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DESIGNING FOR METAL ADDITIVE MANUFACTURING:
DESIGN CHALLENGES WITH THREE INDUSTRY RELEVANT COMPONENTS

A Thesis in

Mechanical Engineering

by

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ABSTRACT

Additive manufacturing (AM) offers unprecedented design freedom to produce complex designs in a single step. Laser-based powder bed fusion, in particular, is a promising metal AM process to fabricate complex metal parts that are otherwise difficult, costly, or impossible to manufacture using traditional means. Many techniques for lightweighting designs and improving part performance such as topology optimization, lattice structures, and part consolidation, often result in designs with complex features that can only be made with AM. Although AM is not necessarily constrained by this geometric complexity, it does require unsupported/overhanging features in the design to be structurally supported by additional structures that can be later removed by post-processing using various techniques such as hand tools, machining, wire EDM (Electrical Discharge Machining), etc. Depending on the complexity of the part, support structures can often be substantial, difficult to access, and complex in shape; therefore, removing the support structures may be very difficult and require multiple post-processing steps. As a result, overall manufacturing cost, material consumption, and manufacturing time may unnecessarily increase, making AM less economical than initially conceived. Additionally, the thermo-mechanical nature of the metal AM process induces residual stresses and distortions in the built parts. In-process distortions can lead to build failures, part curling and warping, and material waste. Therefore, many designs cannot be easily manufactured using AM or may actually cost more to produce with AM.

Design for Additive Manufacturing (DfAM) can remedy these limitations. DfAM encompasses a set of principles or guidelines based on theory and experience to help design parts to be manufactured easily with AM. Effective implementation of DfAM during the design phase can result in parts suitable for AM, which can be affordable to make and easier to produce. However, the strategies to implement DfAM principles are not generalized and vary from part to part, process to process, and material to material. These part-specific requirements may require modifications in the existing design workflow, and a single workflow may not be suitable for all the design cases. To understand some of these differences, this thesis focuses on investigating the design process for leveraging metal AM capabilities at different levels of design complexities by redesigning three industry relevant components for additive manufacturing. In each case, the design conceptualization, workflow, design tools, DfAM principles, and improvement in product performance are compared and contrasted. Based on these three cases, recommendations are

made for improving the design tools, and ultimately for improving the design workflow to reduce the computation time and improve the information flow across the software platforms.

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Chapter 1

Overview of Metal Additive Manufacturing and Research Motivation

Additive manufacturing (AM) offers unprecedented design freedom to produce complex designs in a single step. AM is an emerging technology capable of disrupting the way many parts are produced and distributed. Many variants of the layered manufacturing techniques have been made available in the market in the last three decades. Numerous potential applications have been conceptualized based on these processes, and as a result, AM is continuing to gain a significant position in various industries as well as in academia [1]. AM is capable of realizing complex functional metal parts resulting from the weight reduction, part consolidation, addition of new functionalities, etc. Due to intricate nature of the geometries resulting out of these design techniques, parts are difficult, if not impossible, to manufacture using traditional manufacturing approaches. The new design freedom offered by AM is a potential solution to manufacture such otherwise difficult to make parts. As a result, engineers are able to envision new opportunities and applications taking advantage of the unique AM capabilities. However, just like any other manufacturing process, there are new set of constraints/challenges when designing parts for metal AM.

AM is a modern manufacturing method for creating a 3D object in a layer-by-layer approach. Successive layers of material are deposited by fusing each layer to the preceding layers of the material. Various processes available in the market currently use a variety of strategies to fuse these consecutive layers, for example, melting, curing, sintering, binding [2,3] etc. In case of metal AM, fusion of consecutive layers is realized mainly by laser, electron beam, plasma transferred arc and binding agents [4,5] etc. In this study, the focus of the discussion is on the laser-based powder bed fusion system. However, the concepts discussed in general are also valid for other AM processes with relevant modifications to specific machine, material or process. In the following sections of the chapter an overview of the metal AM process and research motivation for the work is presented.

1.1. Metal Additive Manufacturing: Laser-based powder bed fusion system

Metal-based additive manufacturing started with laser-engineered net shaping (LENS) metal powder system, commercialized by Optomec [6]. Since then different techniques of AM with metal powder have been developed. One of the currently popular metal AM systems is laser-based powder bed fusion system manufactured by EOS GmbH [7]. This process is also known as Direct Metal Laser Sintering (DMLS). Currently, the process is capable of handling various commercialized powders based on stainless steel, inconel, aluminum alloy, Cobalt chrome, and titanium alloy. The metal powder is stored in the powder reservoir bins (see Figure 1-1), and a recoater blade uniformly spreads the metal powder to the required layer thickness. A laser is then scanned over the desired pattern according to the layerwise contour information derived from the CAD data. The EOS system uses Yb (Ytterbium) fiber laser as an energy source to fuse the successive layers of the metal powder. After processing each layer, the build plate moves downward by a distance equal to layer thickness so that a new layer of powder can be spread and the process is repeated. The schematic of a powder layer recoating and laser scanning is shown in Figure 1-1.

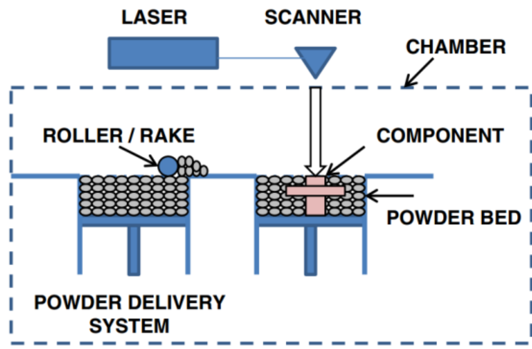


Figure 1-1: Illustration of powder layer deposition and laser scanning in EOS machine [4]

Laser-based metal additive manufacturing processes are capable of creating fully dense metallic components and are currently being explored by aerospace, automotive, and medical industries [8]. Direct Metal Laser Sintering (DMLS), in particular, is currently widely used to manufacture metallic AM parts [9], including functional parts [10]. Many industries are currently exploring the opportunities to leverage AM capabilities. A range of parts in the automotive, aerospace, and medical industries that are currently being manufactured using traditional manufacturing processes can be redesigned with improved design features to improve their performance. Parts with complex features cannot be easily manufactured with traditional manufacturing processes due to geometric complexities. Metal AM is not necessarily constrained by the geometric complexity and can be a potential solution to realize complex design features. However, AM does require unsupported/overhanging features in the design to be structurally supported by additional structures that can be later removed by post-processing using various techniques such as hand tools, machining, wire EDM (Electrical Discharge Machining), etc. These support structures not only provide structural support to the unsupported features but also act as the pathways to effectively conduct the heat way from the melt zones. Frequent heating and cooling induces residual stresses and distortions in the built parts. These thermal distortions can cause build failure, delamination from the substrate, material waste, etc. Therefore, many designs cannot be easily produced using AM or may actually cost more to produce with AM as the supports need to be removed after the part is built. Designing for metal AM is challenging and requires knowledge of design for additive manufacturing (DfAM) to make parts that inexpensive and easy to produce. The following section presents some insights from designing for metal AM case studies found in literature.

1.2. Research Motivation

DMLS is one of the few metal AM technologies used for many applications in aerospace, automotive and medical industries [10–12]. The main advantage of this technology is the ability to produce complex metal parts that are otherwise difficult to manufacture using casting or machining. For example, novel geometric features for internal cooling channels in gas turbines for the effective heat transfer can be manufactured using the DMLS process [13]. Gas turbine design engineers are interested in controlling the roughness and tolerances in the internal channels so as to control the heat transfer. The desired profiles are difficult to manufacture using traditional manufacturing processes and additive manufacturing provides an opportunity to realize these features of interest to aid gas turbine cooling technologies. However, the challenges in fabricating the cooling channel profiles are yet to be solved to be able to produce high quality internal cooling channels using metal AM. From the design aspect, these cooling channels are required to be self-supporting, because it is difficult to remove support structures from an internal channel. Also, the shape of the cooling channel may affect the accuracy of the channels created (see Figure 1-2). Figure 1-2 shows a comparison of the designed cross-sections against the actually manufactured cross-sections. The fabricated cross-sections are not anymore as intended circular, diamond, or tear drop shaped. Such non-uniformity and distortions cause the actual features to deviate from the designed features, therefore, resulting in deviation in performance from designed performance. Therefore, designing for metal AM is not straightforward, and successful creation of such internal profiles requires a thorough implementation of DfAM.

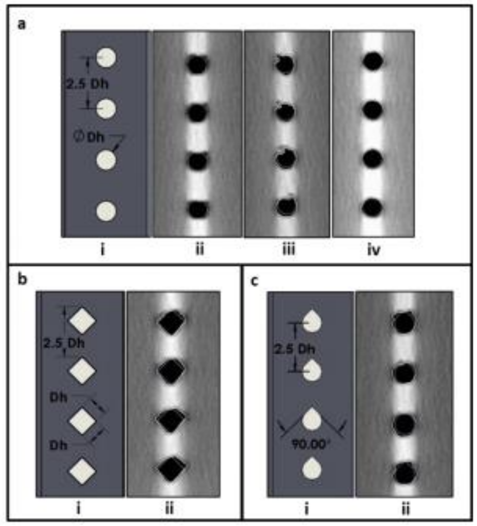


Figure 1-2: Showing comparison of designed cross-sections with manufactured cross-sections [13]

The aforementioned issue is not unique to cross-sections of channels but can be seen during manufacturing simple rectangular blocks. Figure 1-3 shows an example of layer delamination and cracking for M2 tool steel material during laser-based metal AM. The reason for such part failure is that the thick and bulky features without stress-relieving geometric features (for instance, fillets) are vulnerable to heavy thermal distortions.

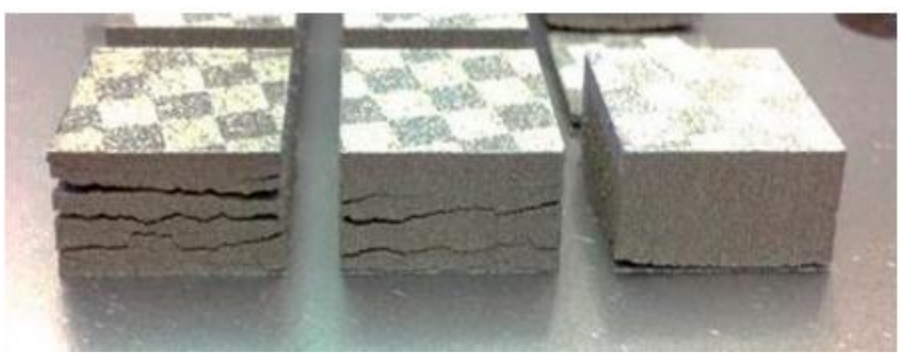


Figure 1-3: Layer delamination and cracking can be a problem in SLM (shown for M2 tool steel) [14]

In another example, NAVAIR Lakehurst has published an AM-based case study on part consolidation of a hydraulic manifold assembly [15]. They tried to reduce the size and weight of a bulky hydraulic test equipment and consolidate the whole assembly into a single portable part. According to the case study, the original component was an assembly of 17 individual parts and too heavy to be portable. Also, as it is an assembly, each of the component-to-component interfaces served as a potential leak point. The schematic and photographs of the original test equipment are shown in Figure 1-4.

