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TOPOLOGY OPTIMZATION STUDY OF LASER POWDER BED FUSION BRACKETS TO ENABLE AM AS A SOURCE OF SUPPLY FOR DMSMS APPLICATIONS

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ABSTRACT

The objective in this paper is to understand the challenges of making additive manufacturing a future source of supply for the Department of Defense through the redesign of a part for metal laser Powder Bed Fusion.

The scope of this paper involved the redesign of a single cast-and-machined part for an Army ground vehicle system. The component was redesigned using topology optimization based on suitable replacement materials and design data from the representative part. In parallel, a brief review of AM standards identified a process to qualify the component through post-processing, non-destructive evaluation, and witness testing. Alongside this redesign analysis, a brief cost analysis was conducted to understand the cost associated with manufacturing and qualifying this part for multiple AM materials.

The resulting analysis demonstrated that for this component, which was subject to high design loads, Scalmalloy, Ti-6Al-4V, and 17-4PH Stainless Steel could produce the most cost-effective parts. Scalmalloy was the lightest part, with a 67% reduction in weight from the original bracket, while 17-4PH could produce the lowest-cost component. Ti-6Al-4V performed in the middle for both. Finally, the research identified further areas of study to advance AM as a tool in DoD sustainment.

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1. INTRODUCTION

The United States Department of Defense (DoD) is challenged daily by the sustainment efforts necessary to maintain its sophisticated weapons systems distributed across the globe [1]. These challenges are exacerbated by the age of some of these systems; for example, the B52 strategic bomber began operations in 1946 and will remain in service until 2040 [2]. Over the course of that 100 years, the Defense Industrial Base (DIB) has and will continue to change drastically. The confluence of DoD procurement strategies that incentivize single sources of supply as well as the closure of small and medium manufacturers (SMMs), who once produced highly specialized castings, machined parts, and forgings for DoD systems, leads to Diminishing Manufacturing Sources and Material Shortages (DMSMS) challenges that can increase the cost and decrease the availability of these critical systems [3].

These DMSMS challenges are defined as the "*loss, or impending loss, of manufacturers or suppliers of items, raw materials, or software*" and represent some of the greatest vulnerabilities to warfighter readiness [3]. Beyond improving procurement practices to reduce the severity of DMSMS challenges on supply chains, the DoD and DIB must embrace emerging technologies like Additive Manufacturing (AM) to redesign and fabricate legacy components [4].

AM, first attempted in the 1960's at Battelle Memorial Institute, was later defined by ASTM F2792 as "*the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [5, 6].* AM's ability to create highly complex internal and external geometry with a range of metallic materials provides unique advantages to the sustainment industry, enabling the creation of complex manifolds, heat-exchangers, and topology-optimized structural components [7].

Although AM allows for highly complex geometries and tooling-free manufacturing, metals parts created with AM suffer from a variety of material challenges. Parts often have inferior elongation and fatigue strength when compared to wrought equivalents due to poor surface finish (caused by sputtering and partially sintered particles) as well as internal porosity (caused by lack of fusion, entrapped gasses, and keyholing) [7,8]. Further, there is significant variance in the experimental data due to the random nature of these flaws, which make the materials difficult to qualify and certify across material batches, different printers, and production runs [7,9]. While these drawbacks are significant, the state of qualification has accelerated rapidly in recent years with standards from organizations like NASA, ISO, ASTM, ASME, SAE, NAVSEA, AWS, and others that have begun to pave the way for qualified parts in demanding industries [4, 10].

Broadly, the problems currently preventing the sustainment community from using AM as a source of supply can be divided into (a) technical and (b) programmatic issues. Technically, the digital data required to create a part might not be available, the part might be made from a material not currently compatible with additive manufacturing (like many aluminum alloys), the post-processing required to produce the part via AM might not justify its expense, and the non-destructive evaluation (NDE) and witness specimen data might not be significant enough to confidently qualify the part for a given use-case [10, 11]. On the programmatic side, the manufacturer might not have the intellectual property necessary to legally produce the part, there might not be equivalent certifications and standards to validate that the part can meet specified requirements, or the part cannot be financially justified to manufacture through AM.

Among the challenges listed previously, this paper focuses on developing a framework by which metal parts can be redesigned for laser Powder Bed Fusion (L-PBF) for a variety of commercialized AM materials using modern AM design tools, and then compared based on mass and cost for a theorized qualification process.

2. METHODS

This paper is separated into three major components: (1) redesign, (2) cost modeling, and (3) part qualification. These components are not distinct, as each levies requirements on the others, and a major goal was to understand how each domain (engineering, economics, and qualification) flows requirements to the others. This framework allows engineers to better understand the design space associated with L-PBF of metal AM and how to create qualified, economically viable solutions to DMSMS challenges.

2.1. Topology Optimization

One computational tool used to redesign this component was topology optimization, which is a "*Finite Element analysis based tool that iteratively modifies a geometry to carry … applied loads to meet … a specific optimization goal*" [12]. Topology optimization generally involves the optimization of a geometry to satisfy loading conditions towards a given optimization metric, like minimized mass or global compliance (e.g., maximized stiffness). Topology optimization takes advantage of the design freedom of AM to create novel geometries that could not be easily created through traditional manufacturing technologies like casting, machining, or stamping. While topology optimization has broadened recently to allow for optimization of these types of subtractive and formative processes, the minimum feature size of AM and simpler tooling requirements make it an attractive medium to demonstrate the capability of topology optimization.

The form of topology optimization used for this project was Fusion 360 Generative Design, and the language used to describe the design inputs to the topology optimization program is consistent with Fusion 360 terminology [13,14]. Fusion 360 is a cloud-based Computer Aided Design (CAD) suite from Autodesk that includes design, simulation, Computer Aided Manufacturing (CAM) and other manufacturing design tools in a single software package. One unique feature of Fusion 360 is their version of topology optimization known as "Generative Design", which allows designers to specify several materials and manufacturing processes and see a multitude of designs that represent each combination of material and manufacturing process. Given this paper's goal to redesign a bracket with multiple materials and compare them based on cost and performance, Fusion 360 Generative Design was a logical choice for this project.

The design inputs to Fusion 360 Generative Design can be split into geometric inputs (known as the design space), loading inputs (known as the design conditions), manufacturing constraints, and optimization objectives (known as the design criteria) and materials [14]. The geometric inputs are "preserve geometry" where the program must place material, "obstacle geometry" where the program cannot place material, and a "starting shape", which can be a useful first iteration for the program to narrow the design search. The loading inputs are the structural loads placed on the part and the structural constraints used to motivate the geometry. Loading can be divided across multiple load cases to design parts that have multiple stressing operational modes. The "design objectives" are the optimization criteria, either choosing to minimize mass of the part for a given Factor of Safety (FoS) or maximizing the stiffness for a given mass and FoS.

The two criteria that impact the number of designs created for a given generative design model are the manufacturing constraints and the materials. The manufacturing constraints allow a designer to give basic design rules by which a part is created, i.e., they could give the size of a cutting tool to ensure a part could be machined on a 2-axis, 3-axis, or 5-axis mill, or they could specify a minimum strut diameter and overhang angle to create an additive part without requiring support material. Lastly, the material assigns a Young's modulus, yield strength, and density to create the part and estimate its FoS, displacement and mass.

Fusion 360 Generative Design then takes those inputs and optimizes a design for each combination of manufacturing constraint and material. After optimization, these designs are visualized in an interactive Graphical User Interface (GUI) to allow the designer to rapidly understand what materials and manufacturing constraints are most relevant to the optimization. This can be seen in Figure 1.

