

Next Generation Additive Manufacturing of Shrouded Turbine Wheel

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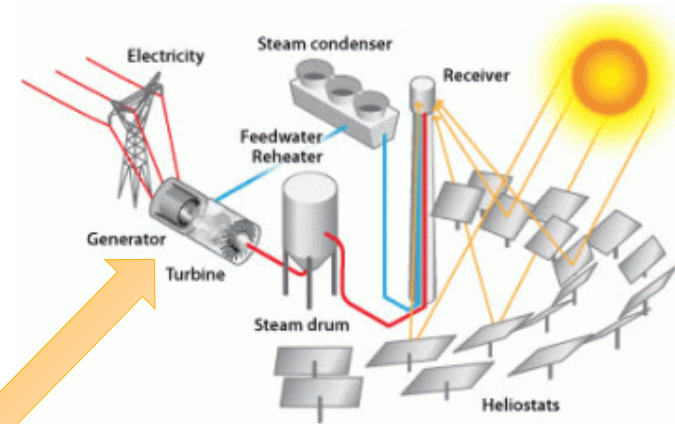


Hanwha Power Systems

stratasys
DIRECT MANUFACTURING

Problem Statement

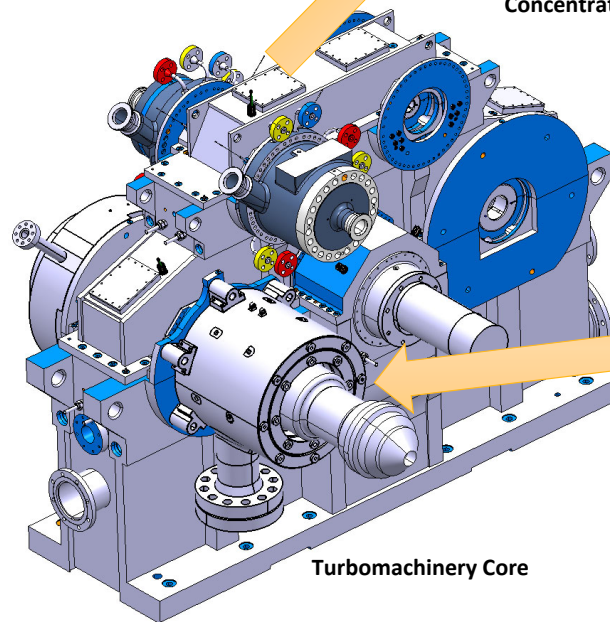
Manufacture a shrouded expander wheel that will be used in a high temperature short duration test of a supercritical CO₂ power generation loop



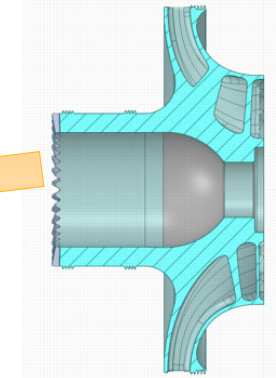
Concentrating Solar Power Generation Plant

Design Criteria:

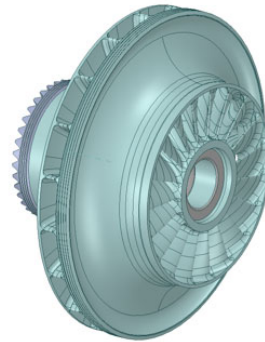
- 705°C operating temperature
- 20-year life
- Maximize performance with an integrated shroud



Turbomachinery Core



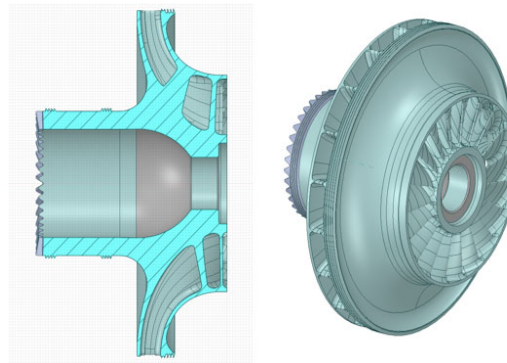
Turbine Wheel



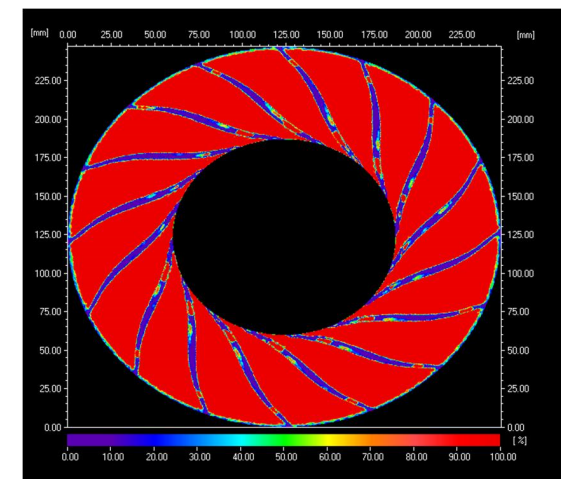
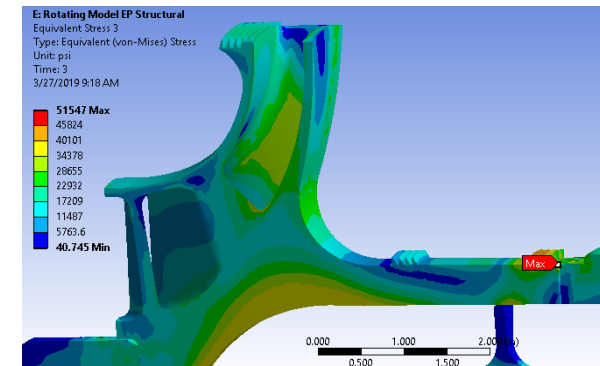
Challenges With Shrouded Impellers

Possible Manufacturing Methods:

- Single piece machining
- Machining & welding
- Machining & brazing
- Casting
- Additive Manufacturing



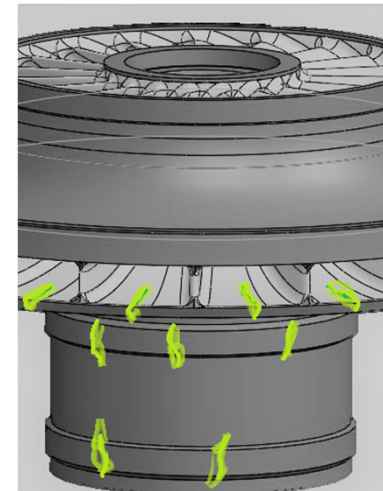
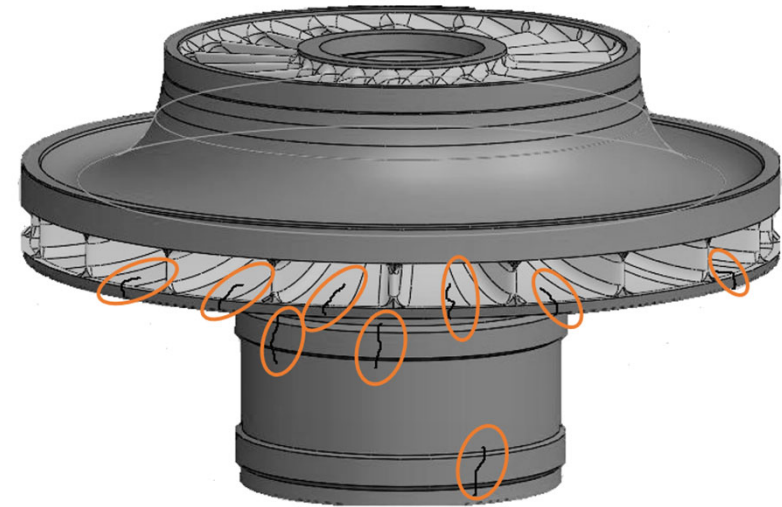
Shrouded Turbine Wheel



Ultrasonic scan
 Failed EB Weld/Braze Joint

Material Selection

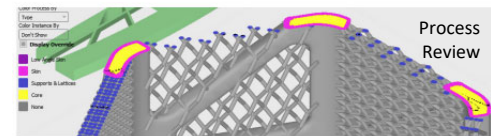
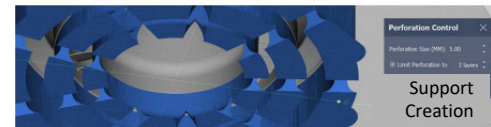
- **Initially selected INCONEL® 738LC** – Good strength and creep resistance at elevated temperatures
- **Experienced issues in manufacture of a In 738LC expander** – cracks appeared after heat treatment
 - Further development needed to AM this turbine wheel in INCONEL 738LC or similar creep resistant alloy for long term commercial use
- **INCONEL 718 was utilized for this build for a short duration test** – Common AM alloy and available from a next generation AM system.