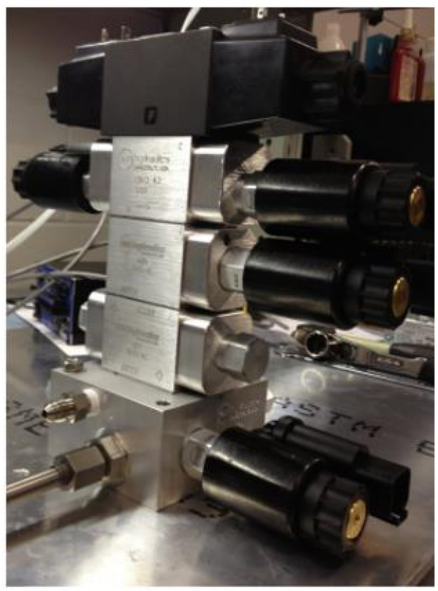


Figure 1-4: Photograph of the original test equipment assembly [15]

The objective in their study was to redesign and consolidate a multicomponent system (see Figure 1-4b) into a single component (see Figure 1-5), which can be 3D printed (made using metal AM). In addition to part consolidation and reducing weight, potential leak points can also be reduced by minimizing the component-to-component contact points. There were many design issues identified during the redesign of this part for metal AM. The most important challenge in ther case study was to create self-supporting internal passages for high pressure fluid transfer. Different cross-sections, for example, round, tear drop and diamond shapes, of the internal passages were examined for manufacturability with AM and for stress analysis (see Figure 1-6). Although passages with round cross-section with small diameter (<0.24 in) were successfully manufactured, the quality of the surface was unacceptable. Tear drop and diamond shape cross-sections were also examined in their paper, but the stress concentration regions and asymmetrical stress distribution were important issues. According to Figure 1-6, stress distribution in case of rounded square/diamond shape is relatively uniform compared to that of teardrop, pear, cylindrical, etc. In addition, there are multiple other design issues and corresponding strategies highlighted in their paper as shown in the Table 1-1.

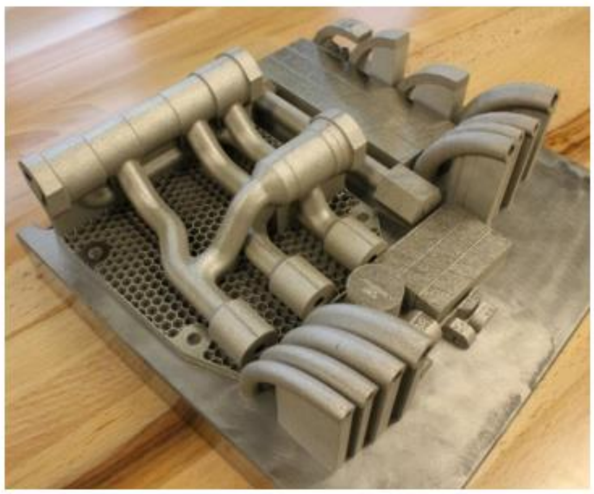


Figure 1-5: Image of final fabricated part [15]

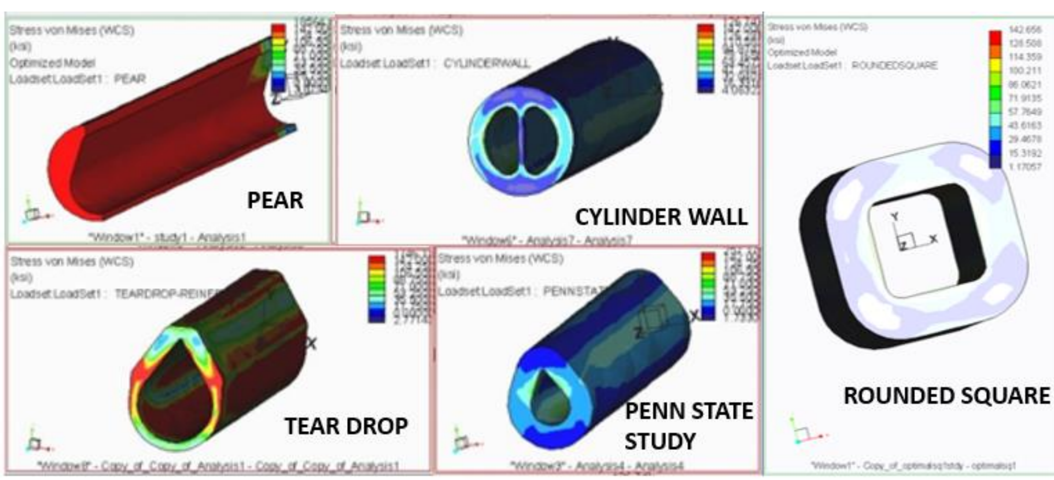


Figure 1-6: Results from stress analysis showing various cross-sections of internal passages in NAVAIR Lakehurst's case study

Table 1-1: Design considerations and the solutions adopted during the redesign of hydraulic manifold as mentioned in the NAVAIR case study

Design issue	**Design solution/strategy**
Supports for internal features or fluid passages	Tear drop and Diamond shaped cross-sections for the internal passages.
Tear drop shape did not generate constant hoop stresses needed in the pressure vessel	Higher wall thickness to achieve 4-to-1 factor of safety
Heavier part due to the thick walls required to generate constant hoop stress with tear drop shape. This was not aligning with one of the objective of this redesign that is to minimize weight.	Diamond cross-section which is symmetric in shape is preferred over tear drop shape
Stress concentration at the vertices of the diamond shape	Filleting/rounded corners to reduce the stresses to below a certain value, while maintaining the radius required for self-supporting the passage.
Supports required if the path of the channel is arbitrary or if the orientation of the diamond shape changes	Paths for the channels are generated in such a way that one corner of the diamond is always pointed upwards (vertical)
Supports required at the interfaces due to shape transition from diamond to round at the interfaces with pre-existing standard parts (see Figure 1-7).	1. Round bosses (requiring supports) for fitting are added as they are external features and can be accessible during post-processing/machining 2. Machining allowance of 0.050 in. for all ports and cavities to absorb building errors and misalignment during post-processing.
Accuracy and precision during post-processing	Registration features are added to the design to achieve precise post-processing tolerances.
Overhang features and abrupt under cuts causing supports	Angles (instead of vertical walls) were used for smooth transition to overhangs to avoid stress risers.
Thick sections (vertical or horizontal) build up high residual stresses and cause separation from the build plate.	Section thicknesses were reduced as much as possible.

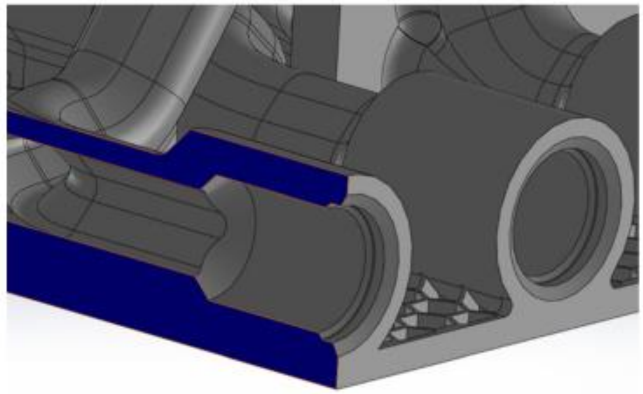


Figure 1-7: Feature showing transition from diamond to round shape in NAVAIR Lakehurst's case study

It is evident from the NAVAIR Lakehurst’s case study that lightweighting and part consolidation using AM fabrication is challenging with multiple design considerations. Additionally, often the designer’s intentions are multi-objective, for example, achieving weight reduction while maintaining mechanical performance and fabrication cost. As observed from the aforementioned case study, efforts to reduce weight result in stress risers due to the complex shape of the features in the final design and efforts to minimize hoop stresses resulted in thick walls and ultimately increased the weight. Also, as the overall complexity of the design increases, the requirement for supports increase. As a result, post-processing of the part becomes intensive and cost expensive; therefore, the part is no longer less expensive or easier to produce. Thus, it is contingent upon the designer to reach a balance between the weight of the part, its mechanical performance, support structures, and fabrication cost.

Few articles report that additive manufacturing allows design freedom at the expense of no additional cost [16]. Although higher geometric complexity in additive manufacturing does not require additional fixture tools or fixtures. Part redesign or consolidation need not always result in positive repercussions on the cost. There are many factors that contribute to the cost of metal AM. One of the factors that is not always proportional to the weight reduction in the part is material cost. Material cost is the combined cost of material used in fabricating the actual part and the necessary support structures. During lightweighting of a part, material required to build the actual part is reduced, however, the geometric complexity of the part may be increased. A complex part may require more support structures. Therefore, the material required for support structures can be substantial despite the reduction in actual mass of the part. As a result, final cost of the part after lightweighting may be significantly higher, if not, even more than the baseline component. For example, consider an example of light weighting the upright used in the suspension of a Formula student race car [17]. The original design was optimized using topology optimization techniques and the optimized design was fabricated using EOS M280 in Ti64. The weight of the actual fabricated part with Ti64 is 0.77 Kg. However, the total material consumption is 2.95 Kg, which is 283% higher than the weight of the actual part. The total material consumed in building the support structures, including the powder that ended up as the trapped powder within the part, is 73.9% of the total material consumed in fabrication. Also, as can be seen from Table 1-2, a significant proportion of cost (73.8 %) and build time (55.6%) is due to building the support structures. Thus, from this example it is apparent that there is further scope for reducing the manufacturing cost and time of this part. However, there is no direct framework available in literature that can be followed to make the optimized upright more suitable for metal AM.

Table 1-2: Summary of fabrication of the upright on EOS M280 [18]

Component	Material	Volume of the model (in^3)	Loose powder trapped inside (in^3)	Build time (Hrs)	Weight (Kg)	Cost ($)
Actual Part	Ti64	10.68	-	24:14	0.77	524.9
Support Structures	Ti64	25.16	5.03	30:23	2.18	1482.4

The aforementioned examples provide motivation to explore the opportunities and constraints from the design aspect when leveraging the AM capabilities. While many industries are curious to know the starting point in adopting AM into their existing process, the engineers at

Renishaw plc proposed a staircase model showing different levels of AM adoption [19] (see Figure 1-8). Rapid prototyping and tooling (Level 0) can be good starting points of leveraging AM capabilities, while the product design remains unchanged. The Level 1 involves directly manufacturing the existing design with metal AM without modifying the part geometry. While Level 0 leverages AM capabilities to realize tools with short cycle time and long durability, Level 1 leverages the cost benefit of using AM in small scale production. Level 2 is really the first step in AM adoption strategy where the part geometry is modified. Part consolidation and addition of new functionalities are two examples of Level 2. Level 3 is the phase of leveraging very advanced capabilities of AM adoption. Here, the parts are redesigned for AM, leveraging the design freedom offered by AM. Porous structures and topology optimized designs are examples of Level 3 implementation.

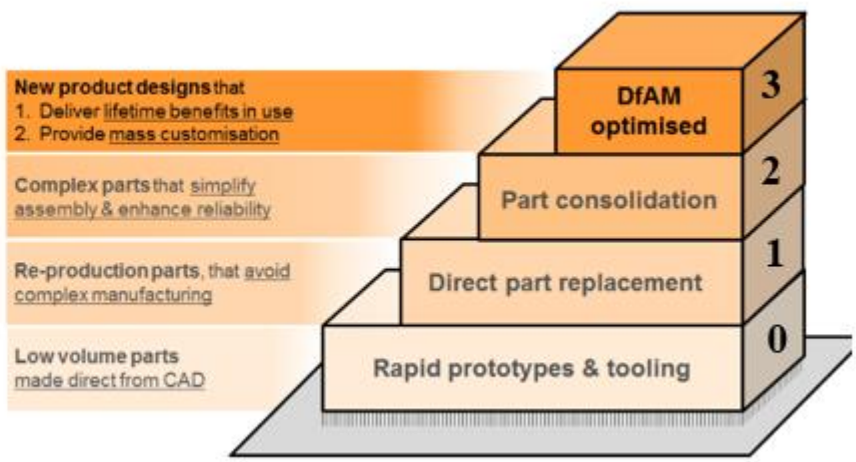


Figure 1-8: AM implementation strategy: provided by Renishaw [19]

Each of these levels vary in complexity of the design process required for redesigning parts for AM. The basic goal is to implement the DfAM principles; however, the strategies to implement are not generalized and may vary from part to part, process to process, and material to material. These part-specific requirements may require modifications in the existing design workflow, and a single workflow may not be suitable for all the design cases.