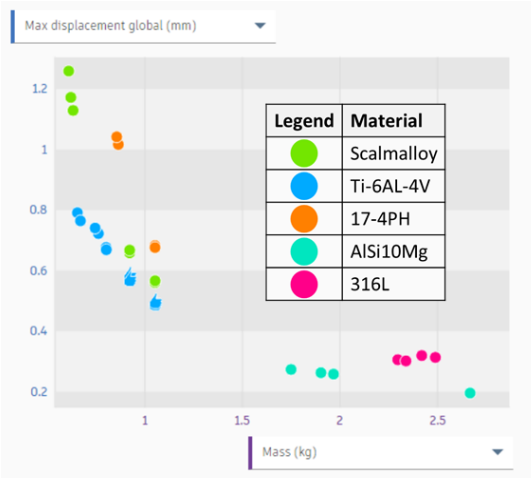


Figure 1: Snapshot of mass versus compliance design space comparing 5 AM materials with a FoS >2

Once optimized, parts can be exported back into the design or simulation workflows to tweak the design, add "as-printed" features like machining guides or full density support material, and simulate the part with a higher resolution Finite Element Model

(FEM) simulation. Finally, the parts can be exported and printed with an AM processing software package.

2.2. Original Part Analysis

The representative part used in this project was created by engineers supporting Army Ground Vehicle System Center (GVSC) and is representative of a bracket that could be problematic to procure if its original manufacturing tooling was lost. The part is investment cast from a A206 aluminum alloy, given a T4 heat treatment, and finally machined to tolerance. Its manufacturing is governed by SAE AMS 4236 Rev. D [15].

A digital model of the original component serves as a valuable source of input data into the Fusion 360 Generative Design optimization. This data was collected by computing the mass of the part in CAD and running a FEM simulation to understand its FoS and displacement under load. Relevant images can be seen in Figure 2.

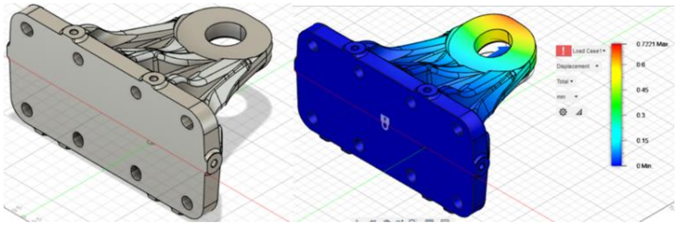


Figure 2: Original part geometry and FEM simulation

The original part has a mass of 3.24 kg and has a maximum displacement of 0.72 mm under the target load of <20,35,20> kN distributed across the upper bearing surface. To make this bracket symmetrical about its central axis, a second load case of <20,35,-20> kN was applied across the upper bearing surface. The bracket was originally designed to a FoS of 2.0. These loading conditions, structural constraints, maximum allowable displacement, and FoS would then be used to fairly compare the additively manufactured designs.

This geometry also influenced the preserve and obstacle geometries for the Fusion 360 Generative Design Study. The first iteration at these geometries used material from the upper bearing surface and lower restraining bolts for the preserve geometry, and clearance access to these volumes as the obstacle geometry. This design can be seen in Figure 3.

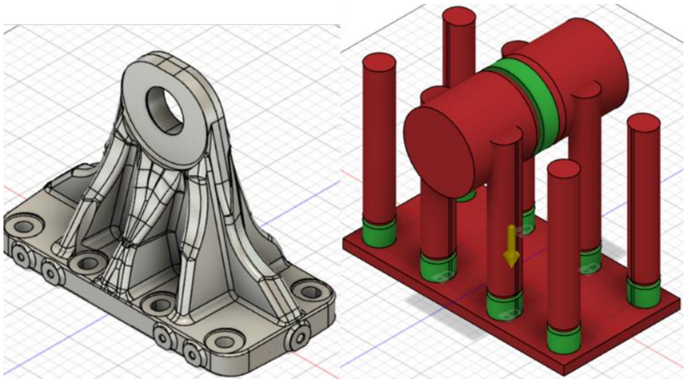


Figure 3: Original geometry, geometry translated into preserve and obstacle geometries

Additionally, the original part geometry served as the starting shape of the optimization. By selecting it as the starting shape during the optimization workflow, the software began by trying to reduce the weight of the current design. While this is generally an effective strategy for redesigning a bracket out of a similar material, the significantly higher material strength of steel or titanium when compared to a cast aluminum alloy resulted in challenges for the optimization software. The issue was surmounted by creating an alternative design that combined all eight of the bottom restraining bolt regions into a single preserve region, analyzing where Generative Design placed structural material, and then removing constraining bolts that did not align with the load path (see Figure 4).

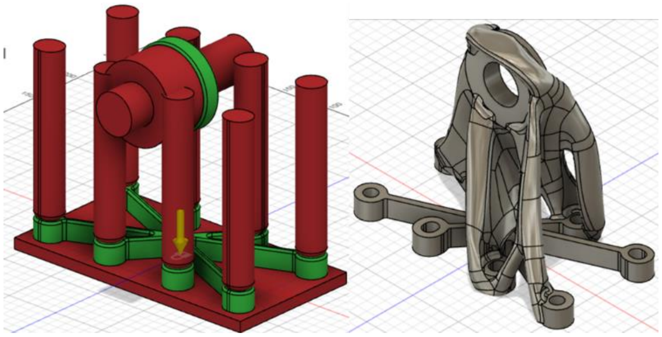


Figure 4: Strategy used to understand which restraining bolts contributed most to load path

This strategy allowed the designer to remove a few of the restraining bolts that contributed the least to the final design. Depending on the material selected, either the rear two or rear four bolts were unselected as preserve geometries in the final designs. Once a near-net shape was determined, it was used as a starting shape for multiple designs and the lightest design that satisfied the FoS and stiffness constraints was selected. Continued variation of the geometries of the starting shapes (radially, axially, and with different edge fillets) is left as an opportunity to further optimize the design.

2.3. Material Selection

With the geometric constraints determined, the next step was selecting valid materials and manufacturing constraints for the optimization. The 3D Systems ProX DMP 320 printer has been qualified to manufacture a wide variety of alloys, with 11 materials commercially available [16]. Some of these alloys – like tool steel, pure titanium, and those from nickel or cobalt-chrome systems – were immediately discounted because their application use cases (generally high temperature or medical implants) were not relevant here and therefore did not justify their cost. Instead, a selection of aluminum, titanium, and steel alloys with good toughness properties were considered as possible replacements for A206-T4. The full table of considered alloys is included in Appendix A [15, 17-23].

The general method for alloy selection was that materials needed to be stronger and have higher elongation than the A206-T4 alloy. Given AlSi10Mg's near ubiquitous use as an aluminum alloy in the AM industry, it was selected even though its elongation was lower than the critical requirements for A206-T4. Once materials were selected, the strongest heat treatment and layer height was chosen that maintained a greater elongation than A206-T4. These five alloys – LaserForm Ti Gr5 (A) (Ti64), Certified Scalmalloy (A) (Scalmalloy), Laserform 316L (A) (316L), Laserform AlSi10Mg (A) (AlSi10Mg), and Laserform 17-4PH (A) (17-4PH) – were then created as custom materials in Fusion 360 Generative Design [17-23].

With five materials selected, the next step was to select the appropriate manufacturing constraints. Fusion 360 Generative Design has an "additive" constraint which allows users to select the overhang angle and minimum strut diameter used to connect different preserve geometries into a single component. Based on design guidelines, a minimum unsupported overhang angle of 45 degrees was selected [24]. Originally, a minimum strut thickness of 1 mm was selected based on the same design guidance and specifications from NASA–STD–6030; however, this was increased to 2 mm to ensure a more conservative design [25].

