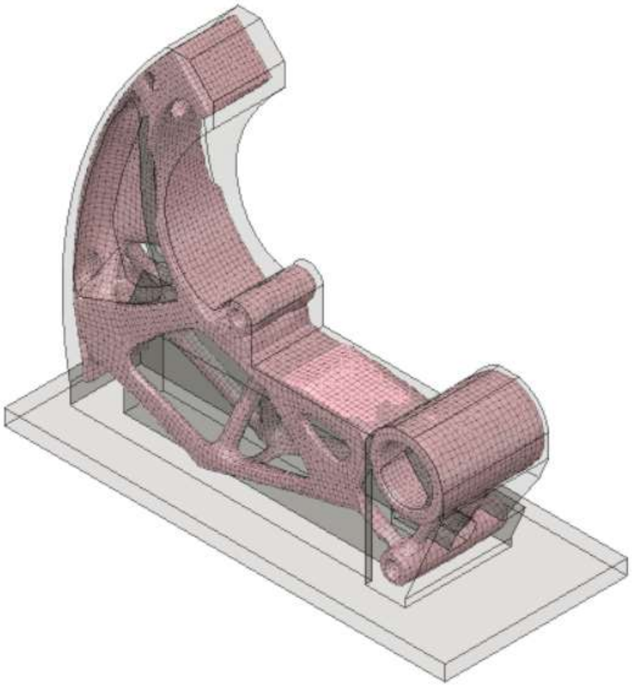


Hybrid Wire-Arc Additive Manufacturing of Topology Optimized Aviation Components

Authors:
Daniel Chirvasuta - chirv@vt.edu
Nathanael High - nathanaelhigh1@vt.edu
Matthew Martin - mtm26403@vt.edu
T. Benjamin Nguyen - tbenen@vt.edu
Omkar Shinde - omkarshinde@vt.edu
Nicolas Tomanelli - nict@vt.edu

Faculty Advisors:
Dr. Chris Williams - cbwill@vt.edu
Sam Pratt - pratts@vt.edu

Industry Advisor:
Dan Braley - daniel.j.braley@boeing.com

I Introduction

The aerospace industry is highly susceptible to supply chain disruption. A given aircraft has hundreds upon thousands of individual components, each with a specific purpose. If just one of these components fail, the aircraft can be grounded for a significant amount of time until a replacement part can be sourced and delivered to the point of need. Additive manufacturing presents an opportunity for on-site production of replacement parts which would eliminate the need for a new part to be delivered. Parts could even be manufactured at the aircraft's destination while it is en-route to minimize the time it is grounded.

Hybrid wire-arc additive manufacturing (hWAAM) is an emerging additive manufacturing (AM) process that is capable of fabricating large metal parts quickly. As hWAAM is both an additive and subtractive process, printed parts can also be finished machined to keep the tight tolerances expected of aerospace applications. Furthermore, hWAAM systems require only argon gas and welding wire, both of which are much easier and cheaper to source and transport than large billets of metal or specialized, combustible metal powder.

The goal of this project was to explore the use of hWAAM for fleet sustainment by redesigning a Boeing aircraft part, which was originally produced via cast magnesium. To ensure the redesigned part would suit aluminum hWAAM capabilities and constraints while meeting the strength and weight specifications of the original part, the team first designed a series of benchmark parts to explore the geometry constraints and material properties of the process. The team used these findings and the anticipated part loading conditions with topology optimization software to design a hWAAM-able part with reduced mass. The team then printed and finished-machined the final redesigned part, and validated the part's performance using a test rig that mimics the original load case.

II Justification of Material and DDM

The team chose Aluminum 5556 alloy as it is a readily-available wire feedstock that is easily processed with the hWAAM's Fronius cold metal transfer (CMT) wire arc welder. Al 5556 is easy to source and relatively inexpensive. The system's other consumable, argon shielding gas, is also readily available and can be sourced locally. Additive manufacturing on the hWAAM platform offers Boeing the ability to quickly produce large parts with structural integrity without the waste of raw material and expensive tooling present in other traditional manufacturing methods. Producing this part by machining out of a billet, for instance, would be nearly impossible due to some of the internal geometries present, and would also result in 60-80% of the original billet being reduced to waste chips. While hWAAM does have higher power consumption than many other AM processes, it is compact, making it ideal for use in the field where space may be limited.

III Design Overview: Determination of Constraints and Process

The team began the design process by identifying key requirements and associated target specifications for part mass, maximum overhang angle, tensile strength, price, and production time (Figure A.1 in Appendix A) .

