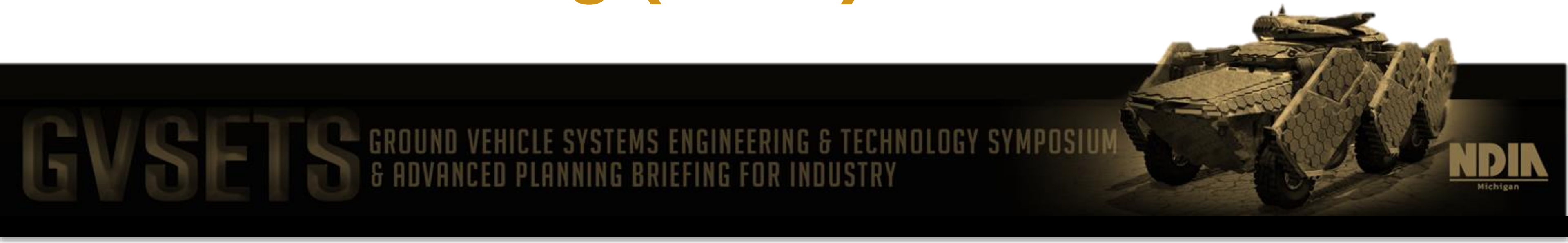
Advanced Materials & Manufacturing (AAM)



TOPOLOGY OPTIMIZATION STUDY OF LASER POWDER BED FUSION BRACKETS TO ENABLE ADDITIVE MANUFACTURING AS A SOURCE OF SUPPLY FOR DMSMS APPLICATIONS

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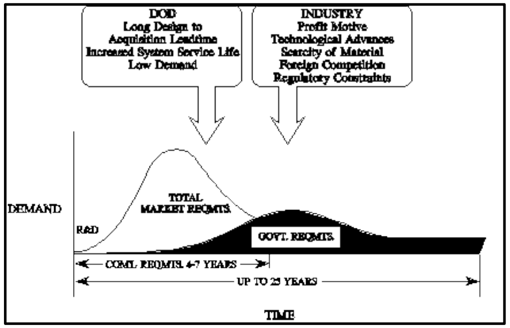
Project Motivation: DfAM for DMSMS

Redesign legacy parts to elucidate challenges applying AM to sustainment

Performance of aging platforms is mired by Diminishing Manufacturing Sources and Material Shortages (DMSMS) challenges. Advanced manufacturing technologies like Digital Engineering (DE) and Additive Manufacturing (AM) provide opportunities to reduce cost, improve performance, and better equip the warfighter at the point of need.

- Project Goals:
  - Redesign representative component using Laser Powder Bed Fusion (L-PBF) Design for Additive Manufacturing (DfAM) best practices
    - Select representative component, 3D printer, and candidate materials
    - Perform generative design
    - Design "as-printed" models using AM best practices
  - Develop "reasonable" test plan to validate part integrity
    - Survey different qualification plans and AM standards
    - Create plan for surface finishing, heat treatment, non-destructive evaluation (NDE), and destructive witness testing
  - Build AM cost model to compare materials on cost and performance



