #19 at 36µm but melted outer to inner.

Five turbo wheels were sent to Ford Motor Company for light scanning to further explore the impact of multiple contour passes and their relative position with respect to final geometric tolerance. Figure 5 shows turbo wheels 08, 11, 13, and 19 for Figure 5(a), (b), (c), and (d), respectively. For each turbo wheel, the hatch extends 31µm beyond the CAD boundary, so the contour study was to observe final geometric tolerances as a function of outermost contour position. The largest discrepancies were noted for wheel #08 in Figure 5(a) and #13 in Figure 5(c) where the outermost contour position extended 36µm and 61µm beyond the CAD boundary, respectively. Whereas wheel #11 of Figure5(b) melted only 11µm beyond CAD and resulted in the best tolerancing. This evidence further supports that the driving factor for accuracy is position of outermost contour. Interestingly, wheel #19 of Figure 5(d) melted with the same 3 positions of contours as wheel #08 of Figure 5(a) but melted outer-to-inner instead of the prototypical inner-to-outer. This suggests there may be an effect of final geometric tolerancing based on the order of melting multiple contour passes.

The next step of the project was to confirm experimental results developed in maraging steel on the FormUp 350 at ORNL in Inconel 718. The same default turbo wheel geometry was sectioned and printed in half sections utilizing a downskin parameter setting. The inclusion of AddUp's downskin parameter allows the slicing software to recognize critical downward-facing surfaces below a user-defined threshold angle. A downskin parameter typically applies a lower energy density setting to melt regions offset from the edge of downward-facing surfaces for a given number of layers. The goal to avoid penetrating into the powder bed and partially melting powder which clings to the surface and causes larger surface roughness values. Figure 6(a) shows an Inconel 718 turbo wheel printed with AddUp's standard parameter and Figure 6(b) shows a turbo wheel printed with a parameter that includes a downskin feature.