Since welded aluminum is anisotropic, the properties of the printed Al5556 needed to first be verified in order to perform accurate simulations on the redesign. Dogbone-shaped tensile specimens in accordance with ASTM E8 were printed and finished machined in XY (i.e., sample printed flat) and ZX (i.e., sample printed vertically off build plate) print orientations and then tested on an Instron tensile tester. The resulting stress-strain curves (Figure A.2 in Appendix A) demonstrate a significant difference between the mechanical properties of XY and ZX print orientations. One sample demonstrated lack of fusion defects (Figure 1), which lowered the average mechanical properties of the specimen trials. These values were used to create a new material property profile in Autodesk Fusion 360 for subsequent part simulation. Since this software does not support anisotropic profiles, the team used the lowest recorded ultimate tensile strength value of 160 MPa and yield strength of 130 MPa.

The team also designed and printed a series of benchmark features to quantify the maximum overhang capabilities and minimum feature size of hWAAM. The resulting V-shaped structures featured a range of overhang angles (Figure 1) demonstrated that a maximum overhang of 40 degrees was achievable.

Figure 1: Internal porosity present in ZX (vertical) dogbone sample and overhang benchmark structures. *Weld beads collapse on themselves on overhang angles greater than 45 degrees.*

Autodesk Fusion 360's shape optimization capability was used to identify a part topology that is capable of meeting the given load conditions while also minimizing part mass. Boeing engineers supplied a realistic load case for the original part, along with geometry constraints (i.e., "keep out zones") required of the part to interface with the existing assembly (Figure 2a). The as-printed material properties were then leveraged in the simulation, along with the determined overhang angle (40 degrees) and the minimum-achievable feature resolution (2.0 mm). Shape optimization studies were performed to locate critical load paths (Figure 2b). The results were used to manually update the part model to reinforce regions with stress concentrations and remove material from non-critical regions (Figure 2c).

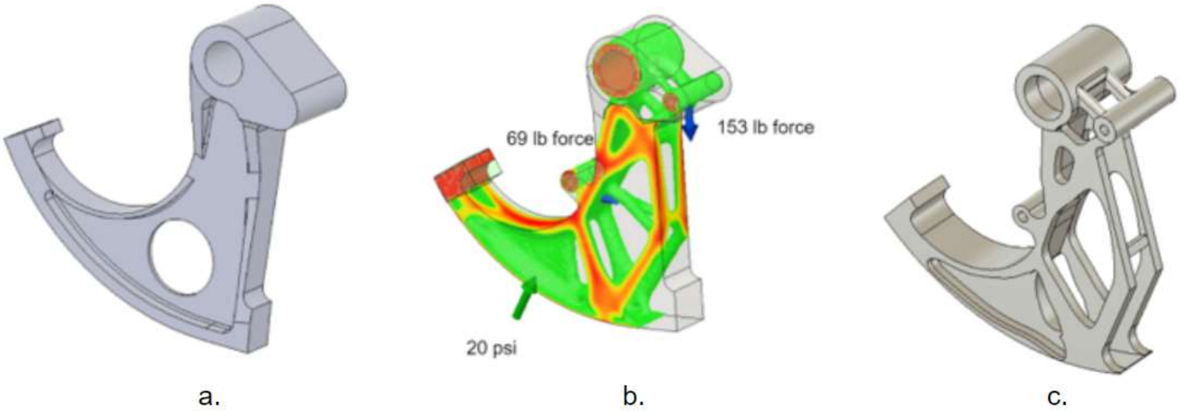


Figure 2: Original cast part model (2a.), Load Case (2b.), and Finished Result (2c.). *Critical load paths drive material deposition.*

Manufacturing this part will be done in two phases. First, hWAAM will be used to deposit material in a near net shape. A model of the planned deposition, and the associated additive deposition toolpath, are shown in Figure 3. The second phase of the manufacturing plan is the finish machining of the deposition model to the design specifications. Fusion 360’s CAM profiling suite was used to generate G-Code for both the additive and subtractive operations. The team is currently running this code on a DMS hWAAM system; the finished part will be fabricated by April 15th.