2.4. AM Cost Model

Cost modeling for AM is a complicated subject and difficult to do effectively without accurate cost data for a variety of capital equipment and consumables [26]. Without this level of detail, a simpler, order-of-magnitude cost model was used for this paper. The cost model selected leveraged material usage and build time data from Atlas3D and procured material and capital costs from 3D Systems suppliers. Lastly, it used a simple multiplier based on the assumed additional costs associated with pre-processing and post-processing [27]. Although this project involved developing a post-processing regime, there was not sufficient detail to cost out each element in the regime and so a single multiplier was used. Because some of this cost data could be considered sensitive, the full equations are redacted from this paper. They generally followed the form of Equation 1.

$$\begin{gathered} Cost\_total = [(time\_build * rate\_build\ ) \\ + (mass_{usage} * \ldots \\ rate\_material\ ) *] * multiplier\_processing \end{gathered}$$

where $time_{build}$ is the build time, $rate_{build}$ is the cost of the machine and its service contract amortized over a seven-year life, $mass_{usage}$ is the mass of powder either used or not recovered from a build, $rate_{material}$ is the cost of the material per kilogram, and $multiplier_{processing}$ is the multiplier assuming that 40% of the total cost is associated with pre-processing and post-processing [28].

Instead of individually costing out each element of post-processing, a single multiplier was used for order-of-magnitude cost estimation and comparison. These multipliers were applied to both the cost of printing a single part along with printing a build with the part along with the witness test specimens necessary to qualify it for mission use. This was quantified by simulating the build twice: (1) just the target part and (2) with the target part and its test specimens. Both costs were multiplied by the post-processing multiplier because the standards consulted generally required significant post-processing of the test specimens. Details of the test specimens are discussed next.

2.5. Qualification Process

The qualification of AM components is the single largest challenge standing in the way of widespread adoption of AM in mission critical applications [10]. This can primarily be attributed to the random nature of flaws in the manufacturing process, the difficulty associated with identifying these flaws with NDE, and the costs associated with reducing them through processes like hot isostatic pressing (HIP) as well as surface machining and polishing [9, 29]. Research has shown that even bulk material removal processes that produce smooth surfaces can uncover internal porosity which can then become crack propagation sites and cause early failure through fatigue [30]. Therefore, a robust AM qualification process would require the ability to standardize as much as possible about the AM process through a comprehensive quality program, create statistically significant material profiles, design component to those profiles, and then validate that a part was made correctly and correlates with that material profile. This can be done by defining relationships between a Qualified Metallurgical Process (QMP), a Material Properties Suite (MPS), a Qualified Part Process (QPP), and managing them through Statistical Process Control (SPC) [31].

The most advanced standardization organization with respect to this strategy is NASA [10]. NASA Marshall Space Flight Center (MSFC) released two technical standards called MSFC–SPEC–3716 and MSFC–SPEC–3717 [32, 33]. These documents were later expanded into two NASA technical standards, NASA–STD–6030 and NASA–STD–6033, which collectively cover the qualification and production of mission critical AM parts for NASA missions [34]. The process begins by defining an Additive Manufacturing Control Plan (AMCP) along with a Quality Management System (QMS), often under ISO AS9100 [25, 35]. The AMCP is the governing document which describes the implementation of requirements in place of defined standards. These standards were written broadly for mature AM technologies like Laser Powder Bed Fusion and Directed Energy Deposition and can be supplemented by conventional standards as they are available [25]. One such place for this is the Equipment and Facility Control Plan (EFCP), which governs the AM equipment and facility, focusing on qualification, maintenance, calibration, and personnel training. There are now a number of AM standards by organizations like ASTM that could be incorporated here, like ISO/ASTM 52902: *Test artifacts – Geometric capability assessment of AM systems*, ISO/ASTM 52930: *Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment*, ISO/ASTM 52942: *Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications*, and in cases where existing standards are still lacking NASA–STD–6033 and MSFC–SPEC–3717 [33, 34, 36-38] can provide guidance. Once the printers are qualified, the personnel are trained, and the processes are standardized, test specimens can be printed across a plurality of builds to characterize the material.

NASA breaks down this material characterization into three stages of the Candidate Qualified Metallurgical Process (C-QMP): (1) feedstock material quality, (2) machine controls, and (3) post-processing controls [25]. Broadly, this covers the process variables that can affect the final part quality and microstructure starting with the raw feedstock, during processing in the machine, and then in any heated post-processing treatment like stress-relief, HIP, heat treatment, precipitation hardening, or aging [31]. Some relevant standards include ASTM F3049:

Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes, SAE AMS-7002: *Process Requirements for Production of Metal Powder Feedstock for Use in AM of Aerospace Parts*, SAE AMS-7003*: Laser Powder Bed Fusion Process*, ISO/ASTM F3301: *Standard specification for thermal post-processing metal parts made via Powder Bed Fusion*, and ISO/ASTM F3122: *Standard Guide for evaluating mechanical properties of metal AM materials* [39-43] The C-QMP involves qualifying the processing parameters of the AM material as well as determining its material properties, microstructure, surface quality, and minimum achievable feature size. Defining the C-QMP requires several qualification builds as defined in NASA–STD–6030 [25,44].

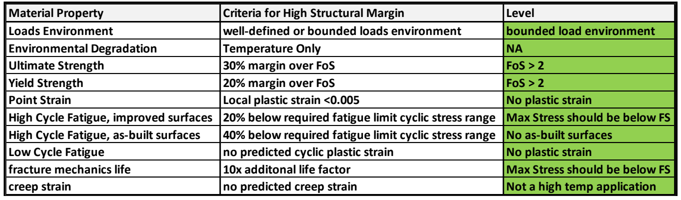
Once matured with statistically relevant data in accordance with NASA–STD–6030, a C-QMP becomes a Qualified Metallurgical Process (QMP). A Master QMP is defined for a specific piece of manufacturing hardware (tied to its serial number) operating a certain version of software and firmware with a specific processing recipe. This Master QMP but can be used as a baseline to qualify other QMPs, known as Sub-QMPs. These Sub-QMP's require the same feedstock controls, AM process parameters, and post-processing regime as the parent QMP but can be qualified through equivalence if they meet acceptance criteria for material quality, microstructure, and reference part metrics instead of requiring full qualification themselves, in accordance with NASA–STD–6030 [25]. This first QMP can then be used to create a "bootstrap" MPS, which is then expanded by multiple material lots, machine-to-machine variability, processing variables, to be a robust, statistically relevant manufacturing baseline for producing quality AM components [25].

The MPS is broader than a single QMP and consists of four major entities: (1) a data repository, (2) design values, (3) Process Control Reference Distribution (PCRD), and (4) SPC acceptance criteria for witness testing [31]. These are all included when the MPS is proposed for review in accordance with NASA–STD–6030 [25]. The MPS contains groupings of QMP's (each a single combination of material/process recipe/heat treatment) based on relevant qualification testing, material characterization, and pro-production article evaluations [25]. These give way to general material properties and can be used as a litmus test to detect critical flaws that may have occurred during a build.

Generally, there are four PCRD design values: (1) Ultimate strength, (2) yield strength, (3) elongation, and (4) fatigue life at a given cyclic stress condition. These then become the standards required for future testing. While NASA doesn't dictate the statistical methods to determine the PCRD, ASTM E2587: *Standard Practice for Use of Control Charts in Statistical Process Control* would be an acceptable standard [25, 45]. NASA–STD–6030 offers relevant discussion on numbers of builds and test specimens on each build necessary to qualify based on multiple factors, separated into Class A, Class B, or Class C materials [25], which is determined based on multiple factors.

An important part of NASA's qualification program is the ability to vary requirements depending on the criticality, structural demand, and AM risk of the component. This allows qualification requirements to scale with the rigor of the application. The first decision gate designates the class of the part, and requires all parts be classified as class A if "*one or more of these criteria are applicable: 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), or if failure would lead to the loss of one or more primary/minimum mission objectives*" [25]. Because failure of the transmission bracket could cause loss of life if its malfunctioned, the bracket was considered a Class A component. The next decision point is based on the structural demand of the part (see Table 1).