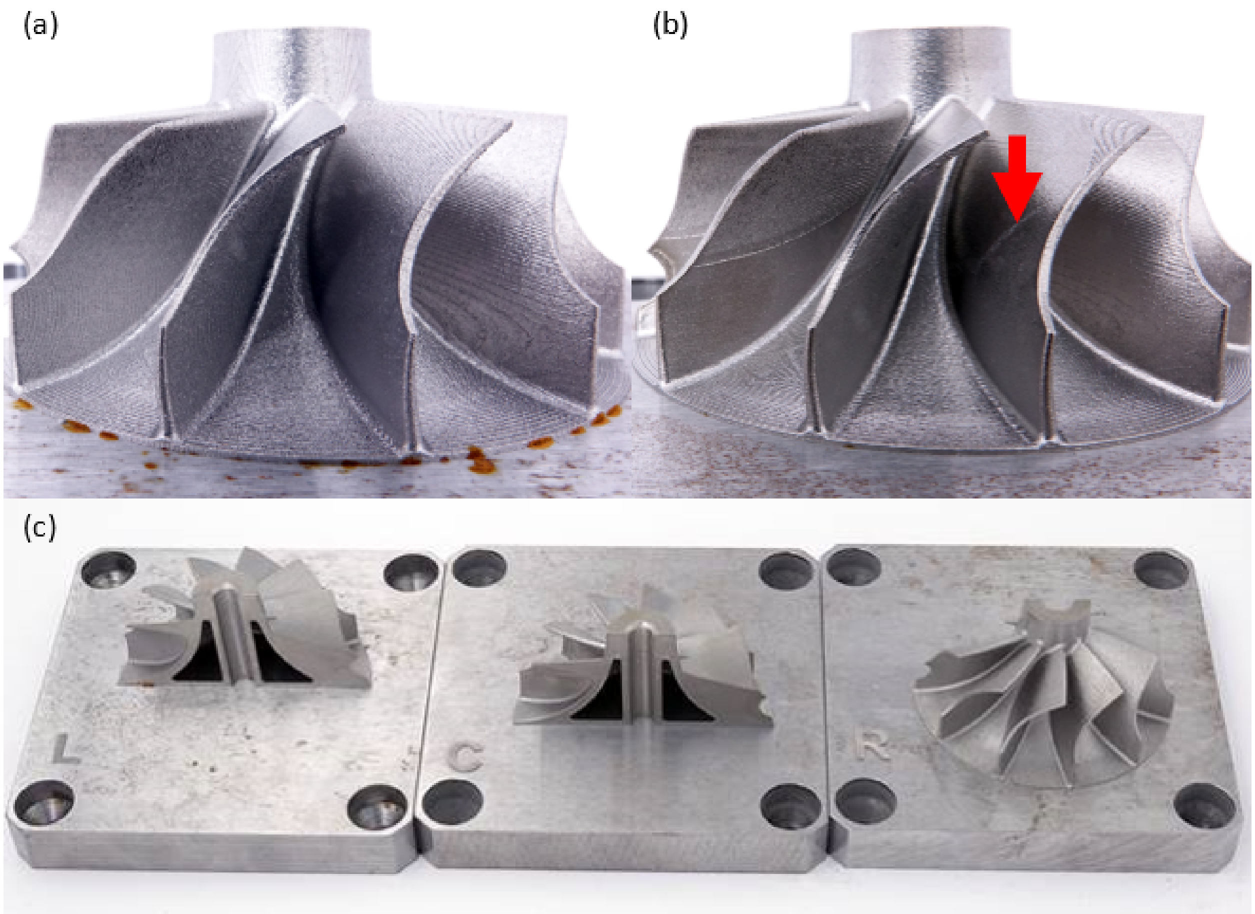

Figure 6. Inc 718 turbo wheels printed where a downskin parameter (a) is not applied and (b) is applied and (c) the full print layout displaying the hollowed geometry.

Given the thorough development performed by AddUp to improve parameter sets, both Figure 6(a) and Figure 6(b) measured an as-fabricated downskin surface finish of 2.2µm. However, the upskin of Figure 6(b) seems to have changed along a threshold line as indicated by the red arrow. It was determined that the downskin parameter was applied for 2mm or about 44 layers beyond the recognition of a downskin surface. This rule applied a downskin parameter which extended beyond the fin thickness and caused a change in upskin texture. This value was changed nearly an order of magnitude to apply for fewer layers and not risk affecting a thin feature through its thickness.

For the second print, AddUp and ORNL attempted to further to optimize the as-fabricated surface finish of the turbo wheel by changing melt order of the core and skin features. This experiment applied a downskin parameter to both turbo wheels only changing the assignment of downksin within core/skin options. This resulted in completed geometries shown in Figure 7.

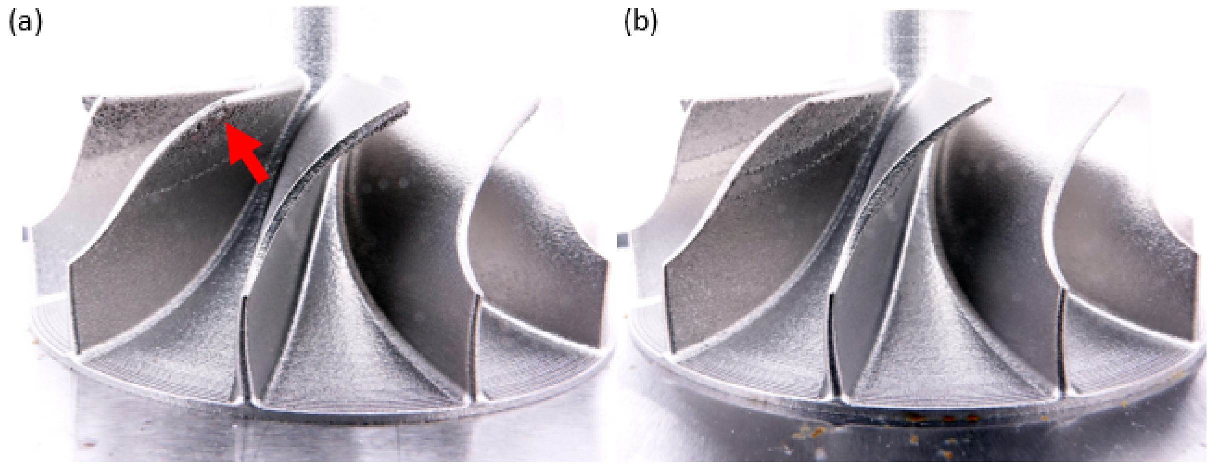

Figure 7. Inconel 718 turbo wheels printed by AddUp with improved downskin parameters applied where (a) melted contours before and after downskin and (b) melted downskin before any contours.