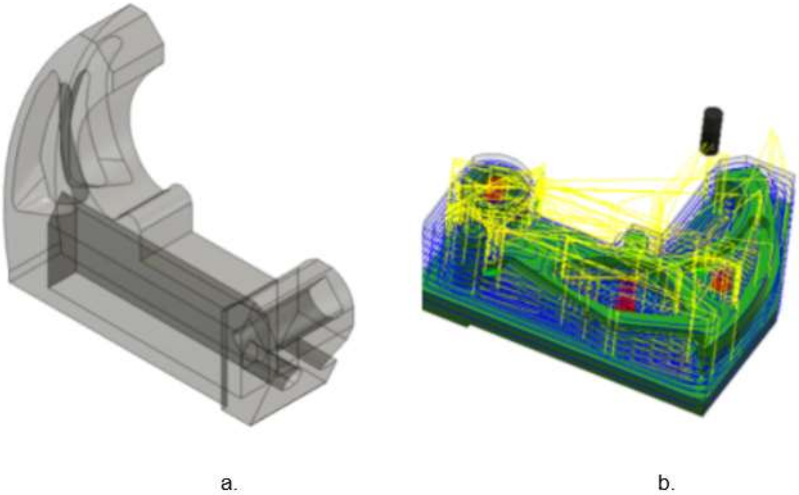


Figure 3. (a) Near net shape deposition model; (b) Finish machining CAM profile

IV Comparison of Design

Using hWAAM, the optimized part consumes one spool of Al-5556 wire ($80), less than one tank of Argon, and ~20-30 machine hours (which includes both deposition and finish machining).For comparison, the team's Boeing advisor estimates that fabricating the sand casting molds required for producing the original parts would cost hundreds of thousands of dollars and require the aid of skilled craftsmen, who often have lead times of several months.

For fabricating a replacement part via conventional subtractive machining would also be costly, as an aircraft-grade billet of Al-7075 that is large enough for this part would cost roughly $300. Accounting for expert machining would likely double this cost. In addition, there are expected delays and costs associated with delivery of this billet and/or the finished machined part.

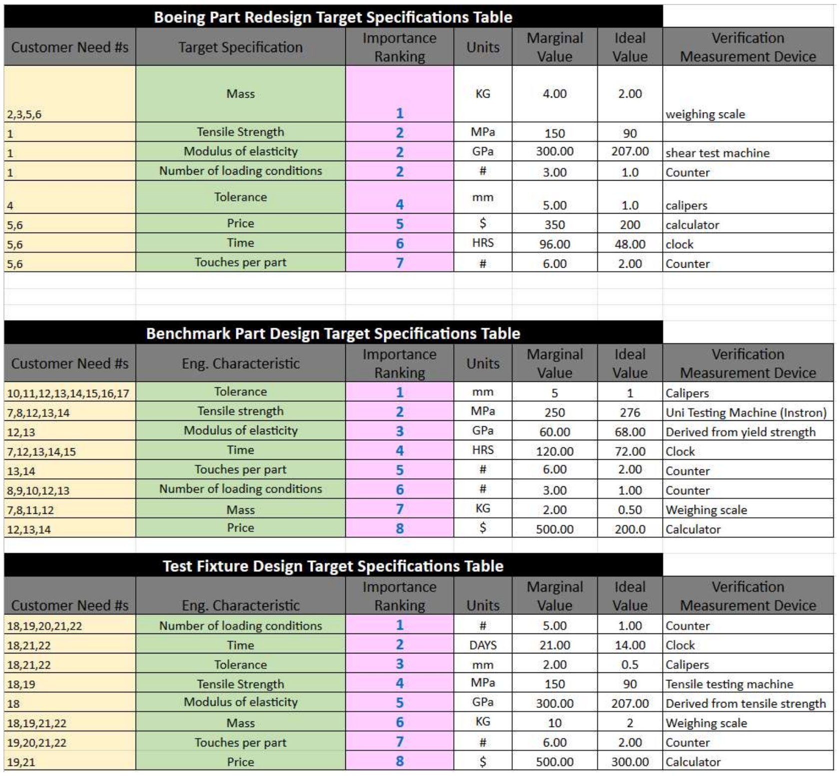
Finally, it is important to account for the life cycle impact of the optimized part. While the original part’s mass was 6.35 lbm, our optimized design was 23% lighter at 4.89 lbm. The reduced mass of this part (and other parts that could be redesigned for fabrication via hWAAM) could significantly reduce the fuel consumption of the aircraft over its lifetime.

V Social and Environmental Impact Analysis

The part printed from hWAAM needs to be assured that it is safe to use for air travel. Therefore, the printed part is in the process of being validated via evaluating its performance on a test rig that mimics its functionality and load conditions. The test rig is designed in such a way that the force applied is measured while it is being applied to the part to verify that the part can accommodate more than the anticipated force.

In terms of environmental analysis, a positive impact of this technology is the reduced material waste. The buy-to-fly ratio (i.e., volume of material used in production vs. volume of final product) is only 2.56 using hWAAM, compared to an average of 10 for billet machining. hWAAM's use of a wire also has environmental benefits compared to other metal AM processes, as it is readily sourced locally, and requires less energy to produce (and generates less waste) than specialized fine powders. Lastly, the ability for hWAAM to provide on-site production of replacement parts eliminates the transportation energy and time required to deliver replacement parts produced by other means. This is especially critical when providing replacement parts to locations where delivery is difficult, and supply chain disruptions are common.