Cracks in INCONEL 738LC AM Turbine Wheel (Not Manufactured by Stratays Direct Manufacturing)

What is Next Generation Additive Manufacturing?

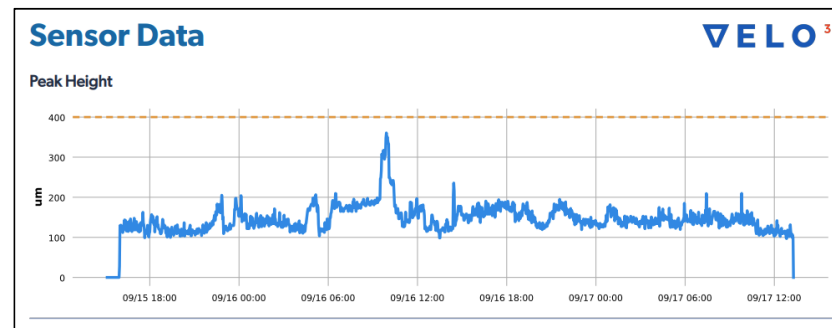
- Streamlined CAD Workflow.** Part-file to build-file is now all in one software.
 - Build files contain all exposure and slice information to produce the same build across multiple platforms or during future production.
- Auto-machine calibration**
 - Tool health checks are now machine operations instead of a manual operation.
- Process monitoring**
 - “Height Mapper” – Provides layer topology
 - Can identify part protrusion & Powder bed erosion (closed loop)
 - Laser power delivery - measured with each layer
 - Closed loop control of Build Environment - (pressure, O₂, powder delivery)
- Design freedom**
 - Support free processes
 - Non-contact re-coater system



Beam Stability				Laser Alignment			
Value	Status	Timestamp		Value	Status	Timestamp	
-36.212	✓	2021/09/10 at 16:03	Optics Box - Window	20	✓	2021/09/10 at 13:49	Overlay Variation ->direction
-25.547	✓	2021/09/10 at 16:03	Laser 2	24	✓	2021/09/10 at 13:49	Overlay Variation -y-direction
-15.893	✓	2021/09/10 at 16:03	Optics Box	3	✓	2021/09/10 at 13:49	Laser Overlay ->direction
0.972	✓	2021/09/10 at 16:03	Laser 1	1	✓	2021/09/10 at 13:49	Laser Overlay -y-direction
			Laser 2	74	✓	2021/09/10 at 13:49	Laser Mapping Accuracy ->direction
				74	✓	2021/09/10 at 13:49	Laser Mapping Accuracy -y-direction

Thermal Sensor Alignment				Laser Focus			
Value	Status	Timestamp		Value	Status	Timestamp	
-0.028	✓	2021/09/10 at 15:57	Offset - x-direction	-4.461	✓	2021/09/10 at 12:05	Spot Size Center Focus
-0.144	✓	2021/09/10 at 15:57	Laser 1	-2.223	✓	2021/09/10 at 12:28	Laser 2
-0.054	✓	2021/09/10 at 15:57	Offset - y-direction	19.489	✓	2021/09/10 at 12:05	Spot Size Focus Across Build Plate
0.073	✓	2021/09/10 at 15:57	Laser 2	19.845	✓	2021/09/10 at 12:28	Laser 1

Legend: ✓ In Spec ✗ Out of Spec ⚠ In Spec older than 7 days 📄 No Data



Why Stratasy Direct?

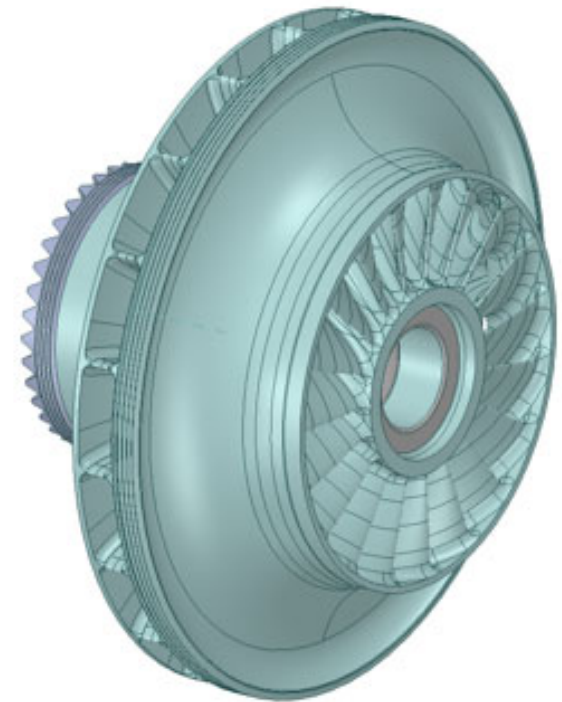
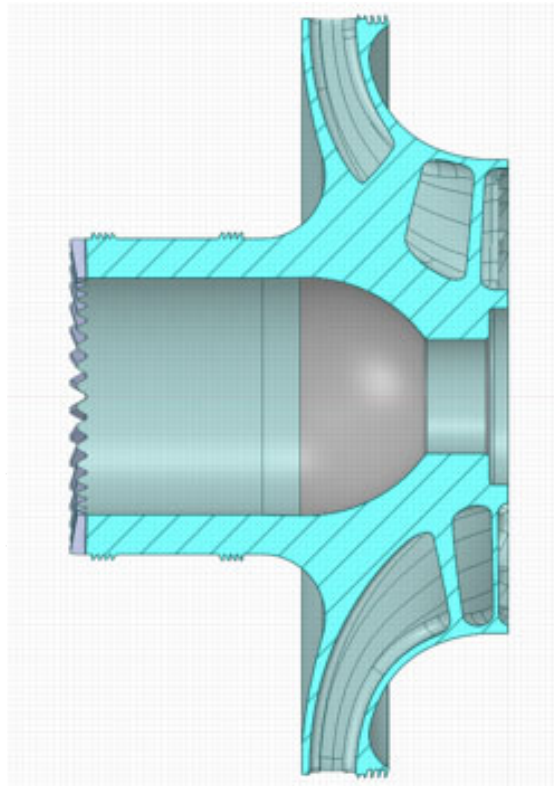
- **Stratasy Direct** has over a decade of experience in providing AM metal services to industry.
 - ✓ Machine fleet composed of 18 Laser based metal powder bed systems.
 - ✓ Dedicated equipment to secondary processing including heat treat furnace, CNC machining centers and quality lab.
 - ✓ Provides expedient, competent, comprehensive, technical expertise, & project management oversight
- **Next-generation AM** platform available at their facility
- *Hanwha previously worked together on shrouded impeller builds and development projects*



Communicating the design intent

NOTES

1. MATERIAL: INCONEL 718 ASTM F3055 CLASS C
2. PART: PROTOTYPE_ROTATINGSHAFTV02.SLDPRT
3. PERFORM FPI PER ASTM E1417
 1. TYPE 1, METHOD D, DEVELOPER D
 2. LEVEL 3 SENSITIVITY PENETRATING AGENT
 3. NO CRACKS ALLOWED
 4. ALLOWABLE INDICATION (NON-LINEAR) MAX 0.080IN, (LINEAR) MAX 0.010IN
 5. MINIMUM DISTANCE BETWEEN INDICATIONS 4 TIMES THE SIZE OF INDICATIONS
 6. MAXIMUM DIAMETER OF CLUSTER INDICATIONS MUST BE 4 TIMES THE SIZE OF THE INDICATIONS
4. PERFORM X-RAY AND CT SCAN
 1. X-RAY ASTM E1030-15
 2. CT SCAN PER ASTM E1814-14
 3. ACCEPTANCE CRITERIA
 1. CRACKS NOT ACCEPTABLE
 2. LINEAR INDICATIONS <0.030IN ARE ACCEPTABLE, EXCLUDING CRACKS
 3. LINEAR INDICATIONS > 0.030IN ARE NOT ACCEPTABLE
5. THERMAL PROCESSING
 1. PER ASTM F3055 CLASS C
6. MECHANICAL TESTING
 1. TEST COUPONS SHALL BE MANUFACTURED ALONG SIDE COMPONENT AND PROCESSED ACCORDING TO THE SAME MANUFACTURING PLAN
 2. A MINIMUM OF TWO TENSILE, FATIGUE, AND STRESS-RUPTURE TESTS SHALL BE CONDUCTED
 1. MINIMUM TENSILE PER ASTM E8
 1. MIN UTS [REDACTED]
 2. MIN YS [REDACTED]
 3. MIN ELONGATION [REDACTED]
 2. MINIMUM FATIGUE
 1. MIN CYCLES TO FAILURE OF 10K AT [REDACTED]
 3. MINIMUM STRESS RUPTURE PER ASTM E139 AT 2375F. NO TEST SHALL RUPTURE IN LESS THAN [REDACTED]
 1. CONDUCT TEST TO RUPTURE
 2. ELONGATION AFTER RUPTURE, MEASURED AT ROOM TEMPERATURE SHALL BE NO LESS THAN [REDACTED]
 4. SUPPLIER SHALL SUPPLY ALL TEST RESULTS
7. PERFORM BALANCING PER ISO 1940-G2.5
 1. BALANCE BY GRINDING HUB IN AREAS INDICATED
 2. BALANCE SPEED 1200RPM
9. LASER MARK IN AREA INDICATED
 1. PART NUMBER, REV, SERIAL NUMBER
 2. MARKING DEPTH: MAX 0.020IN
10. ABRASIVE FLOW OR CHEM MILL INTERNAL SURFACES TO 75MICRO-IN RA MAX