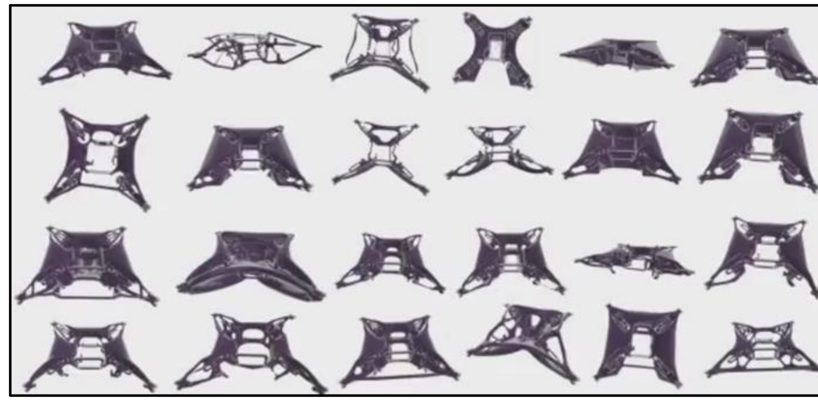
Contributing factors to DMSMS

JLTV Platform

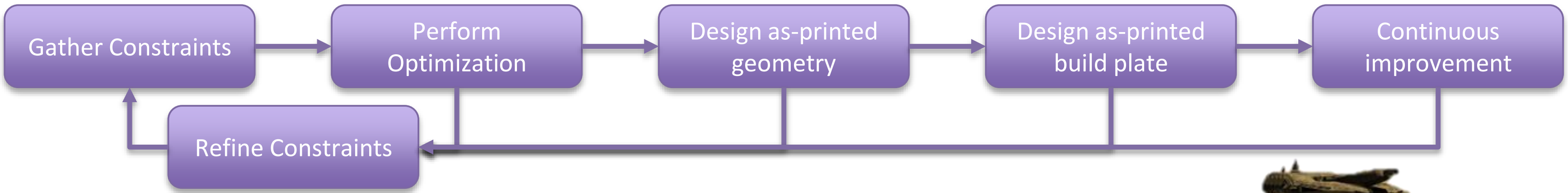
Generative Design (GD): Form of Topology Optimization (TO) for exploring optimization space

GD allows users to explore multiple parallel optimizations based on different materials and manufacturing processes, and then compare them on the basis on stress, strain, mass, cost, and other optimization criteria.

- **Constraints:**
  - **Geometry**: Preserve, Obstacle, Starting Shape
  - **Loading**: FoS, Load cases, load paths
  - **Material**: Ultimate/Yield Strength, Strain, Young's Modulus, Density
  - **Manufacturing Constraints**: Geometric Complexity, Cost considerations
  - **Post-processing**: Machining, E-ISF, other surface treatments
  - **Qualification**: Minimum Feature Size, Down-skin Surfaces



Generative Design (Credit: Autodesk)

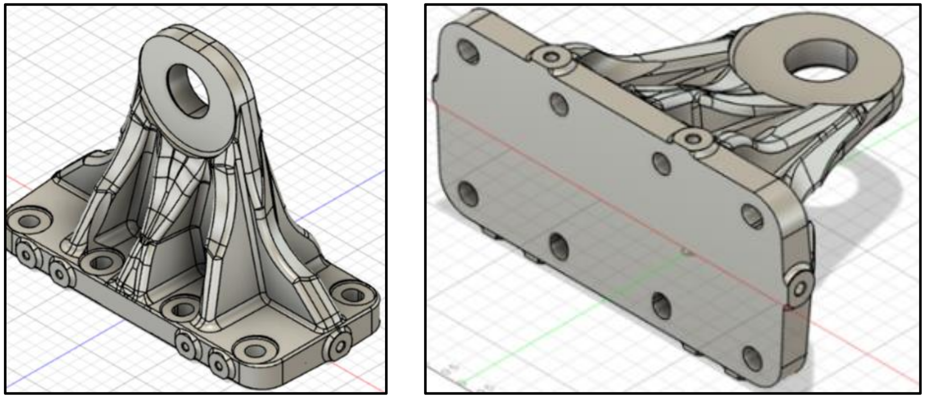


Selecting Representative component

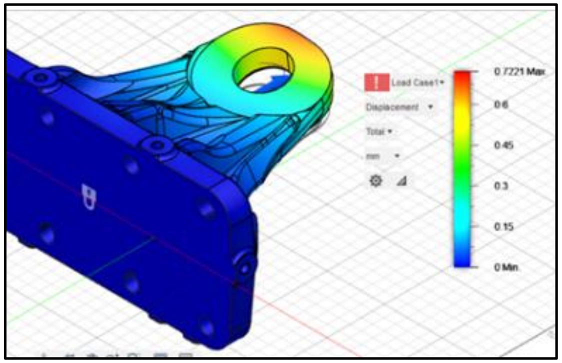
Legacy component

Goal was to create a "candidate component" for comparing AM results. This component was similar to load-bearing components from a ground vehicle platform.