Table 1: Defining the structural demand of a qualified component [25]

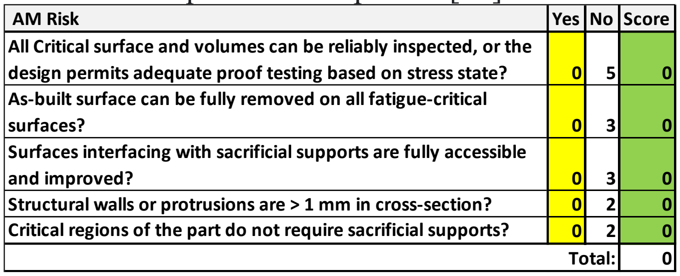


Material Property	Criteria for High Structural Margin	Level
Loads Environment	well-defined or bounded loads environment	bounded load environment
Environmental Degradation	Temperature Only	NA
Ultimate Strength	30% margin over FoS	FoS > 2
Yield Strength	20% margin over FoS	FoS > 2
Point Strain	Local plastic 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

*FS = Fatigue Strength, FoS = Factor of Safety

Alternatively, these considerations can be levied as requirements during the design phase to later reduce qualification costs. By doing this, the structural demand of the bracket in this study was determined to be low. Finally, the AM risk of the part must be assessed. This was done in Table 2.

Table 2: Defining the structural demand of a qualified component [25]



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

Similarly, understanding the requirements levied by the qualification process can enable reduction of the qualification class of the part. This was done by modifying the minimum wall thickness to 2.0 mm, requiring post-processing to remove the as-built surface roughness, and using a constrained optimization that did not require sacrificial supports over critical regions. In this study, all generatively designed geometry was considered "fatigue-critical", with all surfaces designed to be self-supporting and accessible to bulk polishing processes after HIP. Qualifying this would be left as an exercise for further study.

Based on these three criteria, this case study's bracket would be a class A4 component. This logic flow is summarized in Figure 5. Table 1, Table 2, and Figure 5 have been enlarged in Appendix B for better viewing.

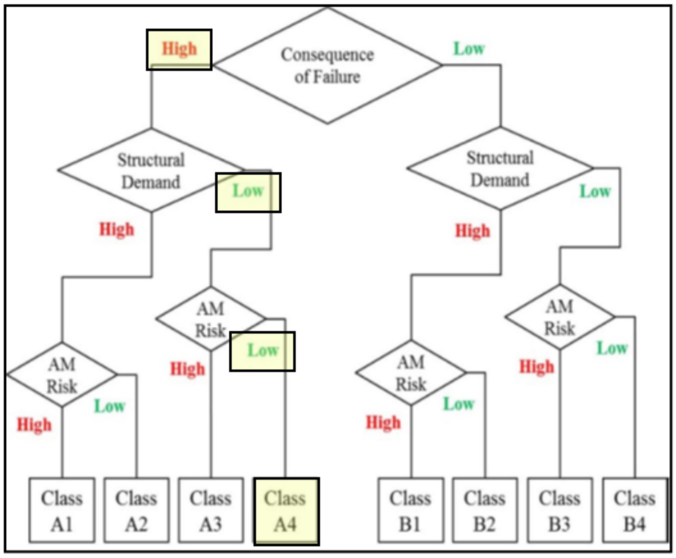


Figure 5: Overview of defining the qualification class of the case study bracket [25]

With the classification of the bracket defined, it is possible to move towards the Part Production Plan (PPP) and pursue an Integrated Structural Integrity Rationale (ISIR). The PPP serves to capture processing controls unique to a part that might not be captured otherwise in the AMCP and to document the intent and risk associated with the design [25]. It is a short document that defines the full intent of the "*design, production, and use of the AM part*" and is combined with the engineering drawing and AMCP to define all relevant information for a component [25]. Requirements for the PPP can be found in NASA – STD – 6030 and include a drawing number or part name, CAD view, purpose of the part, operational environment, referenced build file, material (along with its specification), relevant QMP and MPS, part marking, cleanliness standards, and qualification plan [25]. The PPP would also include an ISIR that would address areas of high structural demand and risk, plans for mitigating residual stresses, NDE coverage and plan, residual risks, and other risk areas as well as how they are addressed in the PPP. This verifies the maturity of the PPP and readiness for an AM Readiness Review (AMRR), conducted by the Cognizant Engineering Organization (CEO) [25]. The AMRR serves as a final check on the component and validation for additive manufacturing. It would include the maturity of all manufacturing controls and

AM performance as defined by the QMP and MPS, results from any relevant preproduction articles, and full validation check that the part meets project requirements [25]. If no deficiencies are identified, then the aforementioned documentation can be rolled into a Qualified Part Process (QPP) to guide the manufacturing and qualification of the AM component. Once defined, the QPP is locked in place and cannot change without approval by the CEO and requalification.

2.6. Post-Processing Plan

Literature has demonstrated that the inherent random errors in the L-PBF process can significantly hamper the fatigue life of AM components, and that significant post-processing (including thermal, volumetric, and surface treatment) is required to produce parts with good fatigue properties [9, 46, 47]. Even with extensive post-processing, surface finishing can still expose internal porosity that can then become crack propagation sites that limit fatigue life [30]. Therefore, it is critical to include NDE to identify and characterize flaws in the AM part. A general AM post-processing regime based on NASA – STD – 6030, ASTM standards, and work done by the Pennsylvania State University Applied Research Laboratory (PSU/ARL) to assess L-PBF parts for flight worthiness was constructed as an overarching post-processing regime [25, 48, 49]. As AM processes continue to mature and qualification technology improves, it will be possible to pare down steps to reduce post-processing costs.

The first steps involved with AM post-processing include bulk powder recovery to remove as much powder as possible from the build. This powder can be recycled and reused in accordance with manufacturer recommendations and guidance from the QMP [25]. In some standards, powder cannot be reused after handling with a polymer brush out of fear of polymer contamination [48]. While this occurs, engineers can review the quality data collected by the 3D Systems printer to detect voids that could potentially cause premature failure [50]. While this detection method is not as precise as Computed Tomography (CT) NDE, it can reliably capture larger voids and could potentially save the end customer money by reducing post-processing costs before scrapping the build [50].

Once loose powder has been removed, witness specimens maintained in the as-built condition like the full-height contingency specimen and powder coffin can be removed (either by bandsaw or EDM) and documented in accordance with the AMCP and QMS [25]. These specimens could be examined immediately or tested later depending on the requirements laid out in the QMP. The rest of the parts can then be stress relieved and removed (either by bandsaw or EDM) from the build platform. In accordance with the QMP, the printed witness specimens go through the same post-processing regime as the final part to validate its material properties.

Next, support material is removed, and the part is thermally post-processed with Hot Isostatic Pressing (HIP) and heat treated in accordance with the QMP NASA–STD–6030 requires all Class A components to be HIP’d in accordance with ASTM F2924, ASTM A1080, or ASTM F3318 for titanium, steel, and aluminum alloys respectively [25,51-53]. HIP is used to close internal pores which can be then validated via CT-NDE in accordance with NASA–STD–5009 and ASTM 3166 [54, 55]. Lastly, the AM part must have its surfaces cleaned and dimensionally-critical surfaces machined.

Although topology optimization can include manufacturing constraints to make parts self-supporting to reduce support requirements, these organic geometries can be both complicated and expensive for full surface machining. Therefore, bulk surface processes can be used to remove a controlled volume of material from a part and improve fatigue resistance. Due to the controlled nature of these processes, with precision up to 2.5 micron, it is possible to first surface machine critical surfaces and then apply Extreme-Isotropic Surface Finishing (E-ISF), a surface finishing process developed through NASA SBIRs, to improve all as-built surfaces in accordance with the AM Risk Matrix of NASA–STD–6030 [25, 30, 47, 56]. Once the AM part and witness specimens are finished, if their control values are in line with the PCRD design values, then the AM part is fully qualified for end use in accordance with the QPP.