VI Appendix A



Boeing Part Redesign Target Specifications Table

Customer Need #s	Target Specification	Importance Ranking	Units	Marginal Value	Ideal Value	Verification Measurement Device
2,3,5,6	Mass	1	KG	4.00	2.00	weighing scale
1	Tensile Strength	2	MPa	150	90	
1	Modulus of elasticity	2	GPa	300.00	207.00	shear test machine
1	Number of loading conditions	2	#	3.00	1.0	Counter
4	Tolerance	4	mm	5.00	1.0	calipers
5,6	Price	5	$	350	200	calculator
5,6	Time	6	HRS	96.00	48.00	clock
5,6	Touches per part	7	#	6.00	2.00	Counter

Benchmark Part Design Target Specifications Table

Customer Need #s	Eng. Characteristic	Importance Ranking	Units	Marginal Value	Ideal Value	Verification Measurement Device
10,11,12,13,14,15,16,17	Tolerance	1	mm	5	1	Calipers
7,8,12,13,14	Tensile strength	2	MPa	250	276	Uni Testing Machine (Instron)
12,13	Modulus of elasticity	3	GPa	60.00	68.00	Derived from yield strength
7,12,13,14,15	Time	4	HRS	120.00	72.00	Clock
13,14	Touches per part	5	#	6.00	2.00	Counter
8,9,10,12,13	Number of loading conditions	6	#	3.00	1.00	Counter
7,8,11,12	Mass	7	KG	2.00	0.50	Weighing scale
12,13,14	Price	8	$	500.00	200.0	Calculator

Test Fixture Design Target Specifications Table

Customer Need #s	Eng. Characteristic	Importance Ranking	Units	Marginal Value	Ideal Value	Verification Measurement Device
18,19,20,21,22	Number of loading conditions	1	#	5.00	1.00	Counter
18,21,22	Time	2	DAYS	21.00	14.00	Clock
18,21,22	Tolerance	3	mm	2.00	0.5	Calipers
18,19	Tensile Strength	4	MPa	150	90	Tensile testing machine
18	Modulus of elasticity	5	GPa	300.00	207.00	Derived from tensile strength
18,19,21,22	Mass	6	KG	10	2	Weighing scale
19,20,21,22	Touches per part	7	#	6.00	2.00	Counter
19,21	Price	8	$	500.00	300.00	Calculator

Figure A.1. Stress-Strain curves from tensile testing data.

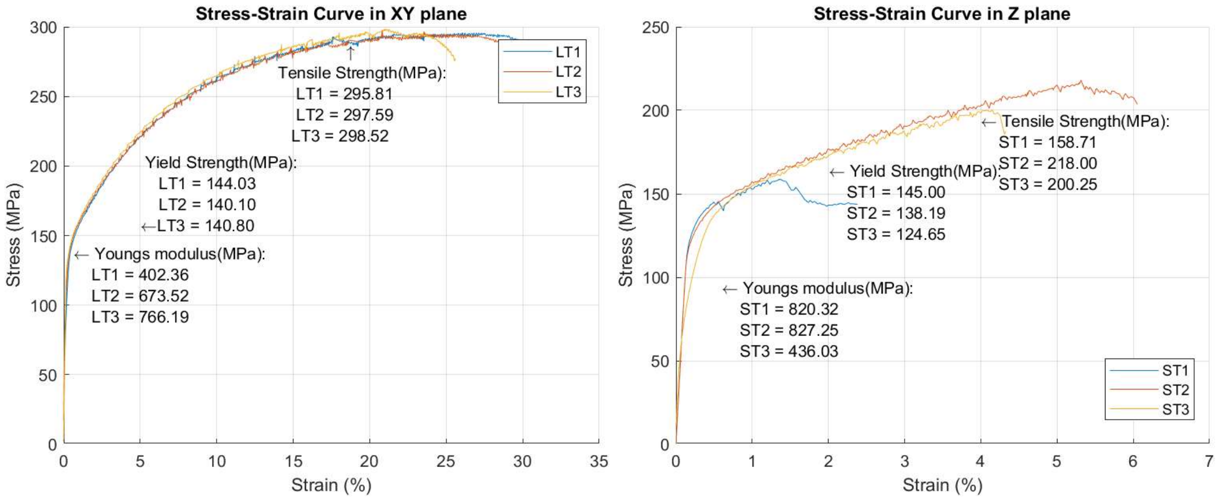


Figure A.2. Stress-Strain curves from tensile testing data.