Therefore, the design process for metal AM is very complex and is not yet streamlined and still requires the use of multiple engineering tools, different file formats, different software platforms, etc. At this stage, it is very interesting to see how different parts can be designed for metal AM, and to know what the differences in the design process are.

1.3. Objectives

The goal in this research is to investigate and understand the design and development process for producing complex designs with metal AM process, especially using laser-based powder bed fusion systems. As noted in the earlier examples in this chapter, the strategies to implement DfAM principles are not generalized and may vary from part to part, process to process, and material to material. In this thesis, three industry relevant components are redesigned for additive manufacturing: (1) automobile piston, (2) high-pressure component relevant to oil & gas industry, and (3) automobile upright, to investigate these differences in greater detail. These three parts can be categorized in different levels of complexities as per Renishaw's staircase model (see Figure 1-8). First, a Level 2 redesign is carried out on an existing part, namely an automobile piston that requires new functionalities is redesigned for AM fabrication. Second, a high-pressure component, relevant to oil & gas industry, that can be considered to be at the intersection of Level 2 and Level 3 is redesigned for AM using lattice structures to achieve lightweighting. Third, a Level 3 strategy involving topology optimization is performed to achieve lightweighting in an automobile part, the upright. In each case, the design conceptualization, workflow, design tools, DfAM principles, and improvement in product performance are compared and contrasted to gain new insight into how AM is changing what and how we design.

1.4. Overview of the Thesis

This thesis is organized into seven chapters. The next chapter introduces the AM workflow, DfAM principles, and the background and literature review on the design requirements for the three cases used in this work. Chapters 3, 4 and 5 discuss the design conceptualization, workflow, design tools, DfAM principles, and resulting product performance in each of the three industry relevant cases. Chapter 6 compares and contrasts the design conceptualization, workflow, design tools, DfAM principles, and improvement in the product performance between the three cases. Chapter 6 also offers recommendations to improve the design tools to ultimately improve the design workflow to reduce the computation time and streamline the information flow across the software platforms used for design and analysis. Chapter 7 summarizes the contributions in the thesis and discusses recommendations, limitations, as well as the scope for future work.

Chapter 2
Literature Review

To understand how the design conceptualization, workflow, design tools, DfAM principles, and resulting product performances vary at multiple levels of AM adoption, three parts that fall into different levels of AM redesign are investigated.

Before comparing the details of the design process, it is important to understand the basic idea of the workflow for AM. The following section presents the different stages in the AM workflow. The rest of the chapter reviews relevant background on DfAM and manufacturability analysis tools as well as the different design requirements of the three cases addressed in this thesis.

2.1. Workflow

An AM specific workflow helps designers and manufacturers to easily follow a procedure to satisfy all the requirements to make successful AM builds. The main phases in the workflow can be divided into design & analysis, manufacturability, pre-processing, process or machine parameters, post-processing, and inspection (see Figure 2-1).

Figure 2-1: Workflow from design to inspection of metal AM parts

Depending on the specific design requirements and need for AM, some of the sections of the workflow become more, or less important. The following sections describe the scope of each of the aforementioned phases.

2.1.1. Design & Analysis

The Design & Analysis Phase contains all the processes from conceptualization to preparation of the final design for fabrication. For existing parts, in particular, part information is generally stored in 2D and .STL formats to avoid any need for specific software. First, this design information has to be converted into a workable 3D model. Second, the new design requirements are implemented into the 3D model and then a final design is created for Finite Element Analysis (FEA). This design is simulated for engineering performance (for instance, structural, heat transfer, fluid flow) using FEA-based computer simulations. The feedback from the FEA simulations is taken back to the 3D modeling where the design is improved for better performance. Furthermore, in light-weighting applications, topology optimization, a finite element approach that optimizes material distribution in a design, is carried out on the models to determine optimum design layouts of the parts. These topology optimized design layouts are again converted into workable 3D models. In addition to topology optimization and FEA, some of the design problems require generation of lattice structures or creation of assemblies. Therefore, many iterations working with multiple engineering design tools takes place in this phase.

Additionally, AM requires support structures for features that are not structurally supported by previous layers, and these supports must be later removed in the Post-Processing Phase. In some cases, these supports are located in the interior regions of the part and are difficult to be removed at later stages. In addition, supports consume additional time and material, leading to a direct/indirect increase in overall manufacturing cost. Thus, it is desirable for designers to ensure that the intended part requires minimum support structures during AM. This is possible to some extent, if not fully, by modifying the support requiring features into self-supporting features. Final 3D models are ultimately prepared to meet the design requirements of the intended part and are exported in .STL format.

However, a point of concern at this stage is the size of the mesh file that can affect the fluidity of the workflow downstream. STL format is a generic format to store CAD data irrespective of the environment that is used to create the 3D models. STL format stores the triangulated CAD data in the form of vertices of triangles and normals. These triangles are surface mesh elements approximated from the original CAD data. Since it is an approximation method, some of the critical information contained in the 3D model may be lost during the approximation [20]. Coarse meshes cannot capture the critical information, in particular, fillets, corners, small features etc. To accurately capture small details of a design, a very fine mesh is required, but that leads to large and bulky files. However, for a smooth work flow, it is desirable to avoid large file sizes. As a result, a trade-off has to be reached between the coarse mesh and large file size by performing Boolean operation between two STL files of different sizes. Two meshes, one at fine resolution, other at coarse resolution, can be combined to create a hybrid mesh capturing the required level of details at considerable file size. The .STL files are then exported to software with capabilities of manufacutability analysis for AM.

2.1.2. Manufacturability

Different metal AM systems have different manufacturing capabilities that are dependent on lasers systems, scanning strategies, materials, and so forth [3]. This dependence forces certain design requirements for metal AM such as maximum overhang length, minimum surface angles, minimum wall thickness, minimum gap width, etc. Thus, different metal AM systems have different limitations on the overhang lengths, surface angles, minimum feature sizes, etc. It is necessary to verify the designs against the process capabilities of an AM system to make successful builds. CAD data in .STL format can be used for assessing the manufacturing feasibility of the designs. There are commercial software available, such as MAGICS [21], to identify the unacceptable features as well as the features requiring external supports. Feedback from this type of manufacturability assessment can be considered back in the Design & Analysis Phase to generate improved design iterations.

After identifying and fixing out-of-spec features, .STL files are then checked for errors in the mesh. During the conversion of 3D model into a mesh format, the approximation can lead to invalid geometries, for instance, mesh triangles intersecting each other [20]. These invalid meshes can lead to errors during the tool path generation and ultimately lead to a 'bad print.' Some of the commercial software allow for both automatic and manual fixing of the .STL errors. However, automatic fixing can eliminate some of the important features while correcting the errors, but sometimes automatic fixing cannot eliminate all the file errors. As a result, manual intervention is often required to correct the error-causing triangles in the mesh. Selective triangles of the meshes can be deleted and recreated with manual inputs.

In addition to validating designs against manufacturing process capabilities, it is important to ensure that the thermal deflections due to frequent heating and cooling cycles during the build process do not cause in-process failures such delamination, fracture, build collapse and recoater jams, etc. Furthermore, the designers are interested in determining the final part distortion to provide machine allowance for subsequent post-processing. Also, for specific applications, part deflection of more than a certain value can be unacceptable for the part usage. CUBES® [22] is one such software which simulates the metal additive manufacturing process and determines the distortions due to thermo-mechanical effects. The thermal deflection information can be useful to help designers redesign and avoid large deflections. Designs validated for feasibility of manufacturing are considered for preparing the files for build process.

2.1.3. Pre-processing: CAD to Slicing

First, support structures are generated for unsupported features in the design, and commercial software such as MAGICS can be used to generate supports. MAGICS also allows for generation of different types of support structures, for example, tree, box, line, cone, volume, etc. [21] However, all of the types of support structures may not be suitable for every design as different support types can affect the process differently and can lead to in-process issues. Thus, understanding how the thermal process is affected by these support types can be useful while deciding the type of supports for a part.

Second, layer-by-layer contour information of the .STL data is generated for both the model and its support structures. The model is sliced into layers based on the selected layer thickness value and contour information for each of the layers is created. These contour slice outputs can be exported in the form of .CLI or .SLC file types. These files can then be used to generate tool paths and later be exported to the machine environment.

2.1.4. Process/ Machine parameters

The next phase in the workflow is to select the machine parameters. In addition to machine parameters, part placement, and build orientation are also an import criterion that can indirectly affect the manufacturing cost of the part. Researchers are developing various cost models that predict the manufacturing cost based on part grouping, material reuse, build times, amount of supports, etc. [23] In addition, part grouping may affect the build plate warpage during the build as well as in the later stages of post-processing. However, this phase is out of the scope of this study.

2.1.5. Post-processing

Post-processing in AM includes stress-relieving, heat treatment, separation of parts from the build plate, removal of supports; and machining the part to accurate dimensions. As metal AM involves continuous heating and cooling cycles, residual stresses are induced. If the part is removed from the build plate before relieving the residual stresses, then the part may distort, curl, warp, crack, etc. Hence, stress relief is required before separation of the part from the build plate to reduce the effect of residual stresses. Additionally, the parts produced by AM can be heat treated to enhance the material properties such as hardness, ductility, tensile strength, etc.

After relieving the residual stresses, the part is cut off from the build plate using wire-EDM. At this stage, the support structures can be cut off, and the trapped powder, if any, is removed. Parts separated from the support structures can be machined off to get the required dimensional accuracy and surface finish.

2.1.6. Inspection

Like any other manufacturing process, metal AM can induce various process defects during the manufacturing of the part; therefore, it is important to have a provision in the workflow to identify and detect defective parts. In this phase of the AM workflow, samples of the built parts are selected for various destructive and non-destructive tests. If a defect is identified, then a root cause analysis of the defect may provide the insight required to take corrective actions in the upstream of this workflow.

2.2. Design for Additive Manufacturing (DfAM): Design Guidelines for Metal AM

Although AM is not necessarily constrained by the geometric complexity, it does require unsupported/overhanging features in the design to be structurally supported by additional structures that can be later removed by post-processing using various techniques such as hand tools, machining, wire EDM, etc. Particularly in metal additive manufacturing, supports structures not only provide mechanical strength to the unsupported layers, but also help in conducting the heat away from the build layer, and prevent distortions due to thermal shrinkage [24]. This requirement for support structures varies from part to part, process to process and material to material. For instance, surfaces at an angle less than a critical value require external supports to prevent the surfaces from collapsing or deflecting during the build, this critical angle varies from process to process and material to material. Topology optimized designs, in particular, are very complex in nature and AM fabrication of these designs may require substantial support structures

Many polymer-based processes have dissolvable support structures, making post-processing easy and less labor intensive [25]. However, metal AM involves metallic support structures that require wire EDM (electric discharge machining), machining, grinding, or hand tools to remove these structures. This makes the post-processing both process- and labor-intensive. Also, extra processing time and material (i.e., powder feedstock) is needed to fabricate the supports, which increases production costs, and removal of supports adds to the overall costs of the production, making the whole process less economical than it is intended to be [26].