2.7. Witness Testing

To comply with the QMP requirements laid out in the AMCP, most witness test specimens must go through similar post-processing steps to the final approved part. In this case, that would include stress relief, HIP, heat treatment, EDM, and E-ISF surface improvement. NASA–STD–6030 lists out clear requirements for Class A-4 components, which includes 6 vertical tensile specimens (in accordance with ASTM E8), two high-cycle fatigue specimens (in accordance with ASTM E466), one microstructure specimen (in accordance with ASTM E3, ASTM E407, and based off PSU/ARL's design), one full height contingency (FHC) specimen (in accordance with MSFC – STD – 1716) and a powder coffin (based off of PSU/ARL's design) [25, 49, 57-60]. A FHC specimen is a vertical cylinder that captures microstructure related to the full height of the part [36]. Its diameter is not specified, but it should be large enough to be turned into either a tensile or high-cycle fatigue specimen [36]. Additionally, it can be used to study the density or microstructure of the build before heat treatment. Similarly, the powder coffin is a thin-walled structure that preserves the powder used for a given build in case it is needed for future analysis [36].

NASA–STD–6030 is flexible to allow inclusion of other customized witness specimens as required. This could include thin features or internal cavities to validate processing parameters for thermal hardware like heat exchangers and tooling with conformal cooling channels. Given that the representative bracket in this case study has purely mechanical requirements, this was not explored further in this study. Expanding these requirements for conformal channels, internal cavities, latticed geometries, or requirements related to extreme temperature swings, thermal creep, or corrosion were not considered in this study.

One oversight in this study was that all tensile specimens were designed to have a machined surface finish while the part has a surface finish improved with E-ISF. Future studies would include customized witness specimens that could be tested after they were post-processed in the same manner as the part in qualification.

While NASA–STD–6030 did not provide requirements on the geometry of the as-built specimens nor the layout of witness specimens on the build platform, MSFC–SPEC–1716 offers some guidance on these topics [25, 32]. For these specimens, the tensile and fatigue specimens would go through the full post-processing regime, the microstructure specimen would go through the thermal post-processing regime, and the FHC and powder coffin would be preserved in the as-built state to offer insight into the quality of the powder used for production and to help diagnose process control challenges.

Beyond the number of specimens, their configuration on the build plate is critical to making them valid quality management resources for the AMCP. NASA–STD–1716 recommends that all tensile and fatigue specimens be designed in the vertical configuration and that tensile specimens should be staggered to cover all critical regions of the build [32]. Additionally, while not giving specific geometry guidance on the design of the FHC specimen, the standard does indicate that it should be an appropriate geometry that it could be processed and used for mechanical testing if required. For this reason, it was given the same diameter as the tensile specimen and spans the full height of the build. Lastly, these specimens are ideally placed behind the part relative to the travel direction of the powder recoater. For logistical purposes, it is important that the FHC and powder coffin specimen can be removed before any thermal processing and without disturbing either the part or other specimens that require thermal processing.

After post-processing, the mechanical and microstructure test specimens would be prepared in accordance with their respective ASTM standards and results would be reported in accordance with ASTM F2971 and ASTM F3122 [43, 61]. These results would be compared with the PCRD design values and discrepancies would be further investigated using the FHC and powder coffin specimen.

3. RESULTS

The five materials - LaserForm Ti Gr5 (A), Certified Scalmalloy (A), Laserform 316L (A), Laserform AlSi10Mg (A), and Laserform 17-4PH (A) - were used to run a generative design study and produce five as-designed AM brackets. The five brackets can be seen in are linked in Appendix C and a summary of their performance can be seen in Table 3.

Table 3: Comparison of bracket performance

Bracket	Mass (kg)	Displacement (mm)	FoS	Volume (mm^3)	Preserve V (mm^3)	Generative V (mm^3)	Generative Volume %
Original	3.240	0.704	2	1.21E+06	NA	NA	NA
Scalmalloy	0.802	0.680	2	3.01E+05	6.90E+04	2.32E+05	23%
Ti64	0.922	0.659	2	2.08E+05	6.90E+04	1.39E+05	33%
17-4PH	1.052	0.676	2	1.35E+05	6.90E+04	6.59E+04	51%
AlSi10Mg	1.749	0.273	2	6.56E+05	7.93E+04	5.77E+05	12%
316L	2.296	0.305	2	2.87E+05	7.93E+04	2.08E+05	28%

Based on the results of Table 3, it is possible to significantly lightweight this bracket by removing material without affecting the stiffness or strength of the final bracket. The lightest bracket, manufactured from the high-performance aerospace aluminum Scalmalloy, can achieve a weight reduction of over 75%. Most brackets were able to achieve significant weight savings, with more economic materials like 17-4PH still able to achieve weight savings of greater than 67%. An example of the lightest bracket that met both the displacement and FoS constraints can be seen in Figure 6.

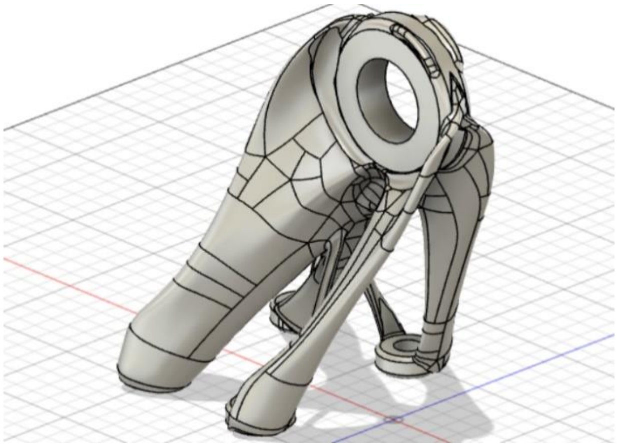


Figure 6: Scalmalloy bracket achieving greater than 75% weight reduction

This bracket used only four of the eight originally provided holes and benefits from Scalmalloy's high strength, low density, and the design freedom provided by the L-PBF process over investment casting. It was additively manufactured with 45 degree overhangs and requires minimal sacrificial supports. A snapshot of its build can be seen in Figure 7.

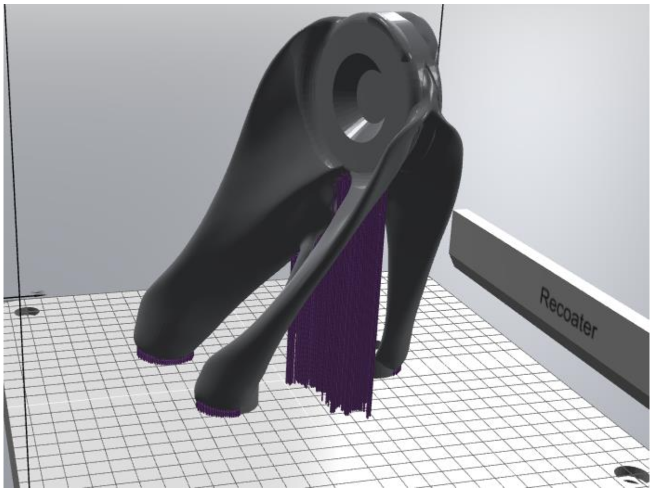


Figure 7: Image capturing how 45-degree overhangs allow for reduction of sacrificial supports

In general, the use of AM constraints on the topology optimization process allowed for the significant reduction in required supports, especially on critical surfaces where loading was highest. However, the areas in which topology optimized geometry met preserve geometry would sometimes fail overhang constraints. This can be seen in Figure 7 where supports are required at the bottom of the build plate where the constraining holes meet the optimized geometry and under the central bearing surface preserve geometry which requires significant support. Improved Design for AM (DfAM) principles when designing these geometries could likely have reduced these supports.

