UPWING CASE STUDY

Enhancing Natural Gas Production: Upwing Drills into Additive Manufacturing

Introduction

Upwing Energy is a gas tech innovator and service company, leading technological breakthroughs in the energy sector, dedicated to meeting global energy needs in an economically and environmentally sustainable manner. Their vision is to ensure affordable access to heat, fuel, electricity and produced goods for all, while safeguarding the environment for current and future generations.

Driven by this vision, Upwing's mission is to assist clients in enhancing natural gas production and recovery from their existing wells, while minimizing human and capital resources and reducing environmental impact.

To accomplish this mission, Upwing has developed a first-of-its-kind Subsurface Compressor System ™ (SCS) (Figure 1). This innovative system efficiently lifts gas from the well's bottom, resulting in remarkable increases of over 200% in incremental production, over 70% in recoverable reserves, and complete elimination of liquids.

By using the SCS, the demand for exploring, drilling, and completing new wells is significantly reduced, resulting in substantial capital savings and the elimination of greenhouse gas emissions associated with drilling, fracking and wellhead compressor operation.

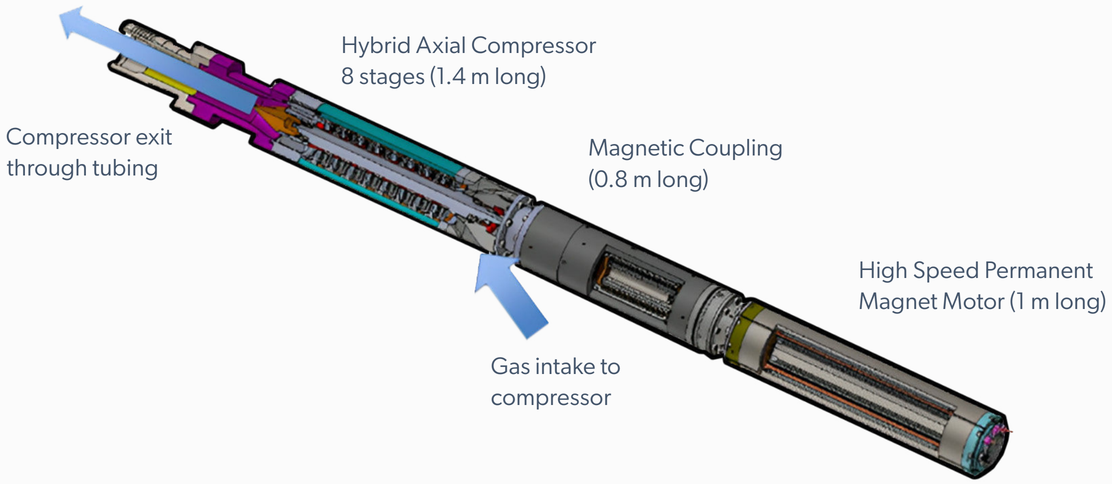


Figure 1: Upwing Subsurface Compressor System

A Detailed Evaluation of Manufacturing Technologies

Upwing's SCS employs a multistage axial compressor to effectively induce artificial lift within gas wells. The SCS's compressor module must be aerodynamically designed to match each Gas Well's specific flow parameters. This module comprises seven (7) primary components, all manufactured from Inconel 718. Among these components, five (5) are uniquely engineered to precisely cater to the Gas Well's flow parameters, including Inlet Housings, Intermediate Inlet Housing, Rotor Blades, Stator Vanes and Exit Housing.

To optimize the manufacturing time needed to support Upwing's SCS Gas Well deployment schedules, three primary manufacturing approaches were considered for producing these 5 components:

1. Wrought stock manufacturing
2. Investment casting manufacturing
3. Metal Additive manufacturing

Out of these three approaches, the goal is to produce these parts within a lead time of 8 weeks (approximately 1 and a half months) or less. Based on Upwing's requirements, the following manufacturing process considerations are:

- Quickly adaptable to component modifications
- Material lead time(s)
- One-off part lead time
- CNC programming
- Unique tooling / fixturing
- Process takt times
- Multiple outsourced process procedures
- Finished part material properties
- Overall part quality and surface finish
- One-off manufacturing cost(s)

To objectively evaluate these considerations and determine the most suitable manufacturing path, they have been formulated into a decision matrix (Figure 2).