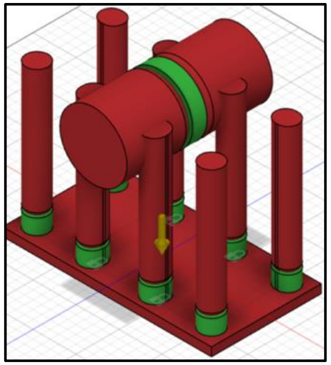
- **Part Name:** Representative transmission bracket
- **Material:** A206-T4
- **Material Standard:** SAE AMS 4236 Rev. D
- **Load Path:** Static, <20, 35, ±20> kN
- **Mass:** 3.24 Kg
- **Maximum Factor of Safety (FoS) under load:** >2.0
- **Maximum Displacement under Load:** <0.72 mm



Original Component Geometry



Original Component FEM Simulation



GD Setup

Selecting Representative 3D printer

Printer: 3D Systems ProX Digital Metal Printing (DMP) 320

The 3D Systems ProX DMP 320 was chosen as a system designed for industrial additive manufacturing is representative of systems being used by Army GVSC (3D Systems DMP Flex 350). The printer ecosystem also comes with verified printing parameters for several applicable alloys.

- **Build-volume:**
  - 275mm x 275mm x 420mm
- **Accessible Materials:**
  - <u>Aluminum</u>: AlSi7Mg0.6(A) or AlSi10Mg (A)
  - <u>Steels</u>: Maraging Steel (A), 17-4PH (A), 316L (A)
  - <u>High-Performance</u>: Ti Gr5 (A) or Scalmalloy (A)
- **Not Considered:**
  - <u>Cobalt Chrome</u>: LaserForm CoCrF75(A)
  - <u>Exotic Steel</u>: M789 (A)
  - <u>Medical Titanium</u>: LaserForm Ti Gr1(A) or LaserForm Ti Gr23(A)
  - <u>Nickel</u>: LaserForm Ni625(A) or LaserForm Ni718(A)

3D Systems ProX DMP 320

Material Selection

Advanced Materials & Manufacturing (AMM)

Selection of potential aluminum, steel, and titanium alloys

Five materials were selected from catalogue of 3D Systems materials based on the below criteria.

- **Original Material: Cast Aluminum A206-T4**
  - high strength combined with good ductility and impact strength
  - Properties dictated by AMS4236
- **Selected Materials:**
  - Steel: 17-4PH (H900) and 316L (ST)
  - Aluminum: Scalmalloy (LT60) and AlSi10Mg (LT60-ST2)
  - Titanium: TI64 Gr 5 (HIP)
- **Selection criteria:**
  - Comparable US, YS, elongation
  - If all elongations higher, selected highest YS
  - If multiple suitable solutions, chose largest layer thickness