Figure 7(a) measured an average of 2.3µm R_A and Figure 7(b) measured an average of 1.1µm. The red arrow in Figure 7(a) shows a much rougher surface finish near the fin as a result of melting the downskin parameter prior to the core melt. A local heat buildup from melting unbound powder without a heatsink from the common raster pattern of the bulk geometry caused this balling of powder that results in a poorer surface quality. Both Figures 7(a) and Figure 7(b) reveal an improved upskin finish without a witness line corresponding to the downskin layer application rule.

The next step was to print a simulation test build of turbo wheels at AddUp Cincinnati. Successful prints shown in Figures 6 and 7 attest to AddUp's FormUp 350 ability to produce AM turbo wheels comparable to investment casting. Figure 8 shows a successful test print of 9 turbo wheels for cost modeling purposes.


Figure 8. A simulation print of 9 turbo wheels taking 44.5 hours.

Upon completion, the samples where stress relieved on the build plate at 650°C for 2 hours under vacuum and were removed from the plate via wire electrical-discharge machining (EDM).

The samples were then subjected to AddUp's standard Inconel 718 heat treatment recipe following build plate removal. Each turbo wheel underwent solutionizing at 1095°C for 2 hours and ageing at 720°C for 8 hours, followed by a furnace cool to 620°C and hold for 8 hours before air cooling to room temperature.

Following the heat treatment, the wheels were returned to machine and finish the support structure under the wheel. An example wheel is shown before and after support removal in Figure 9. Due to AM Inconel 718's high hardness value, grinding machining took approximately 30 hours. This is an area to examine in the future for optimization both from a machining and design perspective. Finally, the bores of all of the turbo wheels were finish-honed to a diameter range of 6.345 - 6.353 mm.

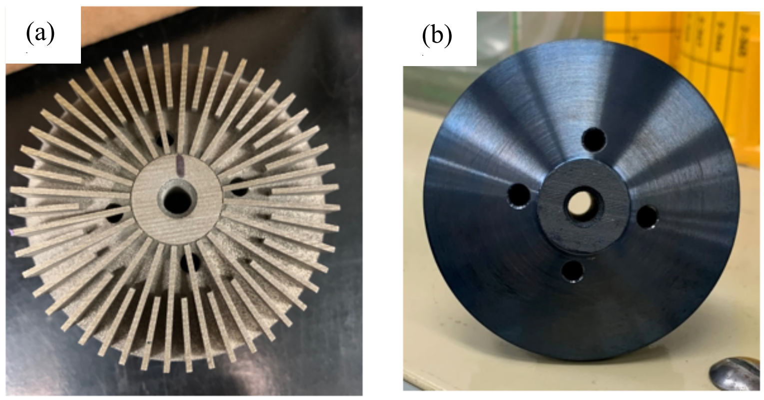

Figure 9. (a) Underside of as-fabricated supported turbo wheel and (b) post-machined underside.

All the wheels were then sent for light-scanning to determine their deviation from the CAD model and repeatability. Of particular interest was the location of different parts of the blades since those regions were built without support structure. Figures 10 and 11 indicate the deviation from CAD for the Blade upskin and downskin, respectively. The box and whisker plots indicate both the average deviation from CAD of the location and the variation within each measurement. The highest deviation from CAD (close to 0.5 mm) was at the very upper edge of the blades. The lowest deviation was at the base of the blades. In general, propulsion applications require tolerances closer to 0.1 mm, so the deviation is unacceptable and would require further development. However, the tolerance within each measurement across the nine turbo wheels indicates little deviation from part to part. This provides confidence in optimizing the design and scan strategy to meet tolerancing in future printed components.