MATERIAL: INCO 718

MFG Process Considerations	Importance Factor	Manufacturing Approaches: Wrought (Billet) Score	Rating	Investment Cast Score	Rating	Additive Mfg Score	Rating
Quickly adaptable to component modifications	3	2	6	1	3	3	9
Material lead time(s)	3	2	6	3	9	3	9
One-off part lead time	3	1	3	1	3	3	9
CNC Programming	3	1	3	2	6	2	6
Unique tooling / fixturing	1	2	2	1	1	2	2
Process takt times	3	2	6	2	6	2	6
Multiple outsourced process procedures	2	3	6	1	2	1	2
Finished part material properties	3	3	9	2	6	2	6
Overall part quality and surface finish	3	3	9	3	9	3	9
One-off mfg cost(s)	2	1	2	1	2	2	4
Total(s) (Better options demonstrate higher scores)			52		47		62

Importance Factor: 1 = Low | 2 = Moderate | 3 = High
Score: 1 = Poor | 2 = Fair | 3 = Good
Rating: (Importance Factor) x (Score)

Figure 2: Decision Matrix

The Decision Matrix (Figure 2) establishes the significance of each Manufacturing Process Consideration concerning the Manufacturing Approaches (Machined from Wrought, Investment Casting, Additive Manufacturing). Each Manufacturing approach is scored based on how well it meets the requirements for producing SCS Compressor components within a eight-week lead-time, with ratings determined by the cross product of "Importance Factor" and "Manufacturing Approach". The highest total for the Manufacturing Approach is then identified as the down select, resulting in Additive Manufacturing (AM) as the preferred manufacturing approach.

Even though AM scored the highest, the critical question remains: Are the mechanical properties of the additive manufactured components suitable for the intended application?

Tensile tests demonstrated that the material properties of additive manufactured Inconel 718 meet ASTM F3055 requirements. However, it was essential to determine whether the additive manufactured parts satisfied the specific requirements of the application.

Velo3D AM Compressor Rotor Test Procedure

To put Velo3D's technology to the test, Upwing constructed a test plan where parts printed on a Velo3D large-format Sapphire XC printer, with a build volume of 600 mm Ø x 550 mm z, would compete head-to-head against parts generated from machined billet.

Often seen as the standard in many industries, wrought metal represents consistent, known and stable material properties and has been proven to work in many industries. This test would evaluate the suitability of Velo3D's AM process to produce robust material– specifically yield strength in the X,Y directions – for Upwing's rotor application.

Upwing is familiar with the material properties of parts produced from billet but did not have experience with materials printed on Velo3D Sapphire printers. They determined that the key to understanding this was testing the printed parts at rotational speeds of 55,000 rpm and higher to simulate the conditions found in their gas compression process. This functional testing, including testing at higher rpm, could potentially expose any structural weaknesses or inconsistencies in the AM parts.

To ensure consistency between the AM parts and wrought parts, the following process flow was performed. For AM, the parts were printed, stress relieved, removed from the build plate, exposed to hot isostatic pressure (HIP), solution and aged and machined to final part geometries. For wrought parts, the material was purchased as wrought stock, went through a similar solution and age process and CNC programming, and was machined by CNC 5 Axis systems to final part geometries.

Velo3D Testing Process

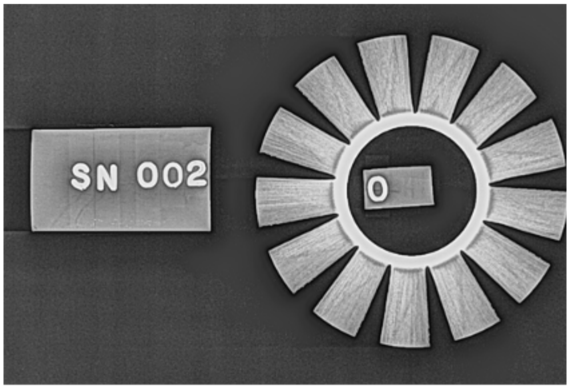
The evaluation process tested 10 total parts: five components produced via AM and five produced via billet. Each part was spun at three speeds: 55,000 rpm (operational overspeed limit), 60,500 rpm, and 66,000 rpm. After each spin, all parts went through detailed inspections (using dye penetrant to reveal any surface-breaking defects), balance check and dimensional inspection. The final evaluation was a spin-to-burst test on three AM and three wrought parts to validate the integrity of the two manufacturing methods.

Process:

1. The AM parts were printed on a Velo3D Sapphire printer and then post processed through stress relief, HIP, and solution age.
2. The hub inner diameter, blade tip outer diameters and hub top and bottom were then machined on the printed parts.
3. Prior to spin testing, each component went through dye-pen, x-ray, and dimensional inspection to baseline the parts.
4. Initial testing spun the rotors at 55,000 rpm.
5. After spin test, dye penetrant, dimensional inspection and balance check were performed to assess any change from baseline results.
6. No changes in the parts were found from the 55,000 rpm test. Thus, steps 4 and 5 were repeated for 60,500 and 66,000 rpm on all ten blades with no change in the parts post spin tests.
7. In preparation for burst testing, two AM and two wrought blades went through final x-ray and hardness testing to confirm no changes were detected from baseline and three AM and Wrought blades were set aside for burst testing.
8. The burst test procedure was an incremental rotational speed increase until the blades failed through hub separation.
9. High speed footage was taken of the spin tests to document the failures.