Material	Alloy	Layer thickness	Temper	US-H (MPa)	US-V (MPa)	YS-H (MPa)	YS-V (MPa)	E-H (%)	E-V (%)	Hardness (HB)	Toughness (J)	density (g/cm3)	Pursue?
Cast Aluminum	A206	NA	T4	345	345	205	205	10	10	85-115 HB	??	2.8	NA
Material	Alloy	Layer thickness	Temper	US-H (MPa)	US-V (MPa)	YS-H (MPa)	YS-V (MPa)	E-H (%)	E-V (%)	Hardness (R-C)	Toughness (J)	density (g/cm3)	Pursue?
Steel	17-4PH	TBD	As-built	NA	1100	NA	830	NA	19	32	71	7.75	NA
		TBD	H900	1450	1380	1280	1260	11	12	40	7	7.75	Best Option
		TBD	H1150	1180	1080	1130	1020	12	16	35	11	7.75	Acceptable
	Maraging	TBD	As-built	1230	1220	1080	1090	13	13	35	64	8.1	NA
		TBD	Aged 1	2210	2120	2125	2030	5	5	55	8	8.1	NA
		TBD	Aged 2	2260	2160	2180	2070	5	2	55	7	8.1	NA
	316L	TBD	ST	660	570	530	440	39	49	90	215	8	Best Option
		TBD	Anneal	610	540	370	320	51	66	83	220	8	Acceptable
Aluminum	Scalmalloy	LT30	Certified	520	520	490	490	15.8	15.8	NA	NA	2.67	Acceptable
		LT60	Certified	530	520	500	490	14	13.1	NA	NA	2.67	Best Option
	AlSi7Mg0.6	TBD	As-built	410	390	240	210	14	11	60	NA	2.67	NA
		TBD	SR	280	290	160	180	18	11	39	NA	2.67	NA
		TBD	Aged	430	430	310	280	10	5	69	NA	2.67	NA
	AlSi10Mg	LT30	NHT	470	460	280	240	13.2	8.3	NA	NA	2.68	NA
			SR1	300	300	190	180	15.6	15.8	NA	NA	2.68	NA
			ST2	400	340	270	250	9.2	5.2	NA	NA	2.68	NA
		LT60	NHT	440	425	260	225	8.9	7.6	NA	NA	2.68	NA
			SR1	290	290	170	170	14	13.2	NA	NA	2.68	Acceptable
			ST2	390	400	255	230	8.6	5.1	NA	NA	2.68	Best Option
Titanium	TI64	TBD	SR1	1180	1160	1090	1080	9	9	40	NA	4.42	Acceptable
		TBD	HIP	1000	1020	910	930	15	14	36	NA	4.42	Best Option

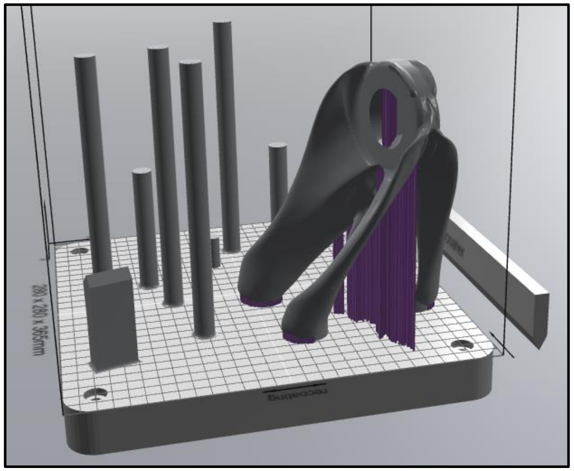
Material Comparison table with selected materials

Overview of Qualification plan

Qualification/Certification plays an integral part in design of AM components to ensure feasibility of design

A literature review of current test guidance was performed and adapted for the use case. It can then be integrated with a cost model to understand the relative manufacturing and qualification costs.

- **Approach:**
  - Quality Management Plan (QMP)
  - Post-processing plan (PPP)
  - Non-Destructive Evaluation (NDE)
  - Witness Coupon Testing (WCT)
  - Plan is broken into four main components; only PPP and WCT encompassed in cost-model
- **Standards:**
  - Considered NASA, ISO/ASTM, NAVSEA, ASME, SAE, ANSI, and other standards
  - Approach based on NASA process and relevant ISO/ASTM testing standards, as well as guidance from PSU-ARL
  - Didn't belabor QMP or NDE, focused on PPP and WCT