Another interesting observation was that brackets fit into one of two categories: (1) stiffness-limited and (2) strength-limited. The three materials with the highest strength-to-weight ratios, Scalmalloy, Ti64, and 17-HP, could have produced brackets that were an additional 30% lighter before running into the manufacturing constraints levied by the test plan (minimum feature size >2 mm). However, these brackets would have been significantly less stiff than the original bracket design, with displacements in the 1.5-2 mm range, changing the dynamics of its structural environment. For all cases, stiffness-limited brackets were significantly (>5%) lighter if they only used four of the eight constraining bolt holes when compared to designs that used six of the eight constraining bolt holes.

On the other hand, brackets made from AlSi10Mg and 316L struggled to reach the required FoS due to their lower yield strength. They benefitted from designs that used six of the constraining holes to spread loads over a greater area. In these materials, designs that utilized 6 holes were lighter than designs that used 4 holes.

Lastly, while these studies were not included in the paper, it was interesting to observe how the stresses applied to the part, along with the volume of preserve geometry, changed which brackets could meet stiffness and strength requirements with the lowest weight. In earlier iterations, where all eight constrain bolt holes were linked and where a lower factor of safety was used, materials like AlSi10Mg were more performance-competitive with alloys like Ti64 and 17-4PH, where their heavier preserve volumes prevented optimization of the bracket. Even in the final design, where preserve volumes were significantly reduced, the preserve volume still contributed 50% of the mass of the 17-4PH bracket. Understanding these relationships and how density and specific strength contribute to appropriateness of alloy choice in light-weighting deserves further study.

3.1. As-Designed vs. As-Built Brackets

Once designed, the brackets required further modification to be printed. Literature has demonstrated that there are challenges associated with machining sacrificial supports, and NASA–STD–6030 declares that sacrificial supports supporting critical regions of the part can increase the risk of the AM part, warranting additional testing [25]. For these reasons, a goal of the project was to redesign this bracket to only use fully-dense supports modeled in the as-printed CAD model. These supports were based on research done by PSU/ARL during the V-22 Nacelle qualification research program. They include fully dense supports under the restraining bolt holes (which provide a superior thermal path for heat dissipation and can be removed easily via EDM after heat-treatment) and fully dense supports in the upper bearing surface which already require machining [49]. These changes can be seen in Figure 8.

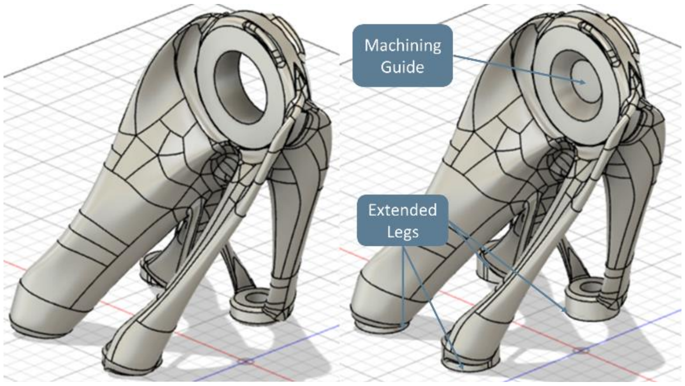


Figure 8: Comparison of as-designed and as-built Scalmalloy brackets

Doing so reduced the total cost of the build, reduced thermal distortion, and simplified mechanical post-processing. These simple changes improve the full lifecycle economics of L-PBF AM. Lastly, the bracket would be thickened a uniform thickness of approximately 150 micron to account for material removed during the Extreme-ISF process [56]. This was not modeled in the as-built brackets due to time constraints.

3.2. Cost Comparison of Bracket Designs

With final geometries and test artifacts identified, it's possible to compare part costs between materials. An example full build for the Scalmalloy bracket and all witness test specimens can be seen in Figure 9.

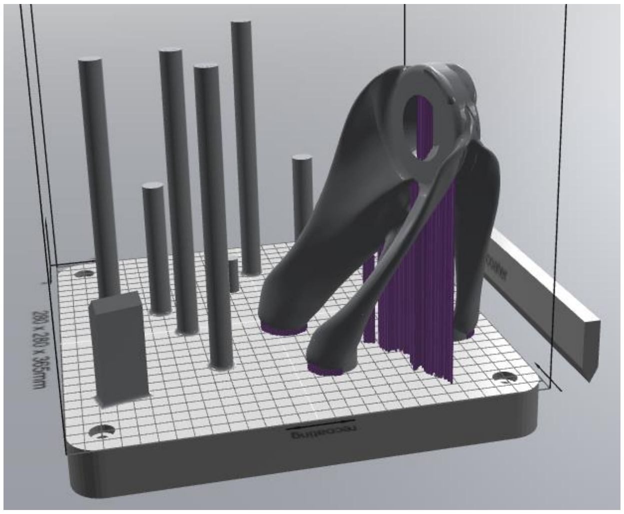


Figure 9: Sample build with bracket and witness test specimens

It is clear from the figure that the test specimens make up a substantial portion of the build and likely a proportionate factor of total cost. This can be seen more clearly in Table 4.

Table 4: Comparison of cost and performance of different brackets

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%

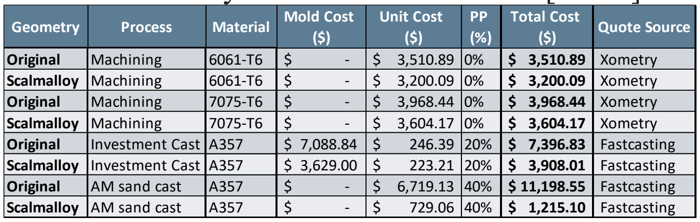
Interestingly, although Scalmalloy and Ti64 require a smaller mass of material, the 17-4PH bracket is substantially less expensive. This is likely due to the low cost of the material and high deposition rate (kg/Hr). While it is 31% heavier than the Scalmalloy bracket, it is 47% cheaper. Similarly, when compared to Ti64, the 17-4PH bracket is 15% heavier but 37% less expensive. For this set of loading conditions, the 316L and AlSi10Mg brackets were neither cost nor performance competitive. However, in other experimentation that used lower design loads, the AlSi10Mg bracket was often mass competitive with the 17-4PH brackets and potentially cost competitive. There are other applications that require ductile steels like 316L that were not fully explored in this case study.

Finally, the rule of thumb that pre-processing and post-processing an AM component accounts for 40% of the total cost likely does not capture costs associated with printing, finishing, and testing witness specimens. For the five different builds included here, adding the witness specimens resulted in a 50-120% increase in used material and a 20-80% increase in build cost. Further study is required to better understand the economics of witness test specimens and how they are best utilized to mitigate AM risk without eroding its economic advantages.

It is only possible to estimate the value of AM over traditional manufacturing if the cost of manufacturing the bracket via AM can be compared to conventionally manufactured materials. For this, three processes were selected: (1) 5-axis machining, (2) investment casting and machining, and (3) 3D-printed sand casting. The machined parts were machined to standard 5 thousands tolerances, and the investment cast parts were manufactured in accordance with SAE AMS 4236 Rev. D, which includes the build of an ASTM E8/E8m tensile specimen, machining of critical surfaces, and die penetrant [15]. Because sand casting can have rougher surfaces that investment cast parts, the sand-cast parts were assumed to go through the same finishing process (HIP, E-ISF, and surface machining) as the AM part. Therefore, a post-processing fraction of 0%, 20%, and 40% were added to the 5-axis machined, investment cast and machined, and 3D-printed sand cast parts.