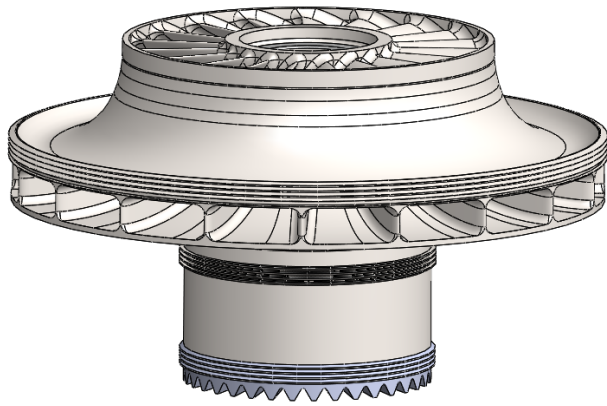


Establish the Manufacturing Plan

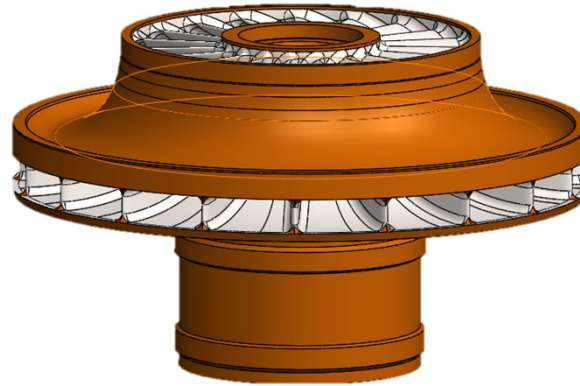
- 35 Operations
- 4 Different Work Cells
- 6 Different Vendors

Sequence	Description	Work Cell
10	Build Prep	MFG
20	Build	MFG
30	Build Breakout	MFG
40	In-process Dimensional Inspection	QC
50	Machining	CNC
60	Powder Removal	MFG
70	Transfer to Vendor for HIP	SHIP
80	Receive from Vendor for HIP	SHIP
90	Visual Inspection	QC
100	Support Removal	MFG
110	Basic Hand Finish	MFG
120	Transform to Vendor for SHT & PHT	SHIP
130	Receive from Vendor for SHT & PHT	SHIP
140	Visual Inspection	QC
150	Media Blasting	MFG
160	Transfer for Vendor for Digital X-Ray	SHIP
170	Receive from Vendor for Digital X-Ray	SHIP
180	Visual Inspection	QC
190	Machining	CNC
200	Visual inspection	QC
210	Laser Marking	MFG
220	Visual Inspection	QC
230	Transfer to Vendor for Special Machining	SHIP
240	Receive from Vendor for Special Machining	SHIP
250	Visual Inspection	QC
260	In-process Dimensional Inspection	QC
270	Transfer to Vendor for Abrasive Flow Machining	SHIP
280	Receive from Vendor for Abrasive Flow Machining	CHIP
290	Visual Inspection	QC
300	Surface finish inspection	QC
310	Transfer to Vendor for FPI	SHIP
320	Receive from Vendor for FPI	SHIP
330	Visual Inspection	QC
340	Final Inspection	QC
350	Ship	SHIP