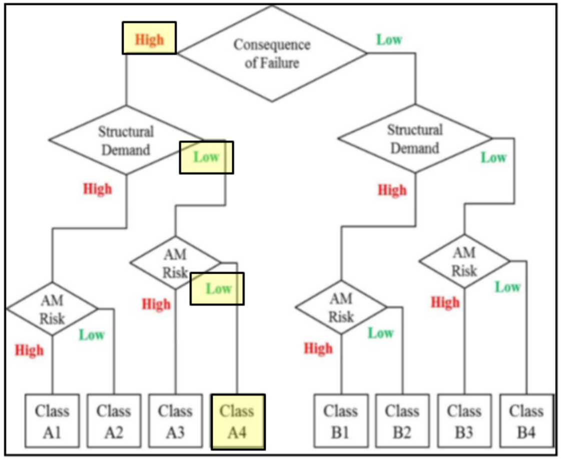


Final part with witness coupons

NASA–STD–6030 and NASA–STD–6033: part qualification

NASA–STD–6030 and NASA–STD–6033 provide varying requirements depending on part consequence of failure, structural demand, and AM risk.

- **Consequence of Failure:** Class A if any of the following
  - Fracture Critical per NASA-STD-5019A
  - **If failure would lead to a catastrophic hazard (loss of life, disabling injury or loss of a major national asset)**
  - If failure would lead to the loss of one or more primary/minimum mission objectives
- **Structural Demand:** Likely Low
- **AM Risk:** Likely Low



Overview of Part Classification

AM Risk	Yes	No	Score
All Critical surface and volumes can be reliably inspected, or the design permits adequate proof testing based on stress state?	0	5	0
As-built surface can be fully removed on all fatigue-critical surfaces?	0	3	0
Surfaces interfacing with sacrificial supports are fully accessible and improved?	0	3	0
Structural walls or protrusions are > 1 mm in cross-section?	0	2	0
Critical regions of the part do not require sacrificial supports?	0	2	0
		Total:	0

AM Risk: low

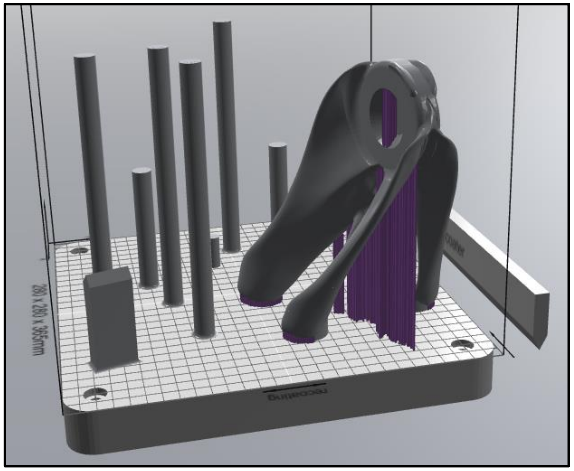
Material Property	Criteria for High Structural Margin	Level
Loads Environment	well-defined or bounded loads environment	bounded load environment
Environmental Degradation	Temperature Only	NA
Ultimate Strength	30% margin over FoS	FoS > 2
Yield Strength	20% margin over FoS	FoS > 2
Point Strain	Local plastic strain <0.005	No plastic strain
High Cycle Fatigue, improved surfaces	20% below required fatigue limit cyclic stress range	Max Stress should be below FS
High Cycle Fatigue, as-built surfaces	40% below required fatigue limit cyclic stress range	No as-built surfaces
Low Cycle Fatigue	no predicted cyclic plastic strain	No plastic strain
fracture mechanics life	10x additonal life factor	Max Stress should be below FS
creep strain	no predicted creep strain	Not a high temp application

Structural Demand: low

NASA Qualification Standards – Witness Coupon Testing (WCT)

WCT allows for destructive testing to validate material properties

- **Requirements for Class A-4 L-PBF components:**
  - 6 x Tensile Test: In Accordance With (IAW) ASTM E8
  - 1 x Full Height Contingency (FHC) Test: IAW MSFC–STD–1716
  - 1 x Micro-structure Test: IAW ASTM E3/ASTM E407
  - 2 x High Cycle Fatigue Test: IAW ASTM E466
  - Customized QMP: Based on guidance from PSU-ARL, chose to include a powder coffin