Finally, quotes were gathered from Xometry.com and Fastcastings.com for machined and cast specimens respectively [62-63]. Because A206-T4 is not traditionally used as a machining alloy, it was compared to 6061-T6 and 7075-T6, two high strength alloys commonly used for machined parts in the automotive and aerospace industries. Because A206-T4 was not available on Fastcasting.com, A357 was substituted. The results can be seen in Table 5.

Table 5: Comparison of cost of various conventionally manufactured brackets [63-64]



Geometry	Process	Material	Mold Cost ($)	Unit Cost ($)	PP (%)	Total Cost ($)	Quote Source
Original	Machining	6061-T6	$ -	$ 3,510.89	0%	**$ 3,510.89**	Xometry
Scalmalloy	Machining	6061-T6	$ -	$ 3,200.09	0%	**$ 3,200.09**	Xometry
Original	Machining	7075-T6	$ -	$ 3,968.44	0%	**$ 3,968.44**	Xometry
Scalmalloy	Machining	7075-T6	$ -	$ 3,604.17	0%	**$ 3,604.17**	Xometry
Original	Investment Cast	A357	$ 7,088.84	$ 246.39	20%	**$ 7,396.83**	Fastcasting
Scalmalloy	Investment Cast	A357	$ 3,629.00	$ 223.21	20%	**$ 3,908.01**	Fastcasting
Original	AM sand cast	A357	$ -	$ 6,719.13	40%	**$ 11,198.55**	Fastcasting
Scalmalloy	AM sand cast	A357	$ -	$ 729.06	40%	**$ 1,215.10**	Fastcasting

Based on this rudimentary cost analysis, the redesigned AM bracket manufactured via L-PBF can be cost competitive with conventional manufacturing at very low manufacturing volumes (1-10). Additionally, the use of AM molds for rapid sand casting is economically promising. Further analysis was not performed to compare the cost-competitiveness of AM versus conventional manufacturing due to the granularity of the analysis during this study.

4. CONCLUSIONS AND FUTURE WORK

An aluminum cast-and-machined bracket was redesigned for L-PBF AM using a set of commercial alloys. A post-processing regime was designed to better approximate costs and a cost model was developed to compare the cost of a build, including the optimized bracket (after it was redesigned for printing with solid supports) and witness test specimens. Finally, results were analyzed to show that in this set of loading conditions the Scalmalloy bracket demonstrated the highest performance, while the 17-4PH bracket demonstrated the lowest cost. The Ti64 bracket demonstrated a good compromise between cost and performance, and the AlSi10Mg and 316L brackets were not competitive on either basis. A preliminary analysis of costs alludes that a 40% earmark for pre-processing and post-processing might not be high enough if the build requires a significant number of test specimens, like a test plan based on NASA-STD-6030 might require.

This exercise offered a preliminary framework by which further study could yield fruitful results. The exercise laid out a process to redesign cast-and-machined brackets for AM, a preliminary qualification test plan, and a basic cost model to compare different AM materials. There are several ways in which additional study could be applied to improve the results.

From a design perspective, preserve geometries could be redesigned to offer better thermal-mechanical performance and fully remove all sacrificial supports, preserve geometries could be modified for each individual material to further optimize performance, figures of merit could be developed to help with alloy selection depending on the loading and stiffness requirements and preserve geometry required, and wire EDM, machining, and surface finishing requirements could be better integrated to design better as-built models. Additionally, work would be required to understand the design criteria necessary to improve all fatigue-critical surfaces with bulk surface-polishing techniques.

From a testing standpoint, manufacturing studies could inform which post-processing steps could be omitted to reduce cost while not incurring additional risk. In some cases, PSU/ARL faculty demonstrated that well-designed support structures could allow for skipping the stress relief process and instead performing HIP while parts are still on the build plate. Depending on how witness specimens are used and how the PRCD matures, it is potentially possible to reduce witness testing requirements in the future.

From a cost perspective, many assumptions were made about the cost model and could be fleshed out for a specific alloy and post-processing regime. This would allow for more granular cost modeling and improved understanding of the cost impact of different factors.

Holistically, the study was limited by only redesigning one bracket across a few materials. Building guidelines to redesign multiple brackets for different loading conditions would allow for a better understanding of which materials are best suited for substitution. This would be informed by more granular cost modeling, a more robust test and witness test plan, and improved DfAM.

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APPENDIX A

Table 6: Comparison of conventional cast alloys and 3D Systems AM materials [15, 17-23]

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

APPENDIX B

Table 7: Defining the structural demand of a qualified component [25]

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

*FS = Fatigue Strength, FoS = Factor of Safety

Table 8: Defining the structural demand of a qualified component [25]

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

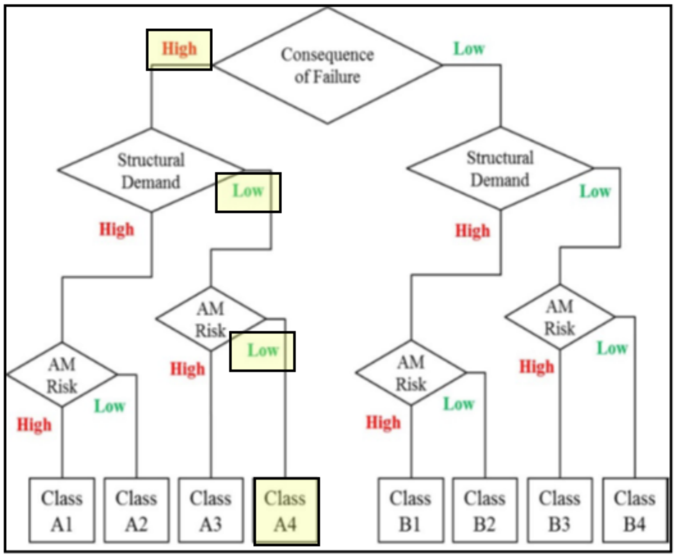

Figure 10: Overview of defining the qualification class of the case study bracket [25]