Digital File Prep: Solid Modeling

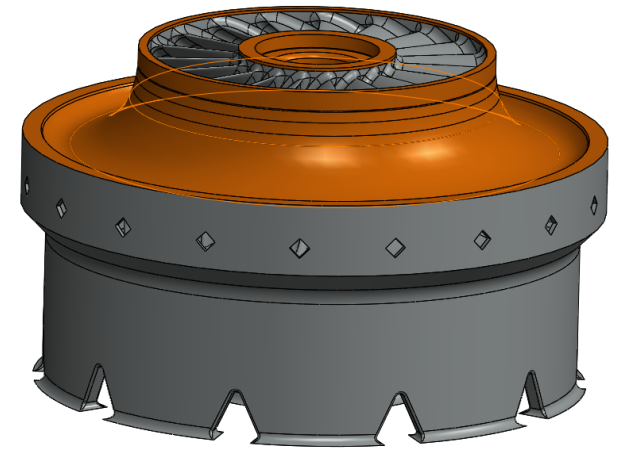


Final Design
Deliverable



Stock for CNC
Machining

+5% Material



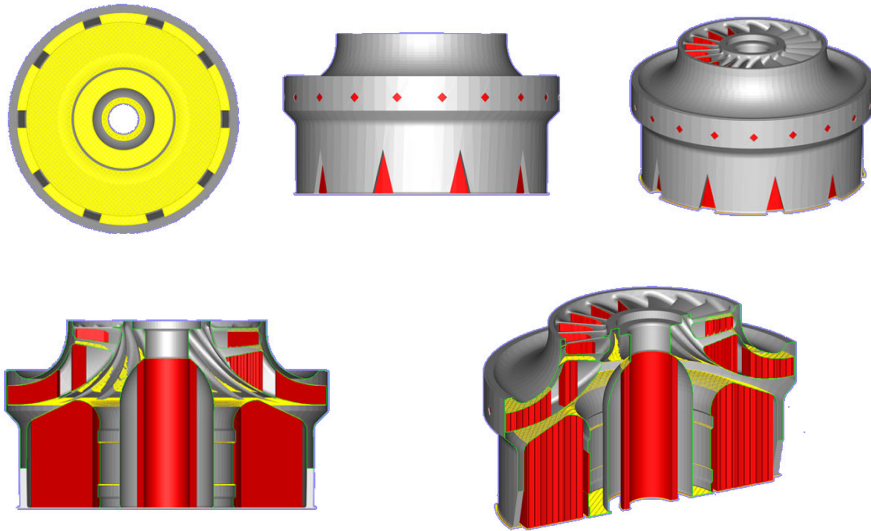
Solid Support
Structures for AM

+40% Material

Digital File Prep: Support Structures

Conventional AM

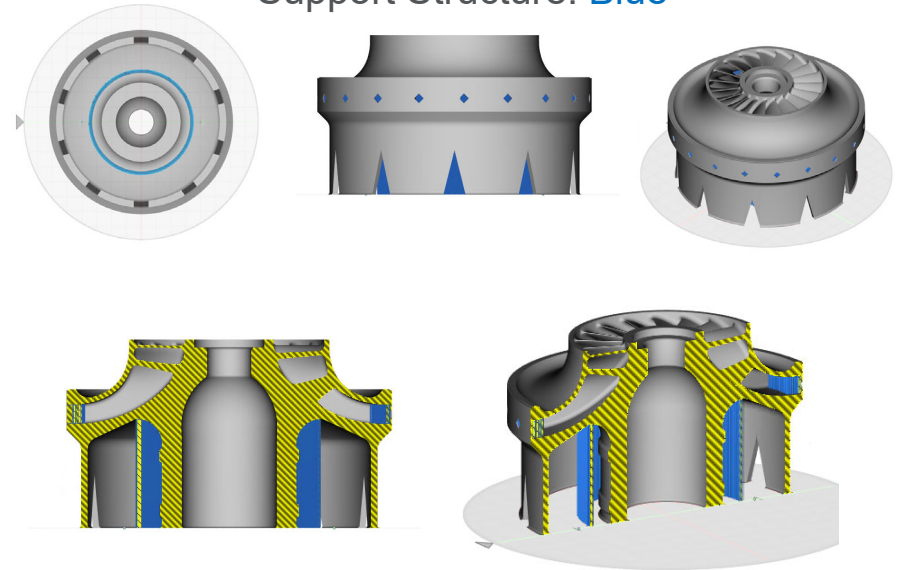
Support Structure: **Red**



Part Volume: 1702 cm³
Support Volume: 686 cm³

Next Generation AM

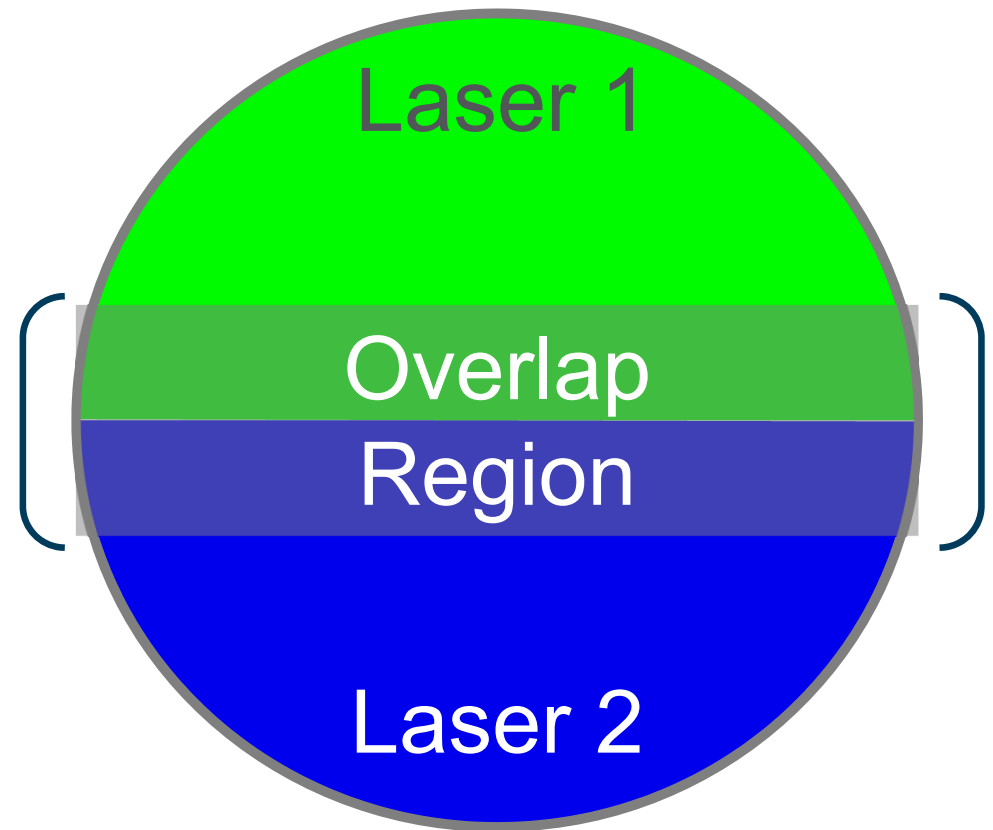
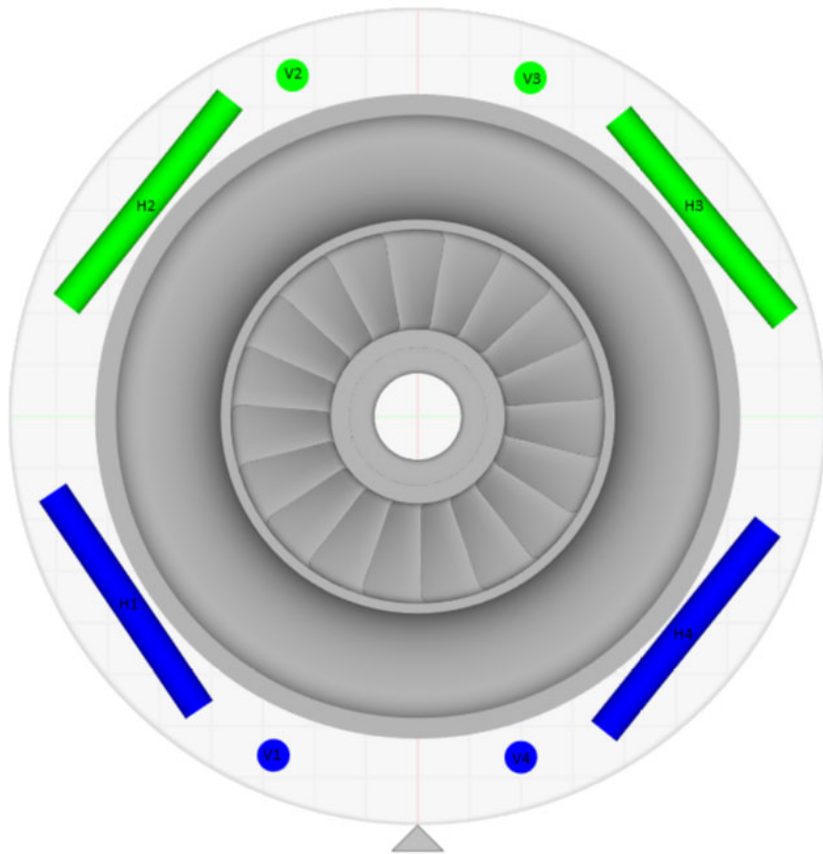
Support Structure: **Blue**



Part Volume: 1704 cm³
Support Volume: 69 cm³

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Digital File Prep: Build Layout



Build Metrics

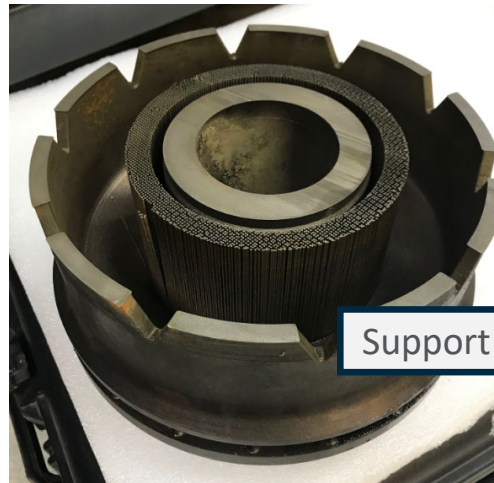
- Weight = 32.5 lbs
- Build Time = 59 hrs



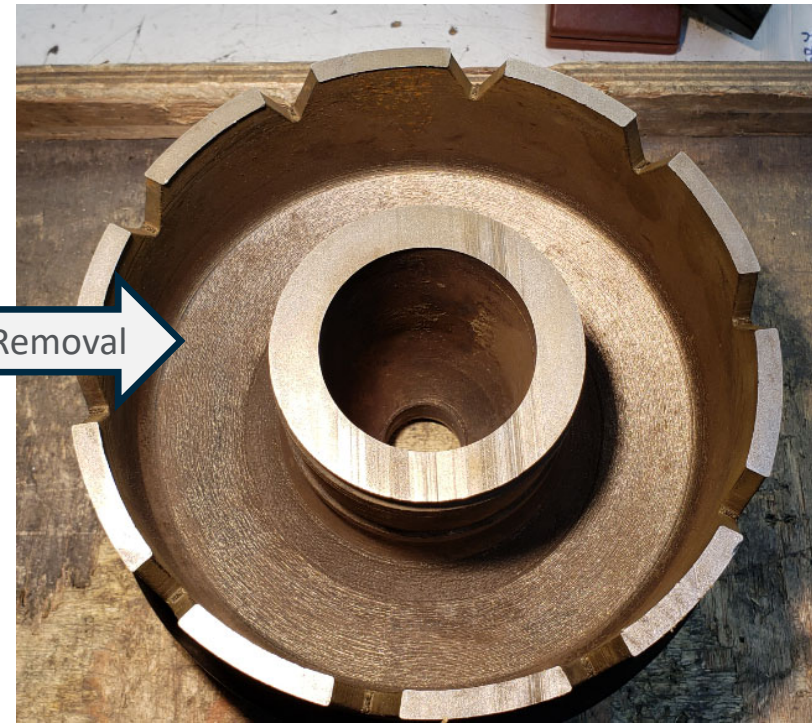
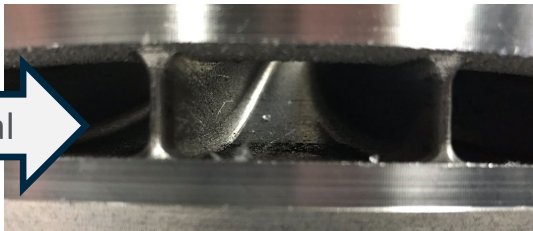
Secondary Operations: Powder, SR, Wire EDM & Support Removal