Witness coupons on build

NASA Qualification Standards – Post Processing Plan (PPP)

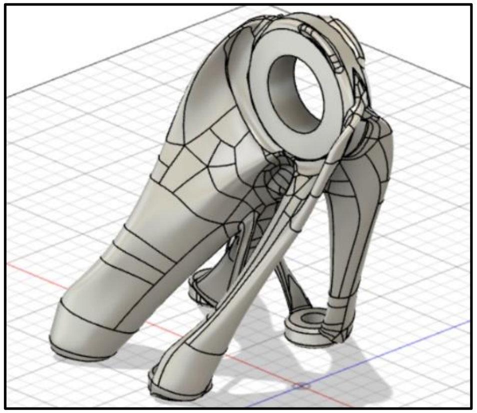
Custom Post Processing Plan

Based on PSU-ARL recommendations and NASA–STD–6030/NASA–STD–6033

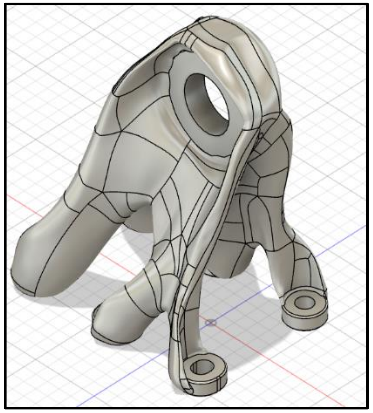
- **Step 1:** Powder Removal
- **Step 2:** Remove FHC Specimen and Powder Coffin
  - These specimens shouldn't be thermally processed, so need to be removed first
- **Step 3:** Stress Relief
  - Remove stresses accumulated during the build
- **Step 4:** Hot Isostatic Pressing (HIP)
  - NASA–STD–6030 requires all Class A parts undergo HIP before use. Some research demonstrates that certain alloys can undergo HIP without stress relief
- **Step 5:** Removal from Build Plate (bandsaw or EDM), and Support Removal
  - Removing from build plate after HIP, reduces displacement
- **Step 6:** Machine Critical Surfaces
  - Because of solid supports on critical surfaces, these require machining before final processing
- **Step 7:** Improve all Surfaces with Extreme-Isotropic Surface Finishing (E-ISF)
  - Because E-ISF has highly controlled surface material removal, its possible to machine first and maintain calibrated machining standards (+/-0.001") while improving all as-built surfaces
- **Step 8:** Final Heat Treatment
  - For parts and all witness coupons, depending on material
- **Step 9:** Process all Witness Coupons

Final Design of Each Bracket

Final Scalmalloy Bracket

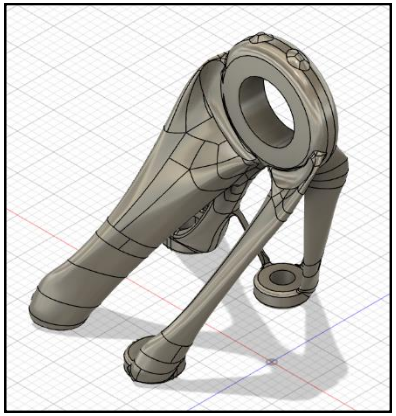


Final AlSi10Mg Bracket

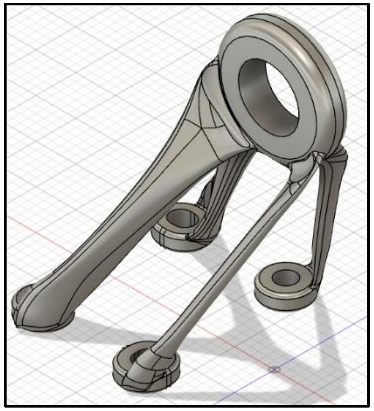


Bracket	Mass (kg)	Volume (mm^3)	Preserve V (mm^3)	Displacement (mm)	FoS
Original	3.24	1.213e6	NA	.7035	2
Scalmalloy	.802	3.010e5	6.899e4	.68	2
Ti64	.922	2.081e5	6.899e4	.67	2
17-4PH	1.052	1,349e5	6.899e4	.692	2
AlSi10Mg	1.602	6.010e5	7.928e4	.292	2
316L	2.256	2.820e5	7.928e4	.319	2