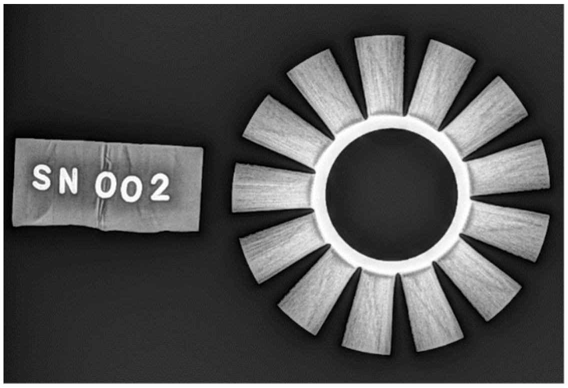
Results and Decision

The Velo3D printed AM parts surpassed expectations. Not only did they successfully endure the standard operational conditions of 55,000 rpm, but they also exceeded the overspeed condition by 2.1 times, reaching 115,000 rpm before burst. It is worth noting that this value exceeded the average for wrought blades by 11% (103,500 rpm). Furthermore, the AM parts demonstrated a tighter overall speed distribution for each failure point indicating consistent manufacturing.

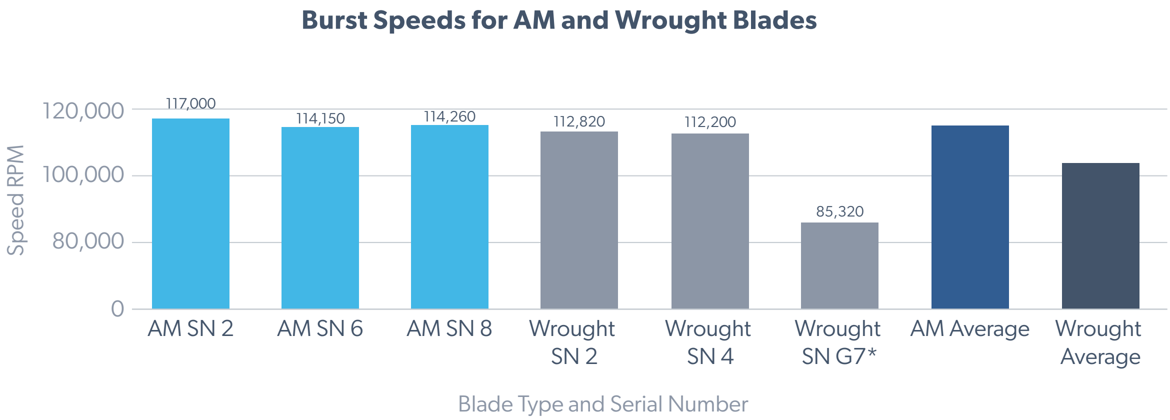


AM - SN* 002 – pretest X-Ray

SN = Serial Number



AM – SN 002 – post 66,000 RPM X-Ray

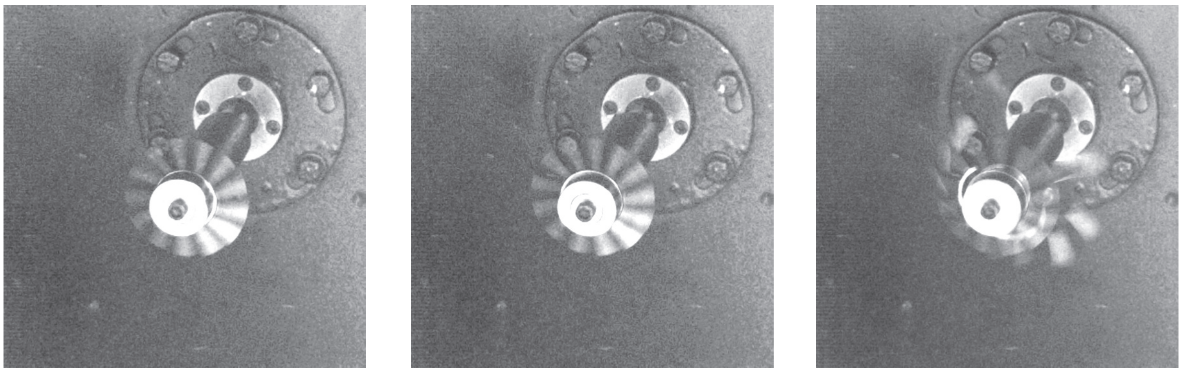


*Note that SN G7 had a below average HRC value.