Powder Removal



Support Removal



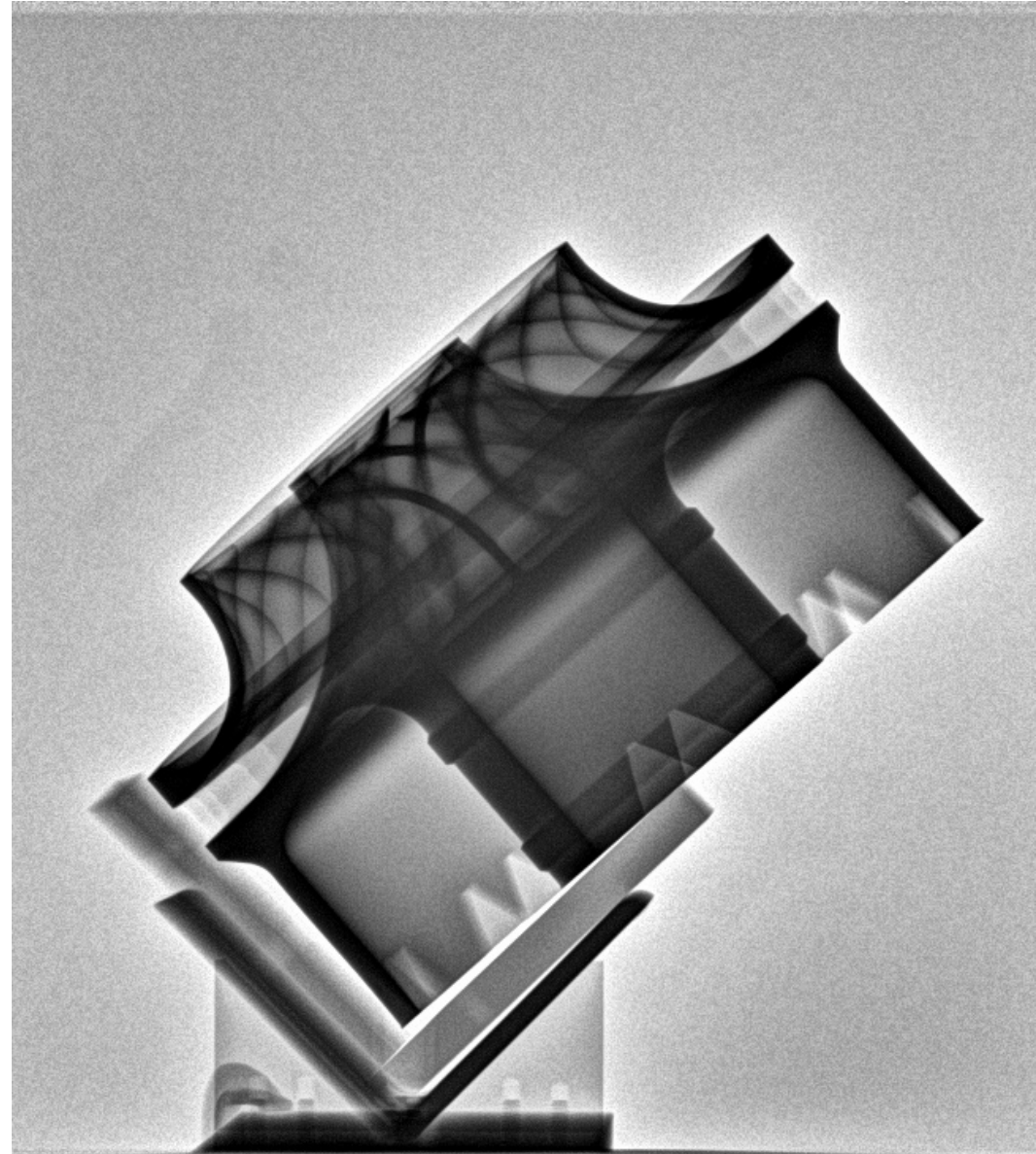
In-process Inspection

2D Digital X-Ray

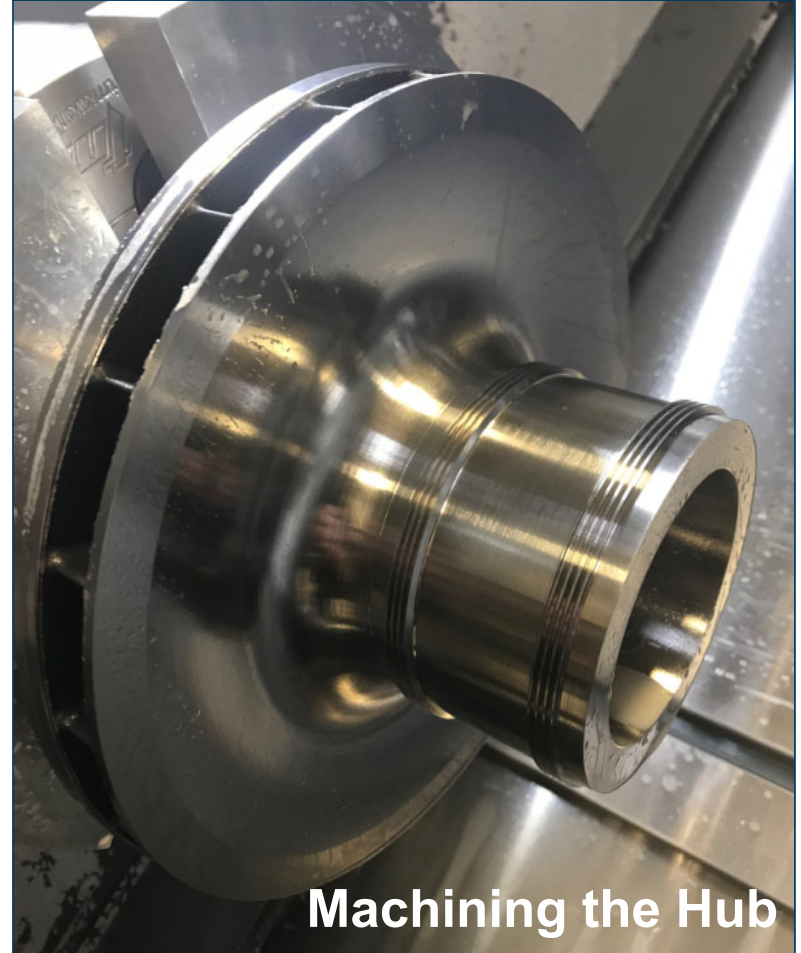
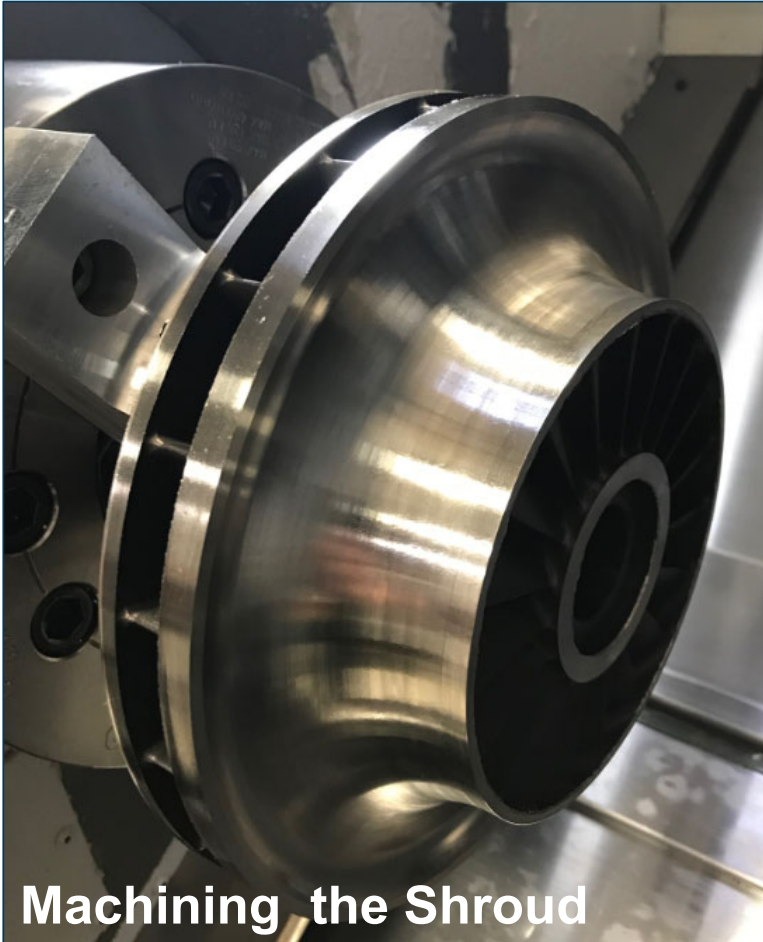
- ✓ Sufficient for identifying trapped powder.
- ✗ Cracks, Voids, Porosity, Lack of Fusion