Design for Manufacturing and Assembly (DfMA) is an engineering practice to modify a part to reduce or eliminate manufacturing difficulties to improve the overall manufacturability of the part and thereby reduce the manufacturing costs, lead time, and logistics [3]. AM design guidelines are different than those for traditional manufacturing approaches; therefore, Design for Additive Manufacturing (DfAM) is a concept developed to address various design issues specific to AM processes [27]. DfAM provides guidelines and suggestions for creating designs that are more suitable for AM [27] and helps reduce post-processing, the need for support structures, and overall manufacturing costs. Because AM is so new for metals, few such guidelines exist. Some examples follow [3]:

1. Complex geometry: Resolution of the scan pattern (X, Y direction) in each layer in a laser-based AM process is limited by the laser spot diameter. Resolution in the build direction is primarily limited by the layer thickness. Additionally, the stresses during the build and over-melting in the Z direction can limit the resolution in the build direction. The complexity of the design that can be realized by AM is constrained by the aforementioned resolution and thermal distortion effects, in addition to the requirement for support structures.
2. Customized geometry: AM can simultaneously fabricate customized geometries on a single machine; therefore, additional tools and fixtures are not necessarily required to fabricate customized geometries. These parts can be directly produced from the digital file without necessarily modifying the manufacturing process.
3. Integrated assemblies: AM enables the fabrication of multiple parts that can move relative to each other. Although the conventional Design for Manufacturing (DFM) guidelines are not relevant to AM, Design for Assembly (DFA) guidelines are still important to AM. This enables the integration of multiple features into a single part and fabrication of these parts fully assembled.
4. Elimination of conventional DFM constraints: Although the DFM guidelines are not relevant to AM, it is challenging for the designers to explore the new design spaces that do not align with the conventional way of designing products. This need for innovation in design cannot be seen as a difficulty, but rather it is recommended to be considered as an opportunity.

An important component of these guidelines is identifying the manufacturing constraints and their critical values. In this work, we focus on manufacturing constraints for metal-powder bed fusion process, in particular, DMLS. Minimum build angle, minimum feature size, bores, gaps, wall thickness, and overhangs are few of the manufacturing constraints observed for metal AM [28]. Benchmark studies have evaluated the process capabilities of different AM processes, and the EOS DMLS process is reported to struggle building overhangs [29]. Therefore care must be taken to avoid overhangs, or if overhangs are present, then supports must be generated for those features. Table 2-1 summarizes the critical values of these constraints reported in the literature.

Table 2-1: Manufacturing constraints for EOS M280/M270 DMLS machine

Feature	**Value**
Min. wall thickness	0.016 in [37] 0.012-0.016 in (Titanium)[39]
Min. build angle	25° [39], 45°[25,41] 30-45°[40]
Allowance for bores	0.024 in undersized [39] Min. size: 0.079 in [37]
Max. overhang length (without supports)	0. 012 in [37]
Min. machining allowance	0.004-0.02 in [39]
Slots	0.5-1.0° draft for polishing [39]
Manufacturable gaps	0.004 in [37]

Although these generalized guidelines and quantified manufacturing constraints exist, a DfAM framework that connects the behavior of the parts with specific aspects of manufacturing process is necessary to help designers better understand the limitations and benefits of AM. DfAM frameworks available in literature are summarized in Table 2-2; however, the database containing design issues and corresponding solutions needs to be developed and validated before these frameworks can be used to redesign for AM. The approach followed in this work is similar to the Bin-Maidin, et al.'s framework (see Table 2-2).

Table 2-2: Summary of few DfAM frameworks

DfAM Framework	Approach
Rosen [30]	Behavior, structure and properties of the parts are mapped to the constraints and advantages of the corresponding manufacturing process
Ponche et al. [31]	Global approach to combine the functional requirement of the part with manufacturing constraints to develop a final geometry. Different from partial approach where the geometry is designed first and then modified to account for manufacturability [32].
Bin-Maidin et al. [33]	Detailed investigation of case studies rather than a predictive approach. Set of feature substitutes to make designs suitable for AM.
Kumke et al. [34]	Modular approach with structured guidelines to exploit AM potentials. Validated for an example in their case study

DfAM modifications can affect the other design requirements such as mechanical performance, weight of the part, etc. For example, modifying the overhangs by adding new features that are 45^{o} to the horizontal can result in sharp edges that act as stress concentration zones. Filleting these sharp edges to eliminate stress concentration can create overhanging features. Therefore, there is extreme interdependence between the design modifications for DfAM and to reduce stress concentrations. Moreover, these DfAM guidelines vary from part to part, process to process and material to material. In this study, to understand these differences, DfAM implementation is investigated by comparing the design workflow for redesigning the three industry relevant parts for AM.

2.3. Part Redesign: Adding New Functionalities to Existing Parts

Additive manufacturing (AM) gives engineers unprecedented design freedom, including the ability to 3D print complex functional parts. In addition to light-weighting through part consolidation and design optimization, existing parts can be improved with new functionalities using AM. For example, GE's LEAP engine fuel nozzle assembly was originally created by welding together twenty conventionally fabricated titanium parts [35]. Using metal AM process, the nozzle was redesigned into a single cobalt-chromium part that increased the durability and reduced the weight by 25%. This resulted in reducing the number of parts to track, eliminating the welds to increase the part quality, and condensing the certification process and paperwork. Additionally, metal AM saved material that was otherwise lost in machining scraps and chips, as a result improving the "Buy-to-Fly" ratio on the aircrafts [35].

Due to the difficulties with manufacturing complex single components with traditional manufacturing, a number of separate components are manufactured and integrated into an assembly to do multiple functions of a system. However, with AM, parts can be designed to be feature-rich and simplify a system by part consolidation, reducing spare part inventory, reducing the design envelope of the part, increasing efficiency, and realizing new features that were previously not explored. Unique capabilities of AM compared to traditional manufacturing are summarized in Table 2-3.

Table 2-3: Some of the unique capabilities of AM that enable feature-rich designs [35]

Complexity	Metal AM advantage
Features	Undercuts, variable wall thicknesses, and deep channels are possible
Geometry	Lattice structures, topology optimized designs, high strength-to-weight designs, porous structures, twisted shapes, etc.
Parts consolidation	Does not need welding or joining for combining different parts
Fabrication	Nested parts that would otherwise require assembly can be manufactured in single step

From a business perspective, differentiating features that can provide superior product performance can be built into an existing part by using AM processes. Particularly in the aerospace industry, AM allows fabrication of hollow as well as bionic structures and as a result, enables implementation of as many technical functions as possible [36], in addition to lower buy-to-fly ratios as noted earlier.

Redesigned AM parts can also have an indirect effect on increasing system performance. For example, modified engine valves with hollow topologies can improve the efficiency of motorsport engines and are also more cost-effective [37]. Similarly, conformal cooling channels are manufactured with selective laser melting for die casting molds that can result in better quality casts [38]. In addition to metal AM, other AM processes also demonstrate the opportunity of taking maximum advantage of design freedom to improve the performance of a mechanical system. For example, fused deposition modeling is used to manufacture intake manifolds with unique features that provide even static pressure throughout the system, which is important to improve the efficiency in the Formula SAE car [39]. In another example, electron beam melting process is used to realize conformal cooling channels in molds for injection molding, as a result better dimensional accuracy and cooling times are achieved in the final part [40].

Part consolidation such as NAVAIR Lakehurst's [15] example also requires redesigning existing parts with additional features that increase the functionalities offered by the part. In another example, a framework to approach part consolidation problems and come up with reduced part count and manufacture using AM is proposed. They demonstrated this approach by redesigning an assembly of triple clamp with 19 components into an assembly of 7 components with 20% less weight [41]. However, there is no direct solution available in literature to address the design challenges in adding new features to an existing part and to be able to fabricate with metal AM. To understand these design challenges, in this work, a piston is redesigned with new features to improve the design.

2.4. Lattice Structures

Lattice structures are open cellular structures with a continuous network of struts (slender beams). These struts can be arranged in different configurations to achieve various types of lattice structures. Due to their lightweight and high compressive load bearing capacity, lattice structures are promising as structural components in many applications in automotive, aerospace and medical industries. Since porosity of these structures is high, they are also useful in effective heat transfer from the structure due to the large surface area exposed to the environment [42]. Lattice structures are also used as deployable structures that can be stored initially in compact configurations and later deployed [43]. Furthermore, the cross-section of the struts can be designed to be hollow, circular or even square to achieve different stiffnesses suitable for specific applications.

Although lattice structures have immense opportunities to be structural members, their use has been limited due to the challenges in manufacturing these structures, particularly in the case of metal lattice structures. Since these structures are networks of slender beams, the final component would take a complex topology. Such complex structures are difficult to be manufactured using machining. Investment casting, drawing, constructed trusses and assembly methods are currently being explored to manufacture these metal lattice structures of different shapes [44,45]. While drawing is feasible on sheet like structures, it is difficult to draw networks of thin truss like members (struts). Assembly methods are susceptible to de-bonding and delamination and are also not promising for structural applications. In constructed truss approaches, metal sheets with 2D ordered hexagonal holes is deformed to create a tetrahedral strut structure [45], for example, a tetrahedral Al lattice [46]. Although this process is affordable, it is feasible only for structures patterned in a planar layer fashion and also the perforation of sheets leads to significant material waste.

Investment casting using sacrificial polymeric patterns can be used to manufacture metallic lattice structures. These polymeric patterns are made by injection molding or rapid prototyping and are coated with a ceramic casting slurry. Then the polymeric material is removed by melting or vaporization, leaving behind the ceramic pattern with negatives of intended lattice structure. Unlike previous processes, investment casting allows for more complex and non-planar lattice structures. This process has been demonstrated to manufacture several types of lattice structures, for example, a Cu/Be tetrahedral [47], Ti-6Al-4V lattice block [48] and Cu/Be 3D Kagome [49] structures. However, low density structures with thin members are difficult to manufacture due to possibility of casting defects. Since the molten has to flow through complex channel of lattice patterns, the material is required to be highly fluidic, making the process feasible to only certain alloys such as Al/Si, Cu/Be, Ti-6Al-4V, and IN 718 [50].

Although investment casting has been used to demonstrate fabrication of metallic lattice structures with different materials, there are limitations with the designing aspect of these structures. Since the process involves making patterns and flowing molten material through the entire lattice channels, it is difficult to realize large complex structures without casting defects. So this investment casting process does not allow for the design freedom required for using lattice structures in many applications. In addition, it is also reported that cast lattice structures lack the required mechanical robustness and are undesirable for some structural applications [46,50]. Thus, no existing traditional manufacturing process is suitable for fabricating large lattice structures, and it is desirable to explore new manufacturing methods for metal lattice structures.

AM allows design freedom to manufacture complex geometries with metals and is currently being explored to manufacture lattice structures. Different metal AM techniques have been investigated to fabricate metal lattice structures including Nickel and Cr bi-metal on direct metal deposition [51], stainless steel on selective laser melting [52,53], Ti-6Al-4V on selective laser melting [54], Ti-6AL-4V on Electron Beam Melting (EBM) [55], and AlSi10Mg on Direct

Metal Laser Sintering [56]. Although EBM was used to demonstrate different lattice structures and porous structures, the parts are characterized by high surface roughness or surface texture. The resulting dimensional accuracy in EBM is lower than that of laser-based powder bed fusion process due to higher layer thickness and low resolution. Furthermore, the minimum possible feature is bigger than laser based process, making it difficult to manufacturing thin lattice features. The layer thickness in EBM is higher than that of laser-based powder bed fusion process; as a result, the dimensional accuracy is lower than that of laser-based AM process. In addition, the compatible materials for EBM are also limited due to the requirement of having good electrical conductivity. Thus, researchers are exploring laser-based approaches to manufacture these lattice structures.