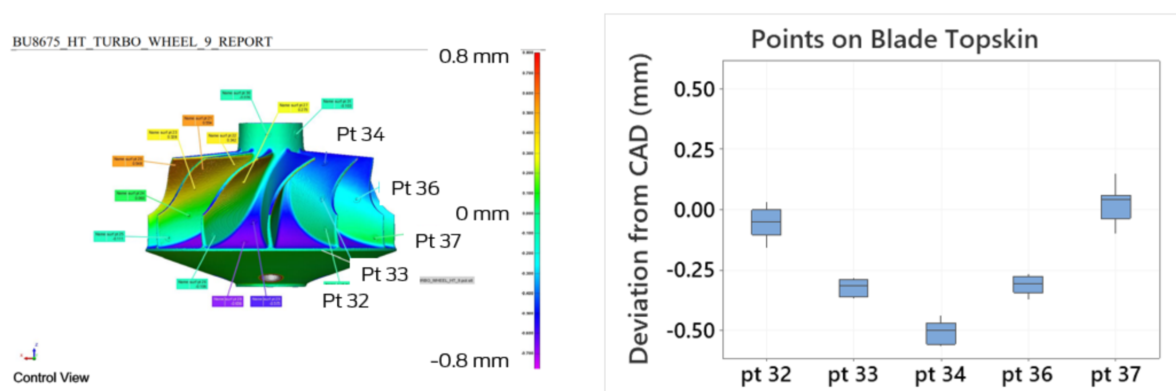

Figure 10. Blade upskin deviation of turbo wheel #09 from CAD.

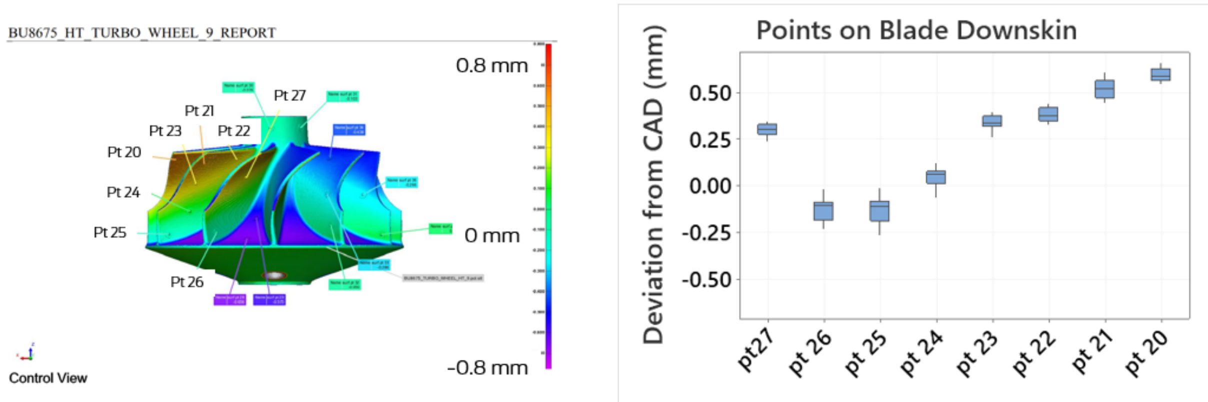

Figure 11. Blade downskin deviations of turbo wheel #09 from CAD.

Though dimensions of turbo wheel #09 varied ±0.5mm at points, results were consistent across turbo wheels which is indicative of a repeatable process. Light scanning results show that fine-tuning of processing parameters or offsetting of CAD models to print specific regions of the turbo wheel more accurately can be used to achieve correct dimensional tolerancing.

Two wheels were selected to be sent to Garrett to be balance tested. Garrett manufactures the GT37 Turbocharger that is used on the Ford Motor Company 6.7 L Powerstroke Engine. The turbo wheels in this study were based on the dimensions for the GT37 Turbocharger so the bench test could accommodate the wheels. A tight fit to the shaft is necessary for precise, repeatable, and safe testing so the #02 and #08 wheels were sent to Garrett Motion as these turbo wheels achieved the tightest bore tolerance. Figure 12 indicates the tolerance required for the bores.