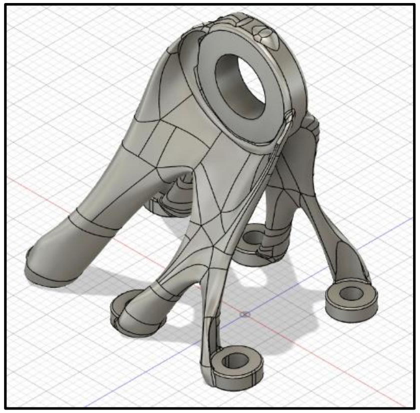
Bracket Comparison



Final Ti-6Al-4V Bracket



Final 17-4PH Bracket



Final 316L Bracket

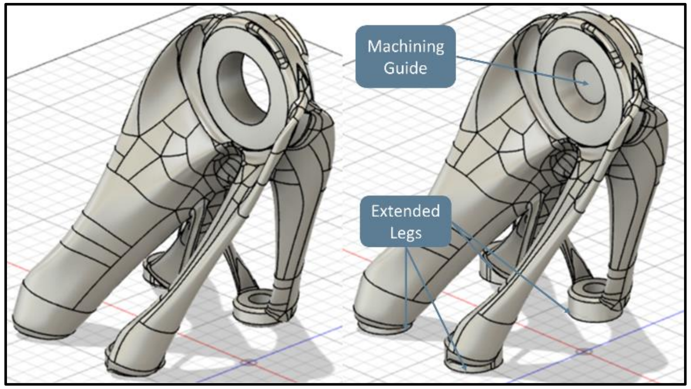
Figure 11: Final Ti-6Al-4V Bracket

Redesign with as-built features

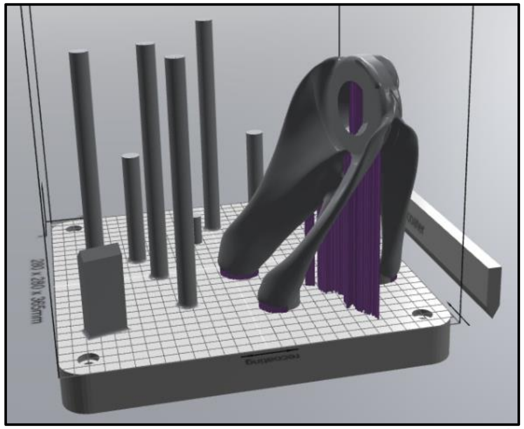
Critical for AM applications are as-built features that reduce post-processing costs

Reducing sacrificial supports reduces material usage, post-processing cost, and technical risk

- **Design changes:**
  - Replace bearing surface with machining guide: the upper bearing surface was given a machining guide that reduces material usage and reduces the cost to remove it
  - Add solid supports below legs: adding solid supports below the “feet” of the bracket provide a conductive path to the build-plate and can be cleanly removed via EDM or band-saw
  - Tweak preserve geometry: adding a groove to the bottom of the upper bearing surface’s preserve geometry reduced sacrificial support usage on some of the brackets.