There are some studies on laser-based AM of lattice structures, but most of them involve small scale lattice specimens. One of the studies identifies the need for studying lattice fabrication starting from FEM analysis of the part, lattice optimization, and final fabrication [57]. In addition to manufacturability, proper selection of the unit cell, unit cell orientation, build orientation, and applied heat treatments is important because each of these choices influences the mechanical properties of the lattice structures to some extent [58]. In this work, design process of lightweighting an industry relevant part using lattice structures and metal AM is investigated.

2.5. Lightweighting using Topology Optimization

For many applications in aerospace, medical and automotive industries, the weight of a component is an important design criterion. These light weight designs are structures with very efficient distribution of material for creating high stiffness. Thus, these structures are often complex in geometry due to the optimized shapes and are difficult to manufacture using traditional processes. Emerging metal AM technology allows for redesign of existing parts or design of new parts that are light weight with the same or better mechanical performance.

Topology optimization is a finite element method (FEM) based approach, where the design space of a structure is discretized into elements, and the optimum densities of these individual elements are calculated using an optimization algorithm [59,60]. Density threshold filters are applied to this optimized density distribution to create a design with continuous material and also that is suitable for manufacturing. Examples of practical applications of topology optimization to create light weight and structurally optimized designs are available in the literature [61–64]. Particularly, in racecar design, lightweight structures enhance the performance of the car and provide extra stability as well as reduce the fuel consumption. Thus, design optimization methods are frequently applied to create efficient high stiffness components for suspension system in automotive vehicles to reduce the weight while ensuring structural performance [63,65,66].

Topology optimization often results in complex and organic lightweight structures. These structures may be difficult to be realized and require multiple tooling, fixtures, and complex process planning to fabricate the optimized design. Thus, optimized design layouts may be difficult, if not impossible, to manufacture using traditional approaches [67]. As a result, topology optimization has had limited use in many possible applications. AM offers a potential solution to fabricate optimized designs, and combining AM with topology optimization can be effective in designing and producing lightweight structures [68,69].

To take full advantage of the topology optimization with additive manufacturing, DfAM principles discussed in Section 2.2 have to be implemented along with the optimization framework. Some of the previous efforts in combining topology optimization for additive manufacturing can be found in [70–74]. In this study, method of application of DfAM rules on a topology optimized design to reduce the need for support structures while considering the weight of the model and mechanical performance is discussed.

2.6. Analysis Tools for Identifying and Fixing Manufacturability Issues

Unlike traditional manufacturing, AM does not require the use of jigs, fixtures, complex tooling, extensive human interaction, or coolants [7]. However, this ease of making parts often comes at the expense of additional build time and cost. AM is not always economical or the best process of manufacturing a part and often traditional manufacturing of a part can be less expensive [75–77]. In a particular case study on metal manufacturing landing gear, laser sintering is cost-effective of manufacturing if the volume of production is less than 42 (see Figure 2-2) [76]. For practical volumes of production, traditional manufacturing processes can be economical.

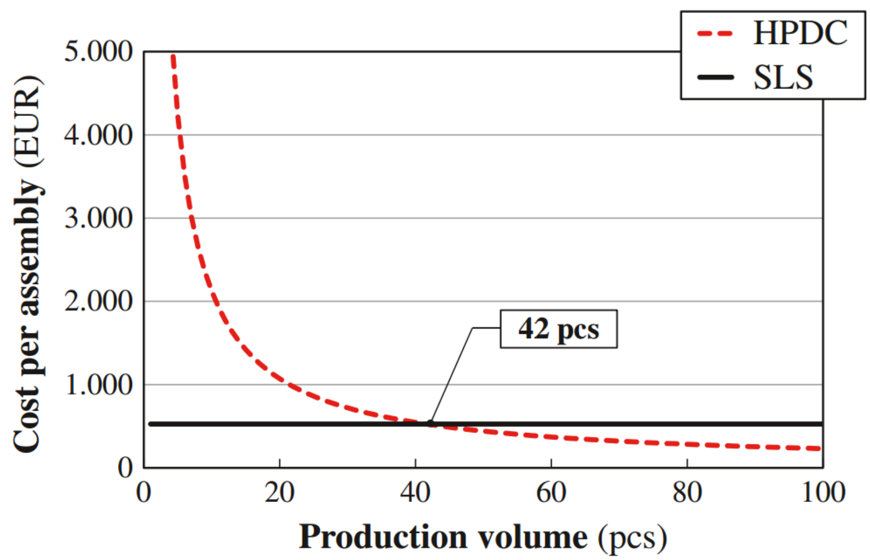


Figure 2-2: Breakeven analysis comparing high pressure die-casting (HPDC) with additive manufacturing using selective laser sintering (SLS) [76]

Therefore, cost is an important factor in decision-making when selecting a suitable process for a particular design. In addition to the actual material consumption needed to build a part, the amount of material required to build support structures and the extent of post-processing significantly contributes to the overall manufacturing cost. Manufacturability analysis of a part for metal AM during the design stage can help identify features that require substantial support structures and features that fall out of scope for AM systems (e.g., Direct Metal Laser Sintering, Directed Energy Deposition, Direct Metal Printing, etc.). Correcting these manufacturability issues early in the design can help to indirectly reduce the manufacturing cost and manufacturing time. However, the current manufacturability analysis tools are disjoint from the 3D modeling software, as a result, designers are required to iteratively use different software platforms for 3D modeling, generating supports, and thermal deflection analysis. For instance, the availability of the support generation tools within a 3D modeler can decrease the need for multiple iterations of file conversions and transferring the design from one 3D modeler to support generation software. Additionally, the results from the support generation software have to be manual interpreted in the 3D modeling software that increases the computation time, as well as demands significant manual effort. Manufacturability analysis tools can also be integrated into the CAD software. Many software allow creation of automated and customized modules through its application programming interface (API). First step towards developing such tools requires developing the algorithms in a common programming language like MATLAB. In chapter 7, MATLAB modules that are developed in this study, to identify thin features, and generate support structures are presented.

In the following chapters, the background on design requirements and DfAM discussed in this chapter is used to understand the differences in various elements of design process in redesigning three industry relevant components to leverage the capabilities of metal AM. These three parts can be categorized in different levels of complexities as per Renishaw's staircase model. First, a Level 2 redesign is carried out on an automobile piston to make it feature-rich by incorporating oil circulating cooling channels and simultaneously making it suitable for metal AM. Second, a part, relevant to oil and gas industry that can be considered to be between Level 2 and Level 3 is redesigned for AM using lattice structures to achieve lightweighting. Third, Level 3 strategy involving topology optimization is carried out to achieve light weight designs of the upright used in suspension system of a Formula student race car. The design conceptualization, workflow, design tools, DfAM principles, and resulting improvement in product performance compared to the corresponding baseline component are compared and contrasted in each case.

Chapter 3

Leveraging AM Capabilities by Addition of New Functionalities

As discussed earlier, many existing parts can be improved with the help of unprecedented design freedom offered by metal AM. Complex designs are difficult to manufacture using traditional manufacturing processes; therefore, functionalities are usually split into many parts rather than integrating them into a single part. These individual parts are assembled to carryout intended functions. Individual parts can be consolidated by adding new functionalities into a single design by leveraging the design freedom offered by AM. According to Renishaw's stair-case model of AM adoption, Level 2 comprises of leveraging AM capabilities by addition of new functionalities. As discussed in chapter 2, this design process is difficult due to the challenges in redesigning the parts by adding new features. To investigate the challenges with design and fabrication of parts with new features, in this chapter, an automobile piston is redesigned with oil circulating channels that contain unique fin structures to improve the performance of the design.

3.1. Introduction

The objective in this redesign process is to leverage the capability of AM and explore the scope for incorporating new design features that can improve the performance of an automobile piston. Important design requirements for the piston are as follows [78,79]

1) Combustion efficient design of piston crown
2) Cooling channels for efficient heat transfer
3) Mechanical strength to operate at high pressures developed during combustion
4) Lightweight
5) Dimensionally accurate grooves for piston rings
6) Interface features with good tolerance

In this study, the top bowl of the piston is not shown in the images to protect the confidential information. Only the portion of the design available for public viewing is included in this document. Cooling/oil flow channels in a piston are currently realized by using a sacrificial mold during investment casting. The function of the oil channels is to efficiently conduct the heat away from the piston crown. In every combustion cycle, an enormous amount of heat is produced in the combustion chamber, and it is important to prevent the heat accumulation to realize combustion efficiency as well as reduce emissions. However, heat transfer is affected by the surface area in contact with the heat transfer medium as well as the flow of the cooling medium. The size of the flow channels cannot be increased due to the limited allowance in the piston crown; therefore, the surface area for heat transfer is limited. However, crest and trough type surface profiles can be added to the flow channels to increase the heat transfer surface area as well as create turbulent flow to increase the heat transfer rate. In addition, other internal features can be added to increase the surface area in contact with the cooling oil. Figure 3-1 shows the design ideas to increase heat transfer efficiency. Yet, these design features are currently not implemented in the pistons due to difficulty in manufacturing with traditional manufacturing processes. Metal AM can help to realize these features, thus opening the opportunities for metal AM in piston manufacturing.

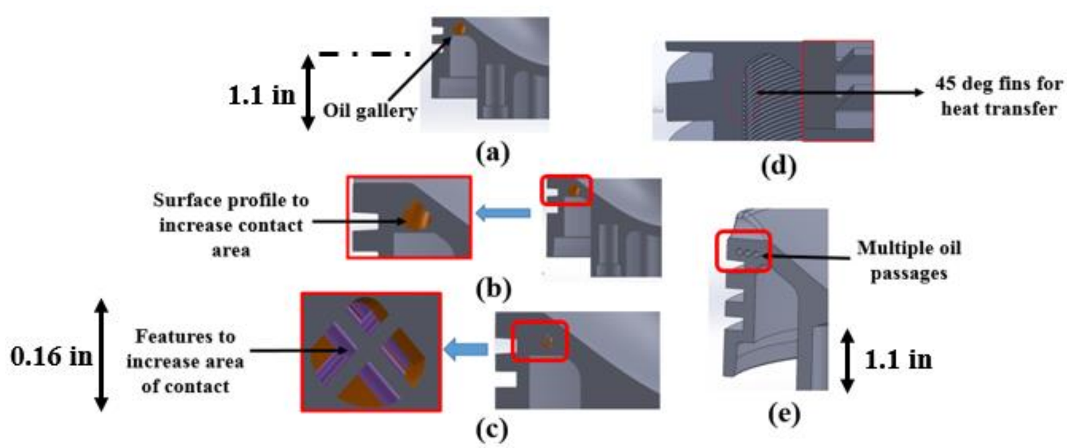


Figure 3-1: Shows different concept features for improving heat transfer in the oil gallery

Metal AM also provides an opportunity to lightweight the pistons. Bulky features (see Figure 3-2) in the existing design can be replaced with thin members and metal AM is capable of manufacturing these designs. This reduces the overall weight of the part and can help to improve the performance of the piston.