CT Scan

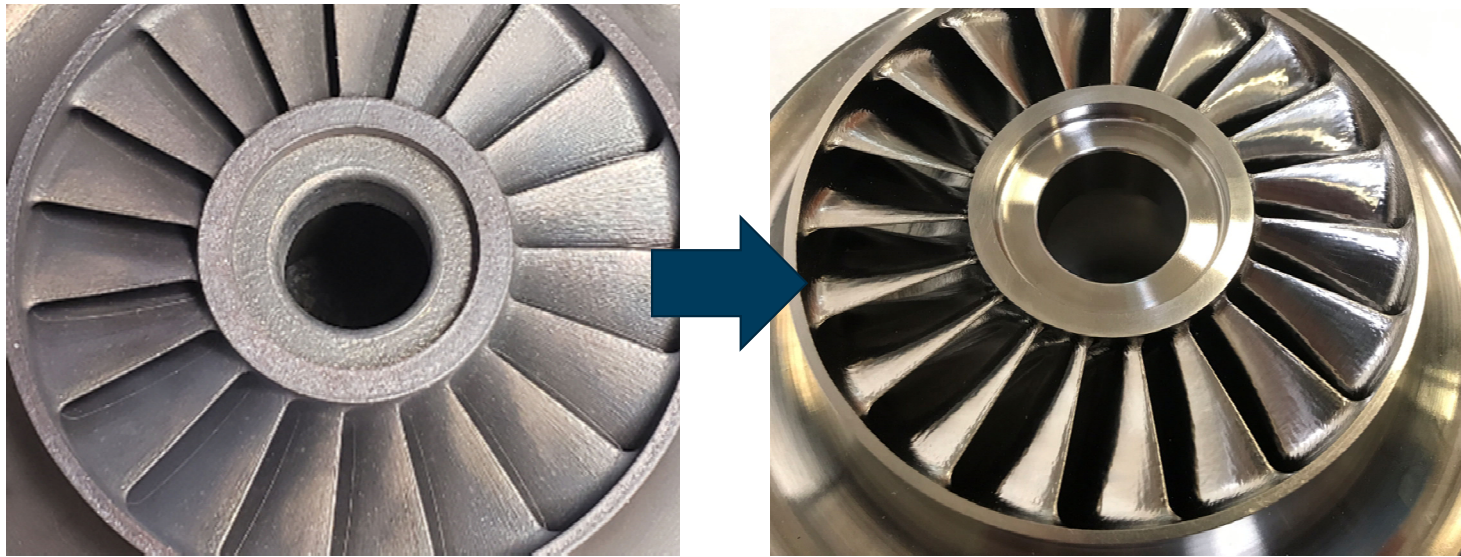
- ✓ Sufficient for identifying trapped powder.
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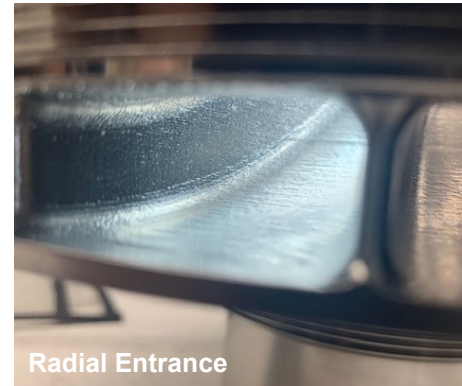
Secondary Operations: CNC Machining



Secondary Operations: Abrasive Flow Machining



- Surface Roughness = $1.6 \mu\text{m Ra}$ (max)
- Material Removed $\approx 0.5 \text{ mm}$

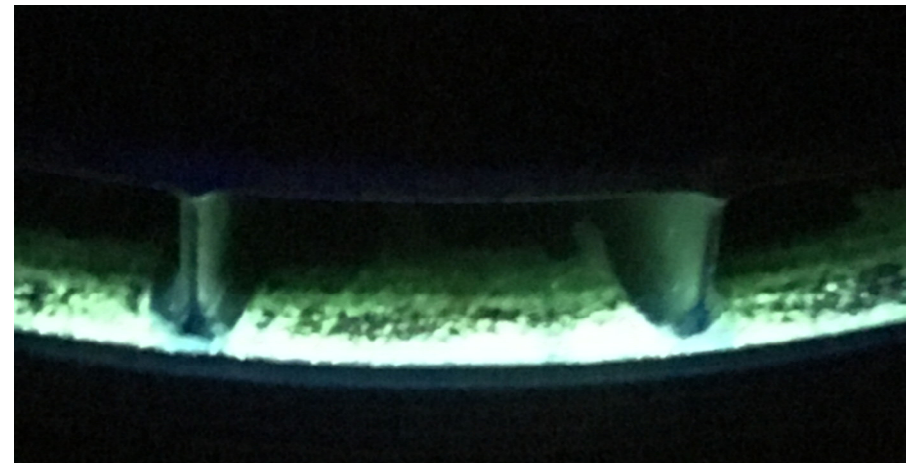
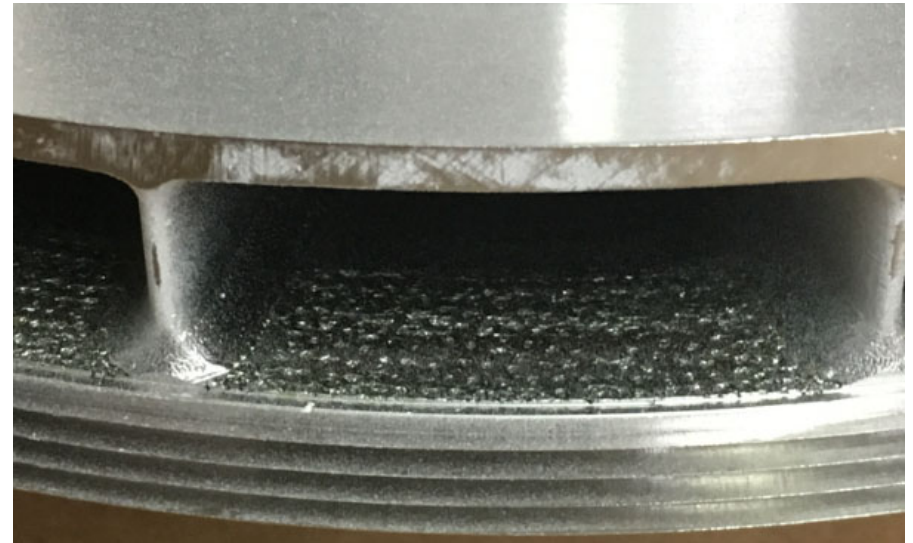


In-process Inspection

Florescent Penetrant Inspection

Identifies cracks and surface discontinuities.

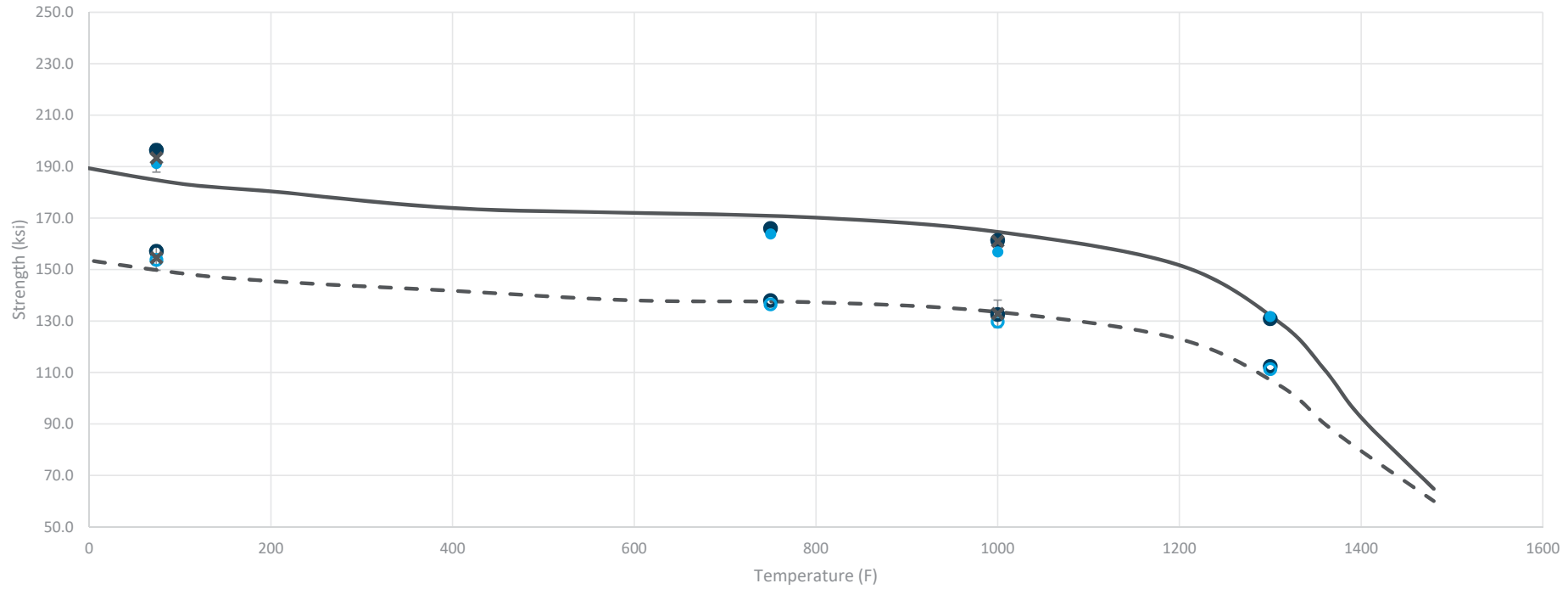
- ✓ Machined Surfaces
- ✗ As Build Surfaces
- ✗ Supported Surfaces