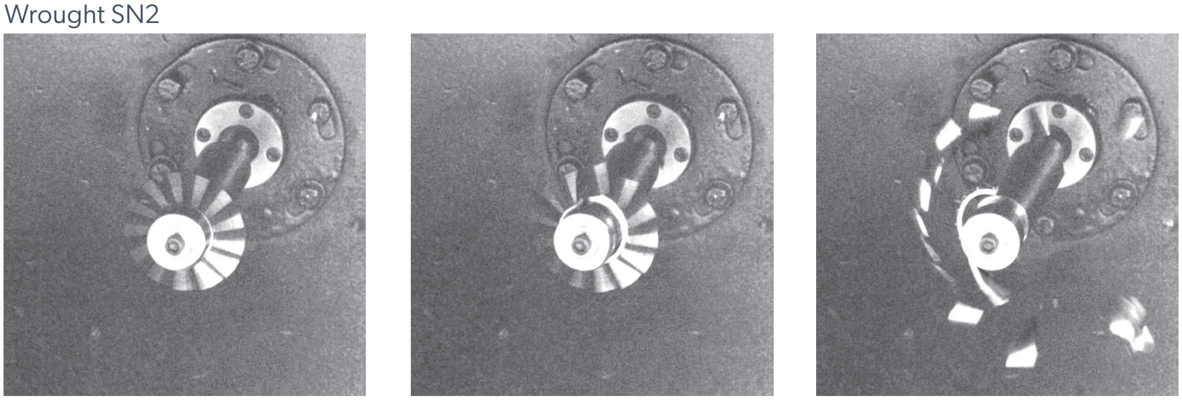
The failure mode, analyzed by examining the high-speed video and debris post-failure, was found to be similar between AM and CNC machined parts. Forces endured at these high speeds led to the central hub deforming and splitting followed by ejection of the blades from the central hub.

High Speed Burst Test

AM SN6



Wrought SN2



A New Path Forward: The Business Case for Metal AM

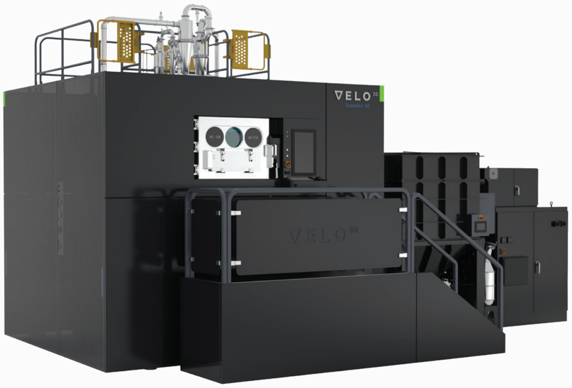
Convinced by these compelling results, Upwing made the strategic decision to integrate AM into their production solution, marking a significant milestone in their manufacturing capabilities. This step involves a thorough qualification process of the 3D printed rotors, underscoring the company's commitment to embracing cutting-edge technology.

By incorporating Velo3D's AM technology, Upwing has positioned itself for a scalable, adaptable, and cost-efficient production process. Velo3D technical team members were also available throughout the evaluation to help Upwing navigate the additive process, providing specific industry and AM expertise where needed. This, in turn, allowed Upwing to gain better proficiency and confidence using Velo3D technology and will allow them to successfully move from the first article into production.

In addition to the discussed geometric and material benefits, AM offers a cost-effective alternative to conventional manufacturing. It removes the necessity for tooling, lessens assembly steps, minimizes material wastage and cuts down on lead times. When put side by side with CNC machining, AM's capacity to produce complex shapes in reduced programming durations with less manual input stands out, making it advantageous for meeting Upwing's production needs.

Velo3D's AM approach employs laser powder bed fusion (LPBF), allowing the creation of intricate designs that were once beyond reach with standard AM methods. One of the outcomes of this breakthrough is the capability to manufacture high-speed rotating components, like Upwing's rotor design. The critical requirement for these rotors is high-quality surface finishes at low angles, challenges traditional AM systems struggle to achieve. However, Velo3D has demonstrated its proficiency in printing low angle geometries with superior surface finish and minimal subsurface porosity.

Beyond the obvious geometric benefits, Upwing recognized the potential in digital inventory. Here, printing instructions are digitally stored, enabling on-demand printing instead of keeping physical stock. This will also aid in Upwing's goal of prioritizing U.S.-made domestic manufacturing. Velo3D's consistent performance in ensuring material properties and geometric precision across its global supply chain, as highlighted in other case studies, played a pivotal role in Upwing's decision to evaluate the technology.



The Velo3D Sapphire XC is a large format metal 3D printer with a build volume of 600 mm Ø by 550 mm z-height and 81 kW lasers.

WITHOUT COMPROMISE

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