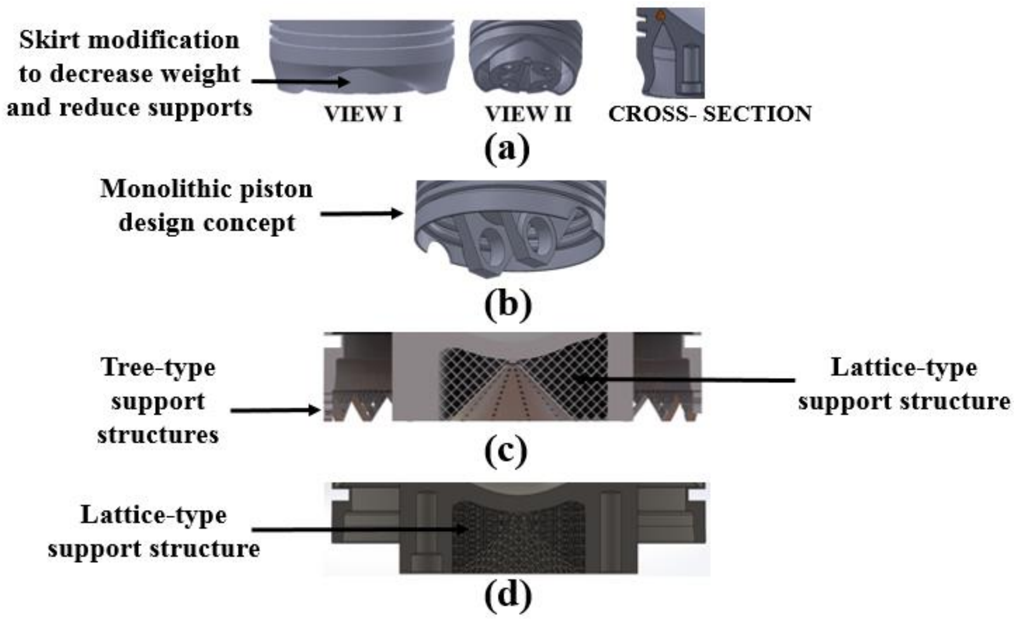


Figure 3-2: Shows different concepts for achieving weight reduction using complex feature substitutes

3.2. Redesign

Initial design (without showing the top surface of the combustion bowl) of the component is shown in Figure 3-3. The two primary design requirements for this redesign process are addition of oil circulating channels and reduction in the amount of support structures during metal AM. The final design (see Figure 3-4) contains unique features (see fins in Figure 3-4) inside the oil channels to increase the heat transfer surface area, as well as to increase the turbulence in the flow. The oil entry gate contains a divider to split the oil into two (left/right) directions. An additional channel underneath the oil channel is added to further lightweight the part. These channels are made self-supporting by sketching the surfaces at an angle more than 45° (see build angle in Table 2-1) with the horizontal. After the basic channels are modeled, the channel cross-sections at the entry and exit gates are smoothed to avoid any stress risers. The finalized features at this iteration are run in MAGICS to identify the overhanging features in the channels. These overhanging features are modified to reduce the requirement for supports in the next step. The model is rerun in MAGICS to identify remaining support requiring features. These iterations continue until a model satisfying the new functionality with minimum support structures is achieved.

Although metal AM is capable of realizing complex designs, the unsupported features in the new design requires support structures that have to be removed in post-processing. The more the supports, the more complex it is to remove these support structures; therefore, increasing the manufacturing cost and time. In this specific case, the supports needed to manufacture the central dome of the piston skirt in initial design (see Figure 3-3) are difficult to be machined due to the complex surface profile of the dome. Therefore, self-supporting features shown in Figure 3-4 (b) are designed to reduce the requirement for support structures.

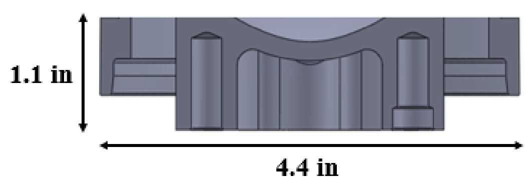


Figure 3-3: Initial design showing the large overhang in the center portion of the part

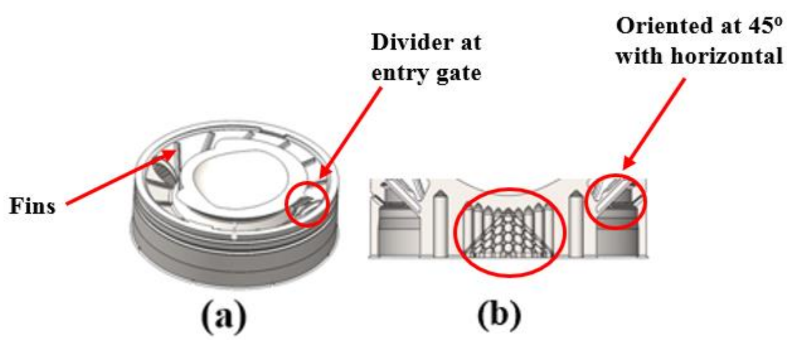


Figure 3-4: Final piston design used for metal fabrication.

3.3. Fabrication

To investigate the internal features of the as-built parts, one full part, one half section, and one quarter section are fabricated with EOS stainless steel GP1 material using standard EOS parameters. The photographs of the as-built parts are shown in Figure 3-5. The entry feature on the oil passage distorted in the z-direction (upward to the build platform); thereby, jamming the recoater blade. As a result, the build failed due to the thermal distortion of the divider feature in the oil galley entrance. In order to identify any additional issues in the design, the final model was analyzed for thermal distortions during the metal AM build using CUBES® software (now a product of Autodesk). CUBES® simulates the thermal process during the layer-by-layer deposition process and calculates the induced thermal distortion. Software can also calculate the relative clearance between the bottom surface of the recoater blade and the top surface of the previous layer. The clearance between the recoater blade and the deposited layer along the z-height is plotted in Figure 3-6. Although the software cannot accurately calculate the clearance due to approximations in the thermal model, this plot indicates the range for z-height that may have lower clearance for recoater blade. This data is used to identify possible problem causing regions in the part and modify the corresponding features to reduce distortion.

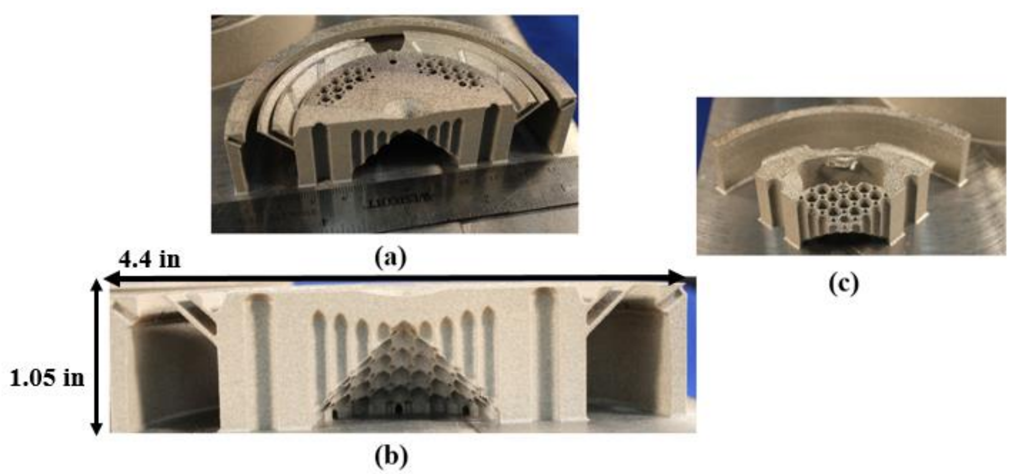


Figure 3-5: Photographs of the as-built parts

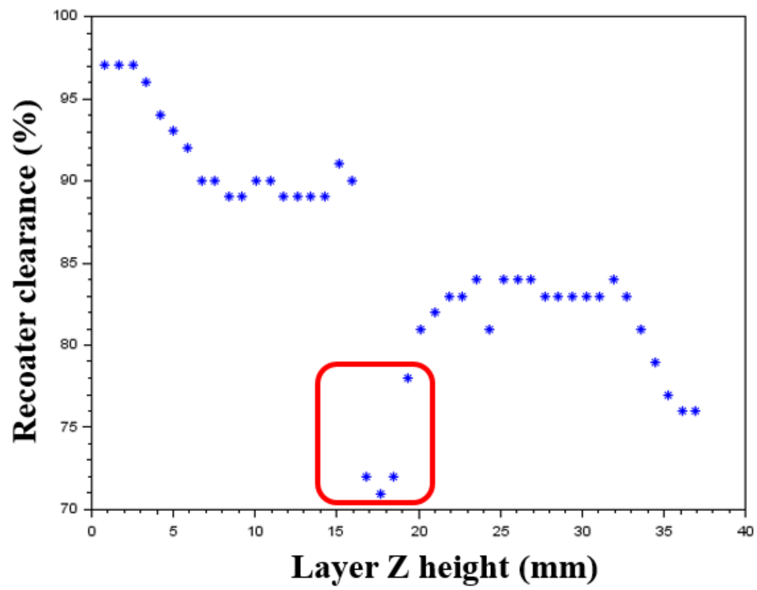


Figure 3-6: Plot showing recoater clearance along Z height of the model. The calculations are based on thermo-mechanical simulations carried out using CUBES®

3.4. Workflow

There is no existing design workflow available; therefore, developing a design workflow is important for repeatability of the design process as well as for decreasing the design computation and iterations for similar components in future. Design workflow followed in redesigning this piston crown with new functionalities is captured and illustrated in Figure 3-7. The process starts with understanding the existing component and identifying the design objectives such as what new functionalities are desired, what should be the minimum feature sizes, which portion of the design can be modified, etc. In this case, novel internal oil channels are added to the current piston design. These channels are sketched following the existing surface profiles in order to maintain the constant distance of 0.2-0.24 inch from the combustion chamber. The profiles of the entry and exit passages are extrude cut from the oil channel. The channel cross-sections at the entry and exit passages are filleted to avoid any stress risers. The finalized features at this iteration are run in MAGICS to generate support structures and identify the overhanging features. Some of these overhanging features are modified, and the model is rerun in MAGICS to identify remaining overhanging features. These iterations continue until a model satisfying the new functionality with minimum support structures is achieved.

The next objective in the redesign process is to reduce the support structures by intuitively modifying overhanging features. Different options (see Figure 3-2 and Figure 3-5) are explored and discussed. The CUBES® software is then used to simulate the thermo-mechanical process that occurs during the AM build. The results shown in Figure 3-6 provide insight into approximate range for z-height that may contain possible features that obstruct the movement of the recoater. Neglecting this thermo-mechanical analysis and going by intuition caused the build failure during initial runs. Although CUBES® software cannot strictly identify the error-causing features, it provides good insight to the designer about how the designed features will behave during the layer-by-layer build process. The final decision on the design is based on discussion with all the stakeholders in the redesign activity.

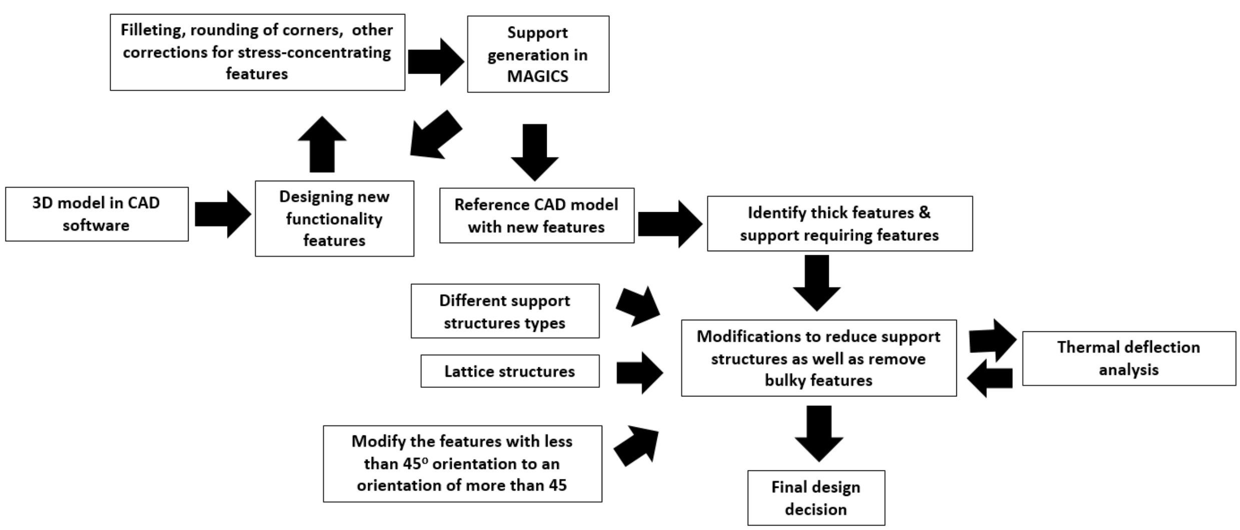


Figure 3-7: Design workflow for redesigning for AM with addition of new functionalities in existing design

3.5. Future work

In the next step, the piston design will be improved by identifying and modifying the features that caused the build failure. Subsequently, the part will be stress-relieved and heat treated to reduce the residual stresses and enhance material properties. The stress relieved part is separated from the build plate and machined off to remove the support material. The machined part will be then inspected for dimensional accuracy and internal defects using CMM and CT scan respectively.