Inspection Mechanical Properties

ASTM F3055 IN718 UTS & YS vs. Temperature

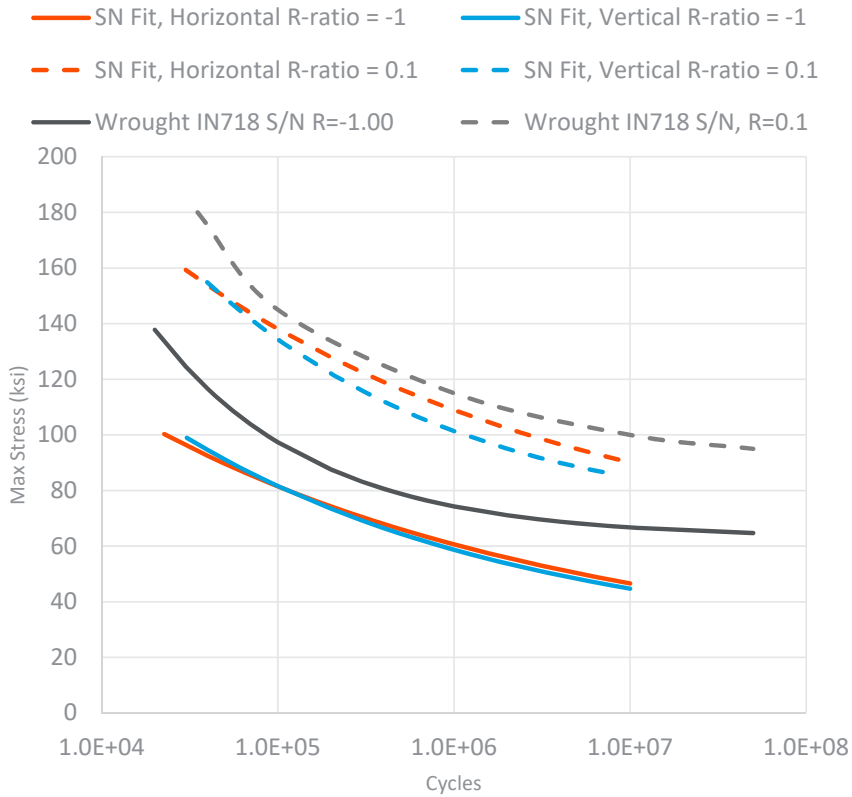
- Horizontal UTS
- Horizontal YS
- Vertical UTS
- Vertical YS
- × SDM's UTS Dataset
- × SDM's YS Dataset
- - - Wrought IN718 YS - (SHT and Aged)
- Wrought IN718 UTS - (SHT and Aged)



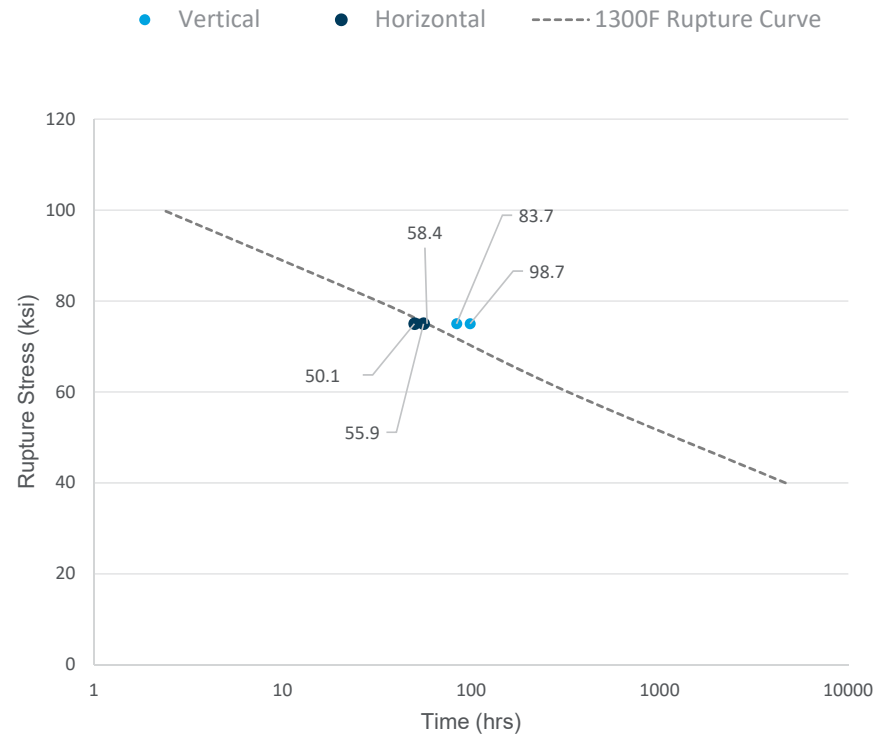
Data was obtained in a joint R&D project with Hanwha Power Systems and Stratasys Direct Manufacturing

Inspection Mechanical Properties

IN718 SN Curves, R-Ratio -1 & 0.1



IN718 Stress Rupture



Data was obtained in a joint R&D project with Hanwha Power Systems and Stratasys Direct Manufacturing

Component Testing

- ✓ Full Speed at 705°C
- ✓ An endurance test at 1-hour at 600°C



End Result

Manufactured and Project Managed by
Stratasys Direct Manufacturing

Designed and Tested by
Hanwha Power Systems

Enabled by the advancements of additive by
Velo3D



Thank you

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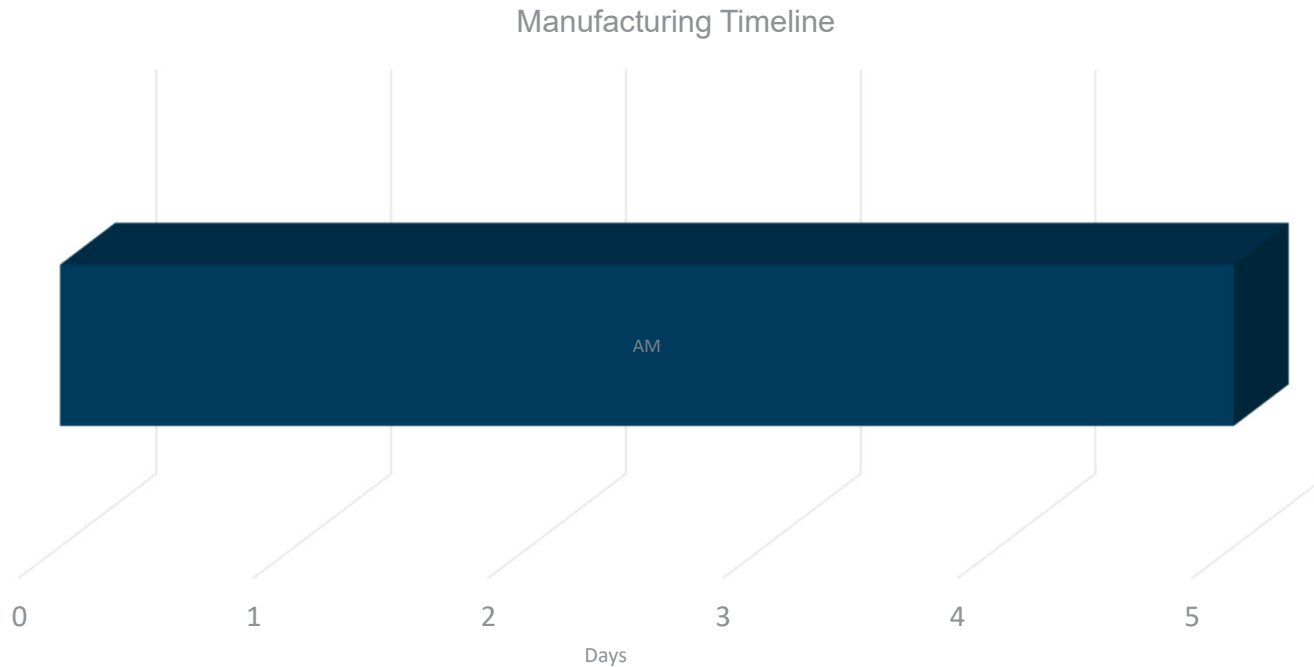
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DIRECT MANUFACTURING