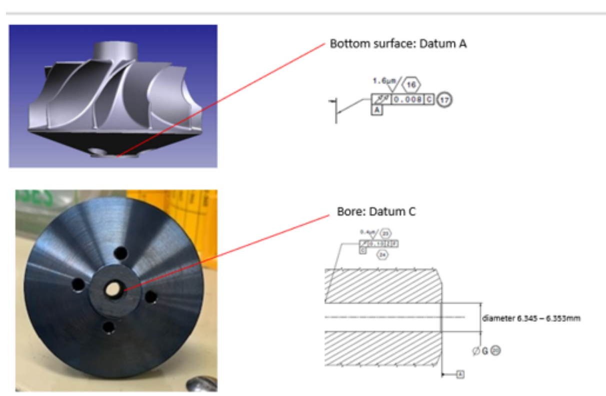

Figure 12. Bore clearance required for the testing.

The test being performed was a balance test. The goal is to determine if the turbo wheels produced had sufficient geometric and density uniformity and overall stability that the standard balancing procedure could be performed. In this testing procedure, the component is spun at a fixed speed while a vibration signal is analyzed to determine the unbalance so that it can be corrected. A calibration is first performed with a known weight, usually a piece of clay, in a known location. The vibration vector is a is function of grams mm (mass along the radius) and an angle. The angle is the angle between where the vibration sensor is mounted and where the phase reference is measuring. Based on these measurements, the location of the heavy spot on the wheel can be determined. Material can be removed from the rotating component in certain locations to get the part back in balance.

Garrett utilized a Vertical stand-alone, air driven balancer to test the wheels. This type of balancer uses only a shaft and the wheel itself so it does not require additional turbocharger hardware. The setup balances only the component. In this particular setup, the load carrying capability was 60-400 grams, the measuring accuracy was 0.06 – 0.150 g mm, and the maximum readable unbalance was 40 g mm. Wax was used for the initial calibration at 2800 RPMs. This example setup is shown below in Figure 13:

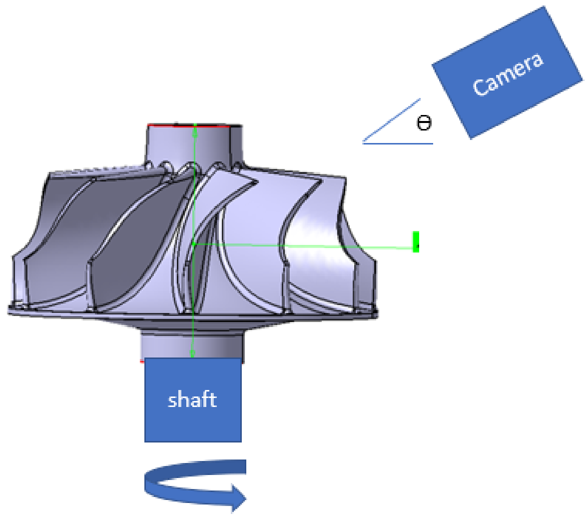

Figure 13. Example of a vertical, stand-alone, air driven balancer.

The calibration was performed on turbo wheel #08. 315g of wax was placed on the edge of the wheel and the vibration vector was measured at the nose and face of the wheel for calibration at 2800RPM. Turbo wheels #02 and #08 were balanced and the results are shown in Table 2.

Table 2. Calibration results where the nose is considered the blade end and face is the underside of the blades.

Nose		**Face**		**Comment**
gr-mm	Angle	gr-mm	Angle	
0.0205	99	0.0343	292	Without artificial weight
2.650	355	0.0835	280	With weight at nose
0.0323	161	8.510	359	With weight at face
1.20%		1.0%		Acceptable error <5%

Once the calibration vector was known, the wheels were tested at the same speed (2800 rpm) and the vibration vector was calculated for both wheels. The maximum target imbalance was 0.186 g-mm for the nose and 0.375 g-mm for the face. The measured vector for each wheel was subtracted from the calibration vibration vector to achieve the location and mass of the heavy spot within each turbo wheel. Material can then be removed from the nose and face to bring the wheels into a minimum target balance. The results are shown below in Table 3 and Figure 14.