APPENDIX C

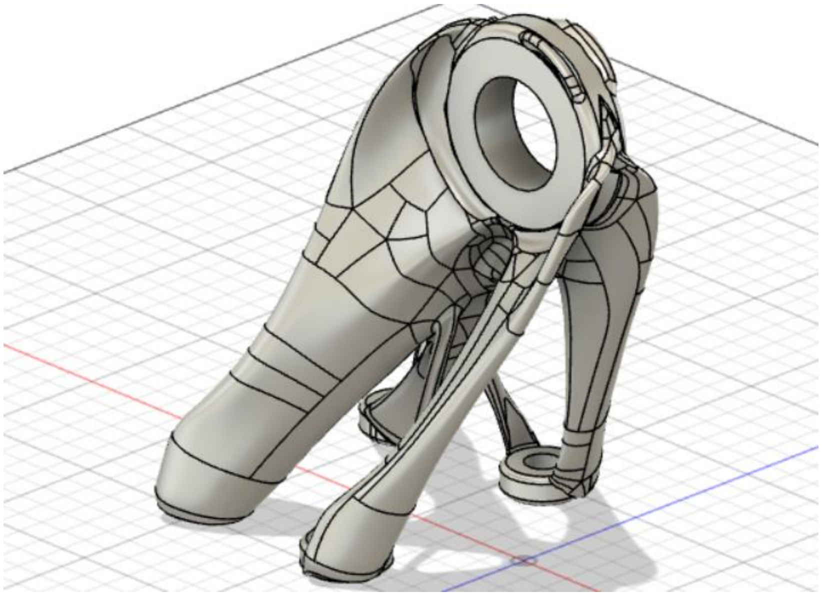

Figure 11: Final Scalmalloy Bracket

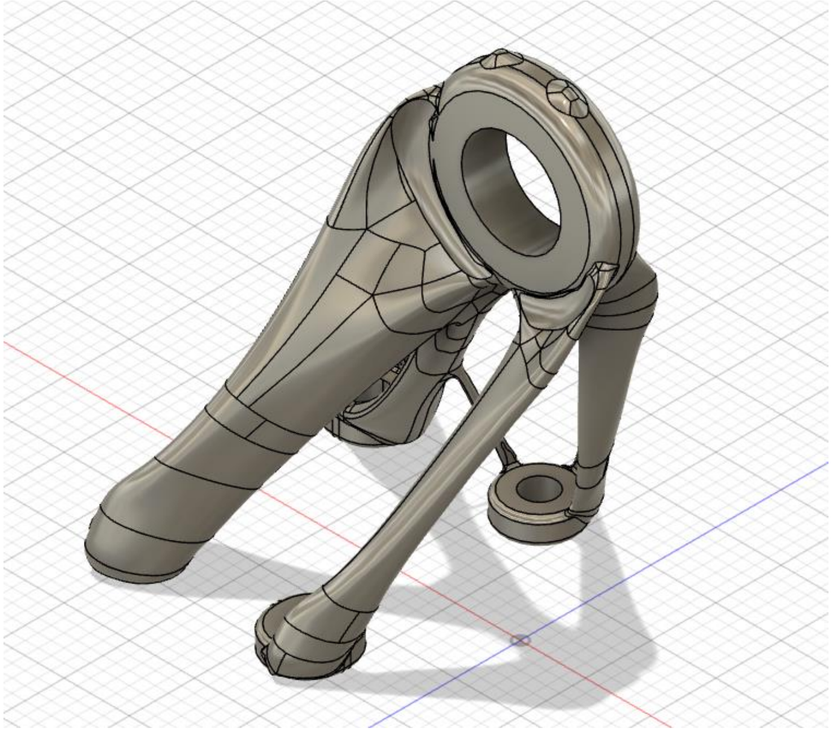

Figure 11: Final Ti-6Al-4V Bracket

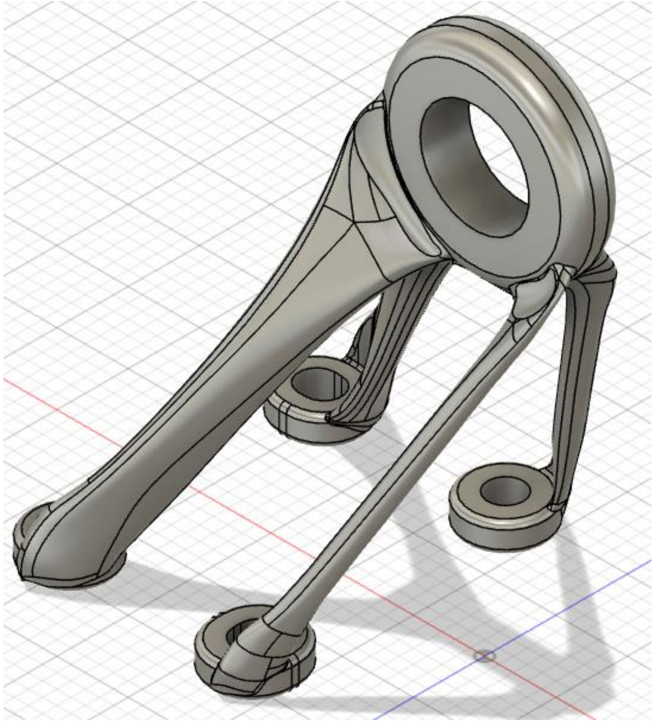

Figure 11: Final 17-4PH Bracket

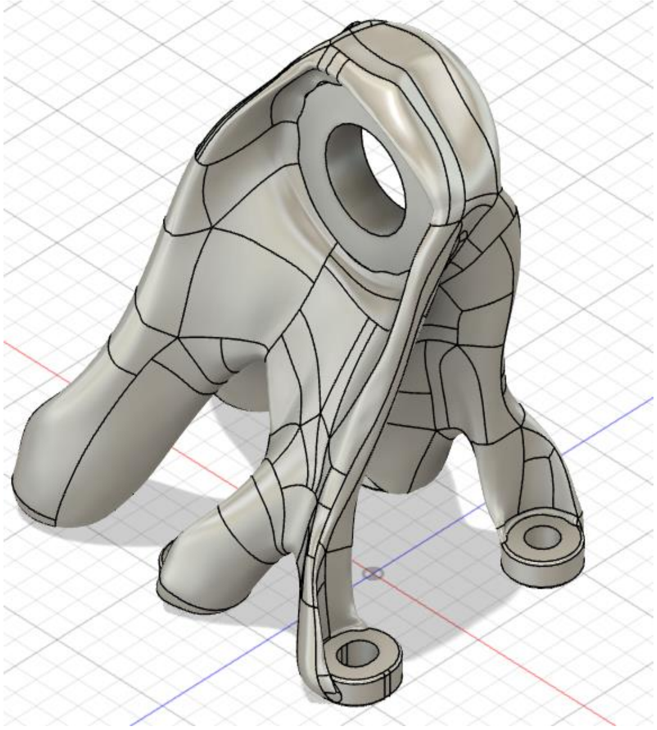

Figure 11: Final AlSi10Mg Bracket

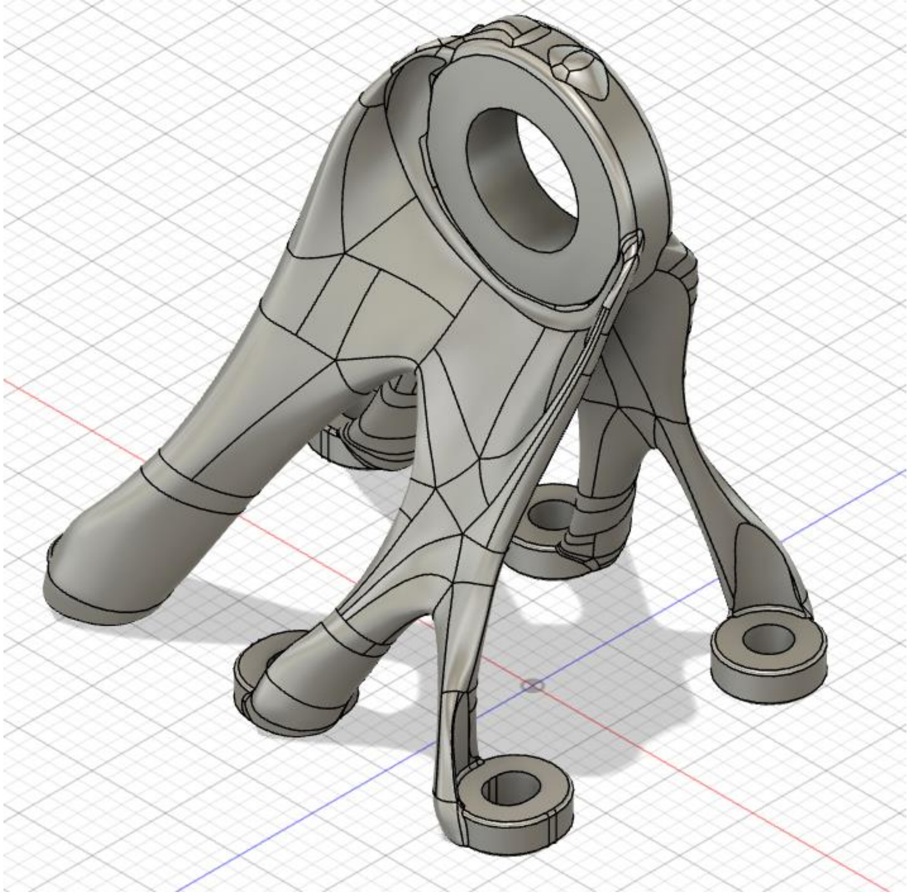

Figure 11: Final 316L Bracket