Final Scalmalloy Bracket, and with as-printed design features



Final Build

Cost Modeling: Basic Model

Cost Model at fidelity of inputs

Due to number of assumptions made and low-fidelity of part data, chose to use low-fidelity cost model

- **Cost Model:**

$$Cost_{total} = multiplier_{processing} * \ldots$$
$$[(time_{build} * rate_{build}) + (mass_{usage} * rate_{material})]$$

- **Rates differed for each material; comparison can be seen below:**

Bracket	Mass (kg)	Bracket Material	Bracket Time	Bracket Cost	Build Material	Build Time	Build Cost	Test Cost %
Original	3.240	NA	NA	NA	NA	NA	NA	NA
Scalmalloy	0.802	0.81	34.25	$ 2,608.09	1.26	50.20	$3,856.80	32.4%
Ti64	0.922	0.99	27.50	$ 2,280.81	1.67	41.90	$3,568.63	36.1%
17-4PH	1.052	1.22	21.68	$ 1,465.00	2.42	36.38	$2,612.43	43.9%
AlSi10Mg	1.749	1.89	68.57	$ 4,533.30	2.26	81.70	$5,404.44	16.1%
316L	2.296	2.45	34.31	$ 2,395.55	3.66	49.13	$3,299.63	27.4%

Cost Comparison of Final Parts

Simple AM Cost Model for Metal Powder Bed Fusion (Single Laser)

User-Defined Inputs:
1. *Material* (see table)
2. *Part Volume* (mm^3), including supports
3. *Max Part Height* (mm)
4. *Machine Operating Cost* ($10-$30/hr)
5. *Pre-/Post-Processing Cost %* (30%-40%)

AM Material Data	Ti64	IN718	SS316L	AlSi10Mg
Density (kg/mm^3)	4.41E-6	8.15E-6	7.9E-6	2.67E-6
Build Rate (mm^3/s)	9.0	4.2	2.0	7.4
Layer Height (mm)	0.06	0.04	0.02	0.03
Recoat Time (sec)	9	9	12	12
Powder Cost ($/kg)	$250-$500	$120-$180	$70-100	$70-$90

Outputs:

$$Material\ Cost(\$) = (Part\ Volume) \times (Material\ Density) \times (Powder\ Cost)$$

$$Build\ Time(hr) = \frac{\frac{(Part\ Volume)}{(Build\ Rate\ \times 80\%)} + \frac{(Max\ Part\ Height)}{(Layer\ Height)} \times (Recoat\ Time)}{3600}$$

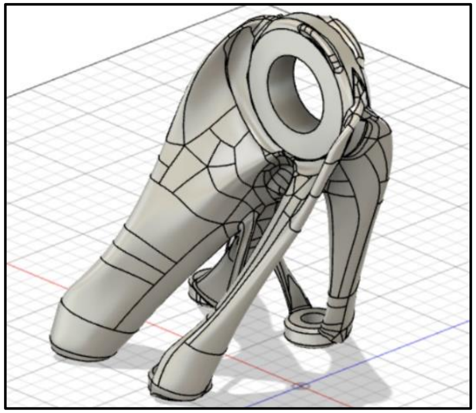
$$Total\ AM\ Part\ Cost(\$) = \frac{(Build\ Time)\ \times (Machine\ Operating\ Cost) + Material\ Cost}{(1 - Pre-/Post-Processing\ Cost\ \%)}$$

Witness Coupons on Build

Conclusion/Further Work

Conclusions:

- 17-4PH was the lowest cost, Scalmalloy was the lightest, Ti64 was a good trade between the two
- 40% earmark for pre-processing and post-processing doesn't account for witness test coupons, which can double the cost of a build



Future Research Questions:

- Design
  - Further optimized preserve/obstacle regions to fully remove sacrificial supports
  - Figures of merit to optimize material usage as a function of loading
  - DfAM for E-ISF
  - Perform study for multiple parts to create redesign recommendations for families of parts
- Testing
  - Validate batch processing technologies for fatigue properties
  - Optimize number and choice of witness coupons for part criticality
  - Explore impact of NDE on test campaign
- Cost modeling
  - Create higher fidelity cost model, incorporate better process data