Chapter 4

Leveraging AM Capabilities through Cellular Structures

In the earlier chapter, design challenges in leveraging AM capabilities by addition of new functionalities are discussed. In this chapter, the design and fabrication process of metal lattice structures will be investigated. The design workflow and fabrication process followed for lattice structures is different from those followed in the earlier chapter. Both these design processes are compared and contrasted in Chapter 6. The following sections present the design requirement, lattice structure generation, design workflow, fabrication, and post-processing of metal lattice structures.

4.1. Introduction

Figure 4-1 shows a functional component used in high pressure applications. The goals in the redesign process are to leverage the capabilities of AM and explore the options to lightweight this part. The part in its application is loaded with 10,000 psi pressure on the cylindrical surface as well as on the inside of the cross-designed flow channels. The initial weight of the part is 10.33 lbs and the objective is to lightweight the part as much as possible while meeting the above performance requirements. The other design requirements are:

1) The outer diameter (3 inch) of the cylinder, length (5 inch) of the cylinder, and diameter (0.109 inch) of the internal flow channels are fixed

2) Surface topology of the outer cylinder (except the end face) is fixed

3) At least one end of the cylinders should have a flat mating surface

4) Mating features on the ends of the cylinder are fixed

5) The dimensions (Φ 0.125 inch) of the autoclave features are standard

6) Any voids created in the cylinder will experience atmospheric pressure

First, topology optimization, a finite-element-based approach that optimizes the material distribution in a design domain using optimization algorithms, is carried out to determine the optimum load paths in the current design and scope for lightweighting under the loading conditions shown in Figure 4-1

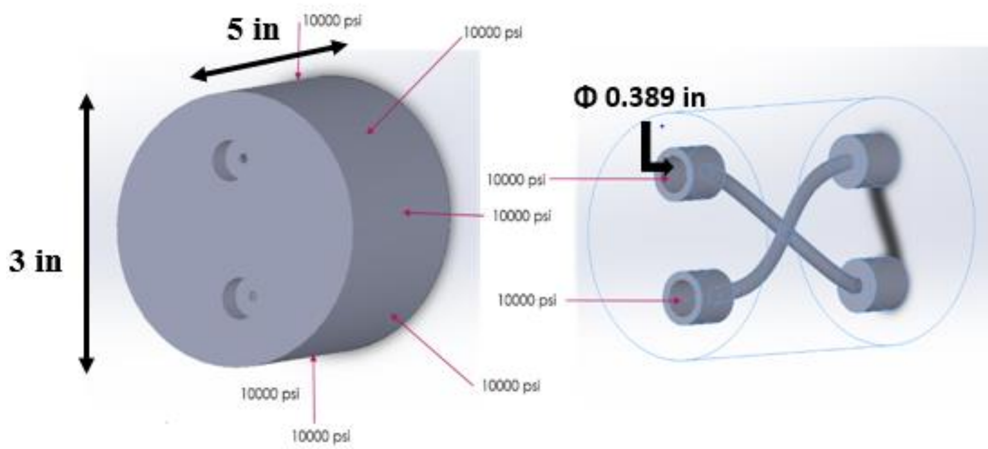


Figure 4-1: Shows pressure loads on the original design of the part. Internal tubular features are highlighted in the picture on the right side.

4.2. Topology Optimization

This topology optimization problem is solved in OPTISTRUCT using minimum compliance approach with volume constraint. The model is meshed and formulated in a preprocessing software called HYPERMESH. The design space of the model is first sectioned into a design region (optimization is carried out only on this part of the design) and a non-design region (fixed design envelope). Non-design regions of any design are the critical features of the design that cannot be changed during redesign process due to their fixed geometry resulting from assembly, mating, and other important aspects that affect rest of the system. The internal channels, autoclave features, mating features and the outer surface (with a finite thickness) of the cylinder are selected under non- design region. And the rest of the design is considered as the design region. Topology optimization modifies only the design region, leaving the non-design region unaltered.

The next step in topology optimization problem setup is to define displacement boundary conditions and loading cases. Due to the fixed nature of the interface features, the displacement of the nodes of these interface features is constrained. A pressure of 10,000 psi is applied on the surface of the outer cylinder as well as inside the flow channels. Next, material properties are assigned as per the functional requirements. The material considered in simulations of this part is IN 718 with properties listed in Table 4-1. The model is meshed with an average element size of 0.027 in. The last step in topology optimization problem is to define design responses and the objective function. Compliance and volume fraction of the model are considered as the design responses. The problem is optimized twice with an objective to minimize the compliance with minimum volume constraint of 20% and 30%. The optimized designs are shown in Figure 4-2 for both the cases.

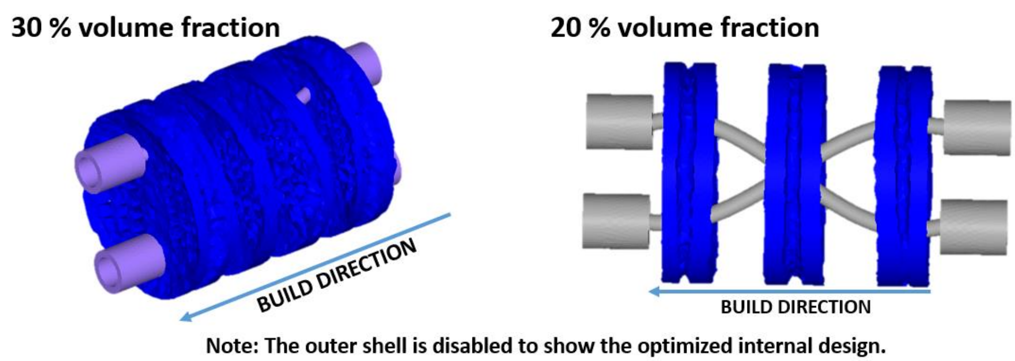


Figure 4-2: Shows the topology optimized design for two different constraint problems, 30% volume fraction constraint and 20% volume fraction constraint. (The image only shows the internal features and there is an outer cylindrical shell enclosing these internal features)

Table 4-1: Material properties of EOS 718 used in FEA

Material	Inconel 718
E	28.8 E+06 psi
Nu	0.29
Density	0.289 lb/in ^3
Yield Strength (after heat treatment)	125 ksi

These results contain obvious disc shaped internal features, and it is impossible to realize such cavities using any manufacturing means without performing an assembly. This optimized design cannot be realized even by using additive manufacturing as the powder material and support structures will be trapped in the cavities. Therefore, it is not a manufacturable part and weight saving cannot be achieved in this method. An important point to learn here is that the topology optimization does not always yield manufacturing-ready parts. Although topology optimization is very essential tool for lightweighting, it is of less use in this particular problem. Given the nature of loading, another solution to reduce weight is by replacing the bulky material with lattice structures and subsequent manufacturing with Direct Metal Laser Sintering (DMLS) process.

4.3. Problem Statement

The objective of this study is to create manufacturable metal lattice structures to achieve lightweighting. Different lattice structures to meet structural requirements are proposed in the literature as discussed in Section 2.4. However, it is important to choose lattice structures that can be manufactured using metal additive manufacturing process, in this case, DMLS. Another important aspect is to analyze these lattice structures using FEA to ensure that the part meets required structural performance. In addition, the study involves framing a workflow for design and additive manufacturing of these lattice structures, selection of post-processing methods and quality inspection of the fabricated parts.

4.4. Design

The design of lattice structures starts with selecting a unit cell. Since the intended lattice structure should be manufacturable with DMLS processes, the unit cell cannot have overhangs above a certain limiting value (see Table 2-2). First, a linear pattern (in the X-direction) of cylindrical struts is created in SOLIDWORKS. Then another linear pattern (in the Y-Direction) of struts crossing the earlier pattern is created forming a layer of intersecting struts. This layer of struts is then patterned in the Z-direction, creating a large grid of lattice structures. Second, a cylindrical sketch is 'extruded-cut' to create a lattice structure bounded by a cylindrical shell. Third, two spline curves that are always at an angle more than 45^o with the horizontal are created, forming the reference curves to create internal tubes. Next, circular sketches are 'sweep-cut' using these spline curves to create the final geometry. Lastly, minor features are made at the interfaces to complete the design requirements according to the original 2D drawing.

This design is analyzed using FEA for maximum stresses and displacement. The important parameters in this design are the strut thickness, length of the strut (or effective cell size), and wall thickness of the cylinder. These parameters are iteratively selected by FEA simulations and manual adjustment. The thickness of the struts and wall thickness of the cylinder are manually changed till the FEA results yielded a 'safe design.' For minor adjustments, only wall thickness is altered because changing the dimensions of unit cells is computationally very intensive. The finalized design is analyzed in MAGICS for manufacturability with DMLS process. The prototype of final design is manufactured with 'ABS plus' using STRATASYS Fortus 250 mc FDM machine. The prototype took 92 hr 42 mins, and consumed 34.2 in^3 of model material and 14.49 in^3 of support material. The prototype (see Fig 4-3) helped in identification of some design issues such as blockage of autoclave feature, which was unnoticed during CAD development. In addition, the prototype helped in discussing the design idea with experienced DMLS engineers as well as with the sponsors. From the evaluation of the prototype, although there is evidence of manufacturing overhangs at this length scales, the design did not look promising to be successfully manufactured in metal. Furthermore, the experience of manufacturing these structures at Penn State's CIMP-3D suggests to avoid overhangs for good manufacturability. As a result, the unit cell is modified to remove any overhangs and the redesigned unit cell shown in Figure 4-5d is used to populate the design. Final design and the internal cross-sections are shown in Figure 4-4 (a), (b) – (c), and (d) respectively. FEA results corresponding to the final design are shown in Figure 4-5; the estimated von Mises stresses and maximum deflection are acceptable to the intended function of this part.