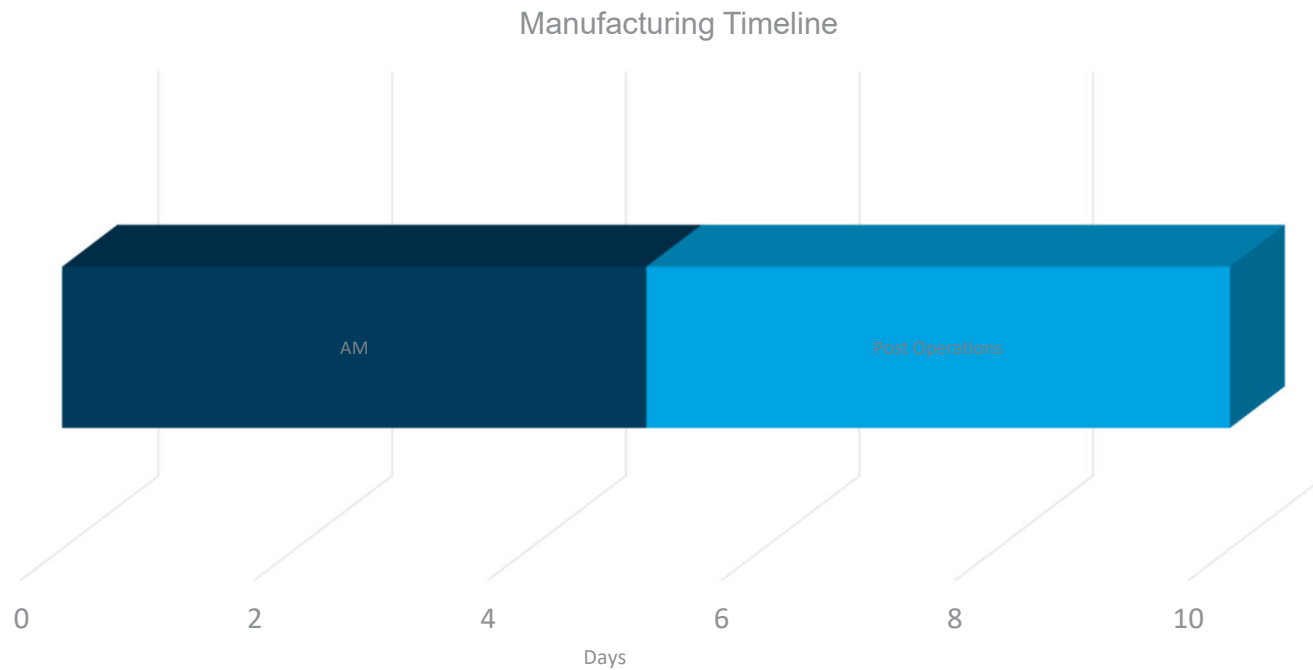
Understanding the Manufacturing Timeline

Perception provides a skewed version of reality...



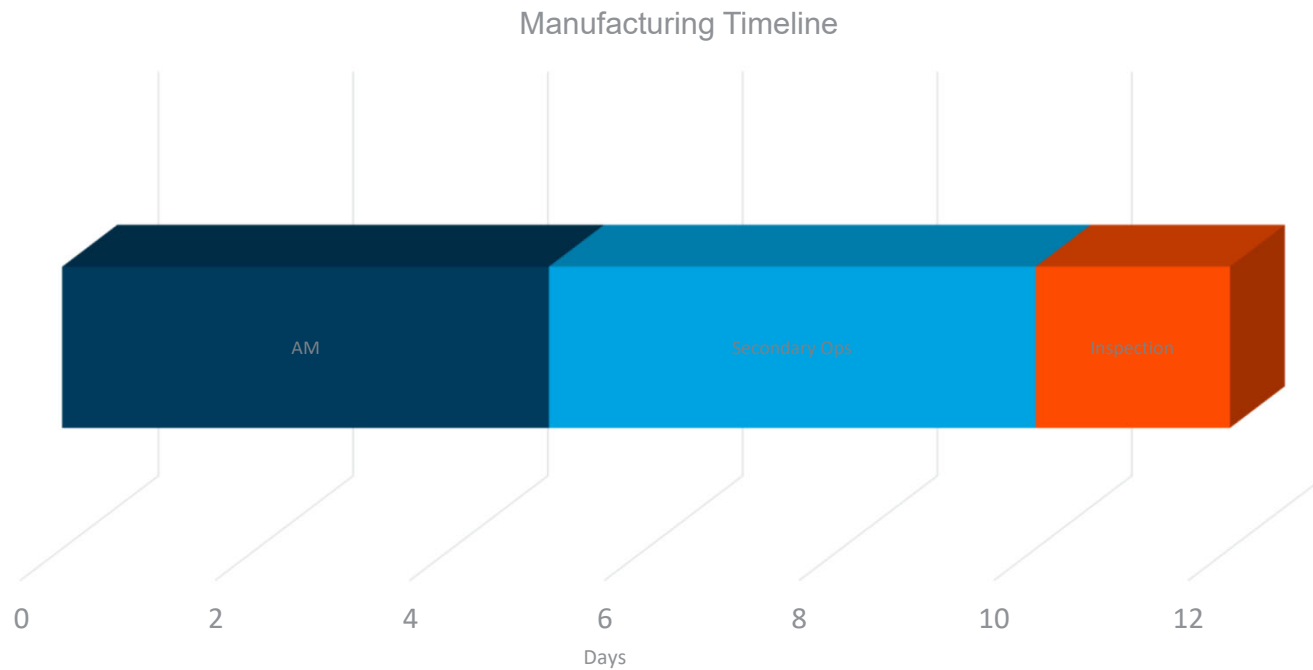
Understanding the Manufacturing Timeline

Need to consider the post operations.

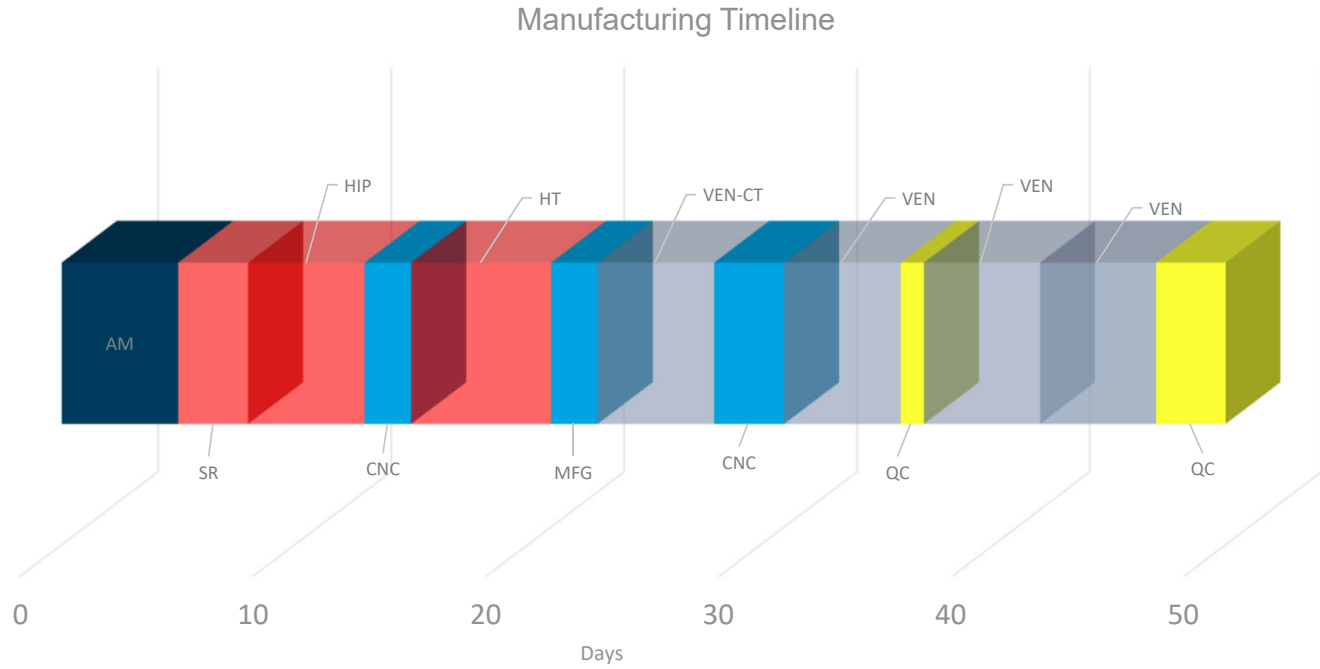


Understanding the Manufacturing Timeline

Post operations include inspection



Understanding the Manufacturing Timeline Reality



Understanding the Manufacturing Timeline



Understanding the Manufacturing Timeline

Monetary Investment