Table 3. Balance results before and after material removal.

	Initial Unbalance				Final Balance			
	Nose		**Face**		**Nose**		**Face**	
SN	gr-mm	angle	gr-mm	angle	gr-mm	angle	gr-mm	angle
HT#2	3.14	139	6.30	107	0.09	143	0.02	104
HT#8	3.97	78	6.31	71	0.05	4	0.06	103

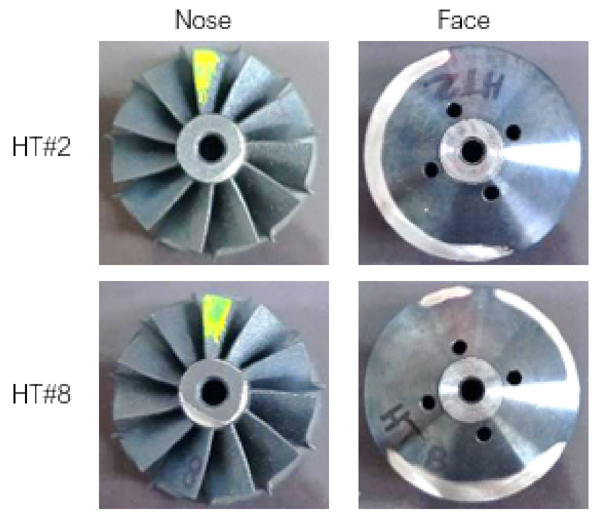

Figure 14. Machining required for balancing.

The results show the turbo wheels produced passed tolerance indicating they could be properly balanced using a standard procedure, and that they could withstand a room temperature, high-speed rotation test.

Finite Element Analysis of the design was performed at Ford. The analysis simulated centrifugal loads based on the yield strength of 920 MPa and the test stand maximum speed of 50,000 rpm. The analysis utilized the properties for Inconel 718 produced in L-PBF as defined in the ASTM standard F3055. The results of the von Mises stresses in different locations is shown in Figure 15. The maximum von Mises stress at 50,000 RPM is 252 MPa, which is well below the yield strength of this material.

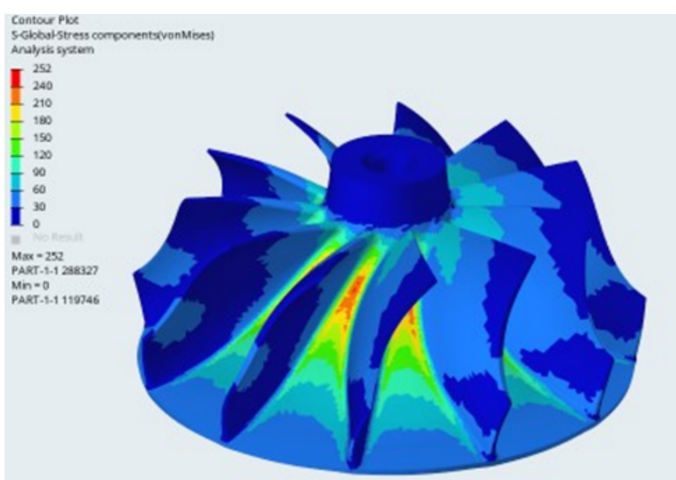

Figure 15. Contour plot of the von Mises stress with a rotation speed of 50,000 rpm

The final design was also examined to determine if it met the original goal, which was a reduction in mass and inertia from the original design with the use of a hollow interior. The results were mixed: while a 20% mass reduction was achieved with the new design, the inertia actually increased by 8%. This was due to the addition of material to the bottom of the wheel to improve manufacturing and powder removal for the hollow section. Figure 16 shows the overlay of the original and new wheel designs indicating the location of the added material. Further design and manufacturing optimization will be required to achieve the desired inertia reduction. Potential solutions could involve more easily removed support structure and better hollow design in the interior for ease of powder removal without the requirement for a large taper.

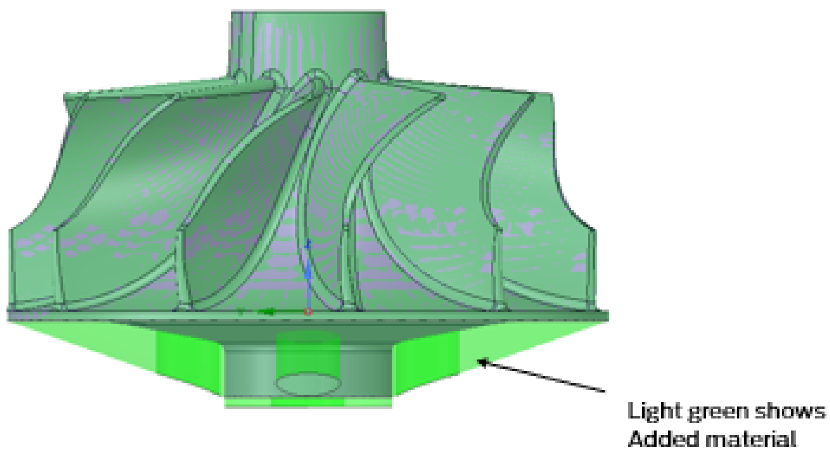

Figure 16. Overlay of original and final designs where light green shows added material for easier machining.

1.3 IMPACTS

AM turbo wheel components printed in this study show feasibility in challenging traditionally manufactured components. Flexible designs allowed by AM can result in increased engine performance due to material selection or geometric designs such as hollowed sections as shown in this study. For the purpose of this study, a cost model was developed to estimate the cost per wheel using L-PBF. Inputs such as material cost, print time, support removal time, and post-processing times are included as main drivers for cost. Though omitted from this report, internal inputs for machine cost, amortization, labor, scrap rate and machine uptime were incorporated from existing models. The results are shown in Table 4.

Table 4. Select Cost Model inputs based on part production.

Part name	Impellor
3D printer make and model	AddUp FormUp 350
Build Plate size	350 x 350 mm2
Number of parts per batch	25
Print time per batch	32.28 hours
Material Cost estimate for Inconel 718	\$70/kg
Mass of part	0.311 kg
Mass of support material	0.05 kg
Depowder time per batch	0.5 hours
Support Removal time per batch	30 hours
Post processing time per batch (heat treatment)	12 hours
Annual volume required	100,000 units per year

A total cost estimate of $71.00 per turbo wheel was calculated. Drivers for cost reduction would include minimizing print and support removal time. These results indicate that this component could be scaled to meet the volume requirements for this application.

1.4 CONCLUSIONS

A hollow turbo wheel was additively manufactured using an AddUp FormUp located at Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF) on an AddUp FormUp 350 using maraging steel. A contour experiment was performed to study skin effects as a function of contouring parameters which determined that a single contour suffices to improve surface finish, but that the manufacturer's offset needed to be increased, that is, the contour pass should be nearer the tips/tails of hatch vectors.

The turbo wheels were hollowed out to reduce weight and achieved a 20% weight reduction. However, additional material added for support to underside of the wheel resulted in an overall 8% increase in inertia. Next, two complete turbo wheels and 3 half turbo wheels were produced from Inconel 718 to study downskin and upskin parameter effects. After determining optimal skin parameter settings, nine Inconel 718 turbo wheels were supported and produced using an AddUp FormUp 350's standard infill parameters and improved skin parameters. Turbo wheels showed a Ra value of 7.9µm on underside regions of the blades. This falls between the D10 and D50 which is lower than an expected surface roughness nearer the D90 of powder feedstock.

From the nine turbo wheels produced in Inconel 718, two were successfully balanced and could be tested in a standard spin test. However, the turbo wheels indicated a variation of slightly greater than 0.5 mm on the edges of the unsupported blades. Furthermore, tolerances of ± 0.2 mm were observed at the base of the blades. Despite this, part to part geometric variation for similar locations indicated good repeatability within a 0.1mm tolerance.

Cost modeling indicated a piece cost of approximately $71. This indicates that the parts could be produced at scale for a reasonable cost. More design iterations would be required to decrease machining time and result in a decrease in overall inertia, but prints were shown to be spatially repeatable within a print as well as temporally from print to print.