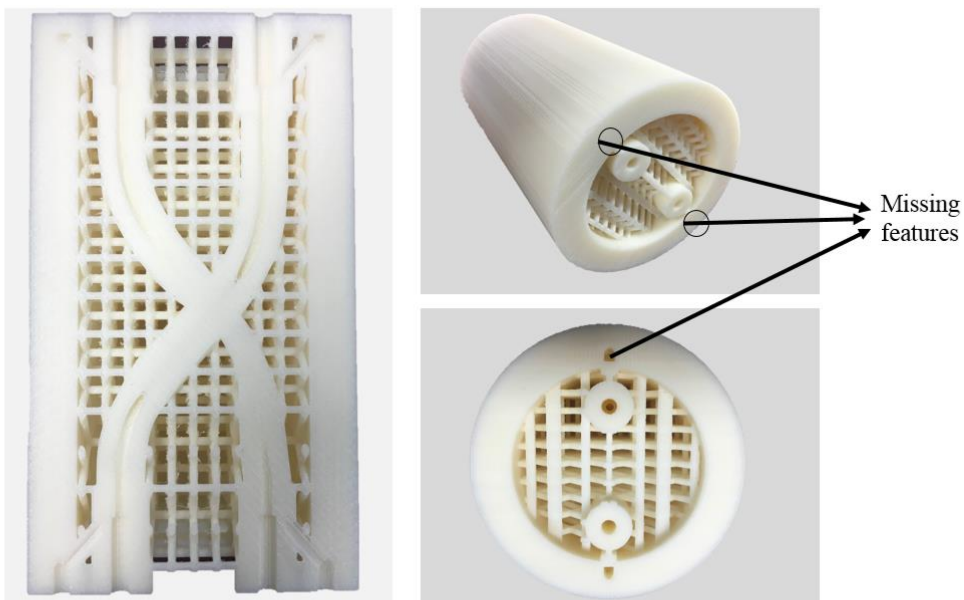


Figure 4-3: Shows the plastic prototype of the lattice structure. Visual inspection of the prototype helped in identifying missing features as highlighted in the figure.

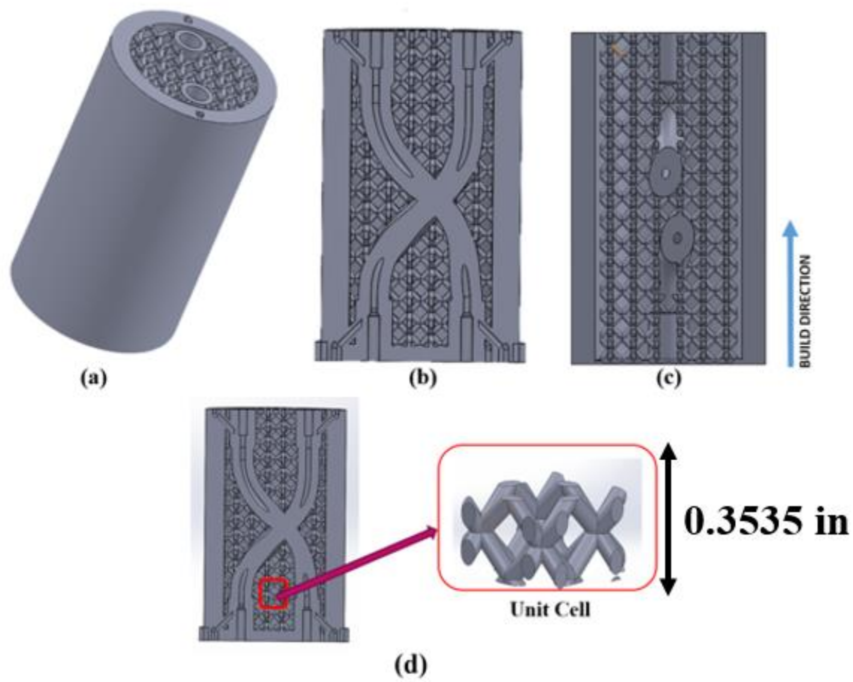


Figure 4-4: Final design of the lattice structure: (a) complete model with interface features; (b) cross-section showing the internal tubes; (c) cross-section showing the lattice structure around internal tubes; (d) unit cell used in the lattice structure

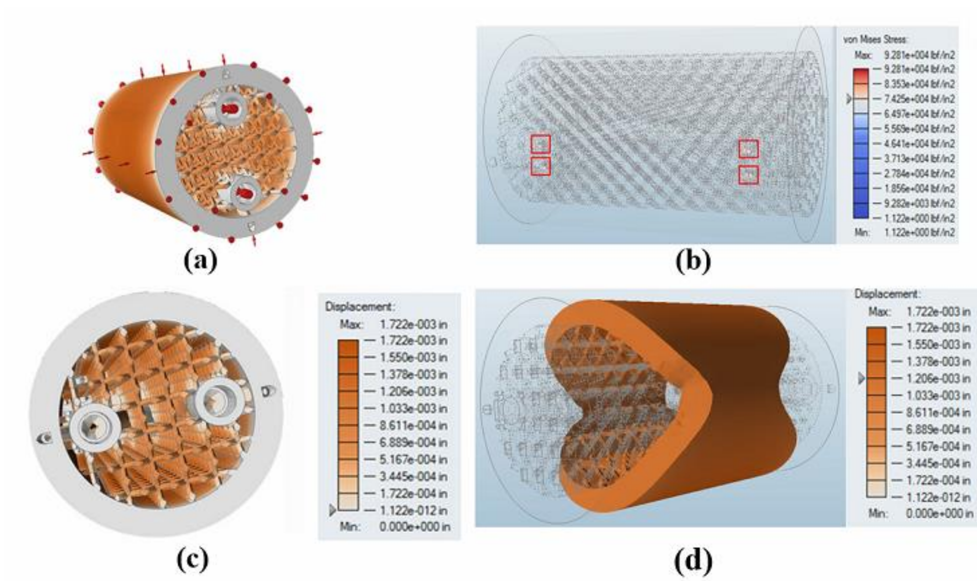


Figure 4-5: Finite element analysis of the lattice structure: (a) Boundary conditions showing pressure loads as well as displacement constraints; (b) von Mises stress map showing 4 critical regions with stresses higher than 74.25 ksi; (c) Deflection map showing deformation during pressure loading; (d) Displacements higher than 0.0012 in.

Once a final design with acceptable maximum stress and displacement results from FEA simulations is created, the design is analyzed for manufacturability. For example, few support requiring features are highlighted in Figure 4-6 (a), (c). These features are redesigned with modifications shown in Figure 4-6 (b), (d). This part is oriented vertically on the build platform for the DMLS processes. As the part is manufactured by layer-by-layer deposition of material, the part undergoes multiple heating and cooling cycles. It is important to have a proper heat transfer from the deposited layer to the substrate or the platform. Support structures usually conduct heat and prevent curling/warping due to heat accumulation in the deposited layer [26]. However, since the structure is self-supporting, there are no support structures to conduct the heat and most of the heat is conducted through the thick walls of the cylinder. Hence, these thick walls may be affected by thermal distortion resulting in delamination and subsequent build errors. To mitigate these effects, the bottom of the lattice structure is modified to create a flat surface to maximize the contact with the substrate. The final design shown in Figure 4-5 (a)-(c) has a thick cylindrical shell that is supposed to attach directly to the build platform. The sharp edges joining the cylindrical shell with the build plate may act as stress-risers and eventually cause delamination. To avoid such build issues, edges joining the part with the build plate are filleted. Functional mechanical components require strict dimensional tolerances; however, as-built parts from metal AM cannot meet the required dimensional accuracy. Therefore, machining allowances are added to the final design so that the dimensional accuracy and smooth surface finish can be achieved by machining during post-processing. Additionally, machining allowances are required to accommodate the shrinkage, distortion, surface defects, etc. in a metal AM part. Radius of outer cylinder is increased by 0.1in as an allowance for machining. A 0.078 in allowance for wire EDM cut is provided to help in separation of the part from the build plate. An allowance of 0.1 in is also provided in length for facing operations on the ends of the cylinder.

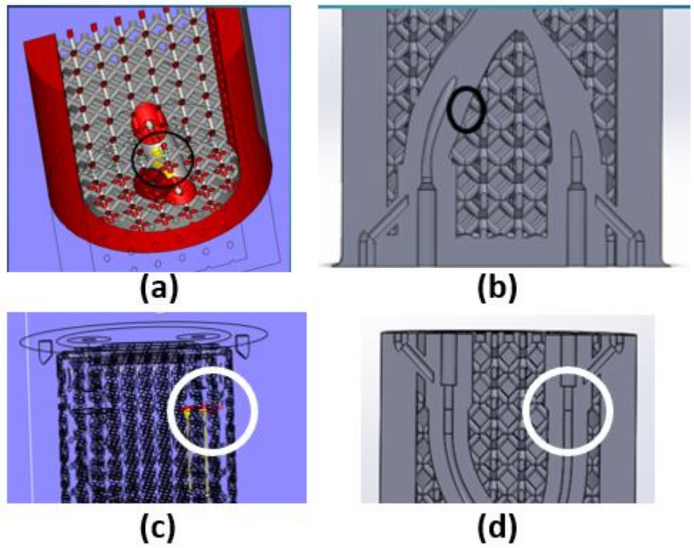


Figure 4-6: Shows few of the support requiring features identified during manufacturability analysis

4.5. Fabrication

The part is manufactured with EOS IN 718 material with material specifications listed in Table 4-1. The process parameters used in this build are present in Table 4-2. Two parts, one for pressure testing and the other for structural inspection, are successfully manufactured as shown in Figure 4-7. The struts were manufactured successfully with good surface finish and there are no obvious defects (see Figure 4-8.). The final weight of the part is 5.95 lbs; therefore, 42.4% reduction in weight is achieved. However, a ring of material (see highlight box in Figure 4-7) is observed around the part, which is a result of extra flash of layer during machine restart after a power glitch. The structural integrity at this region will also be investigated during inspection.

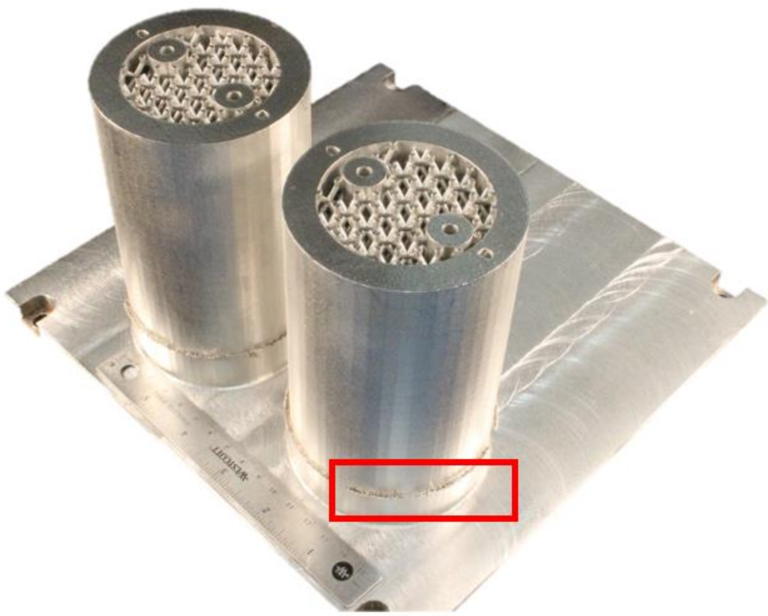


Figure 4-7: Photograph showing as-built parts using IN 718

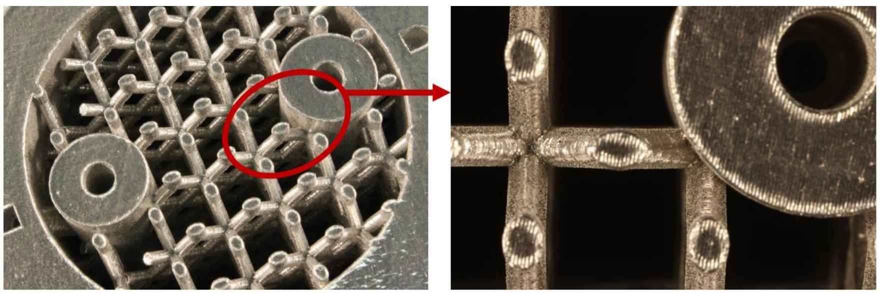


Figure 4-8: Photograph showing the details on the struts in the lattice structure

Table 4-2: Process parameters used to manufacture the final parts

Process parameter	Value
Laser Power	370 W
Laser scanning speed	51.18 in/s
Layer thickness	0.0015 in
Hatching distance	0.0043 in

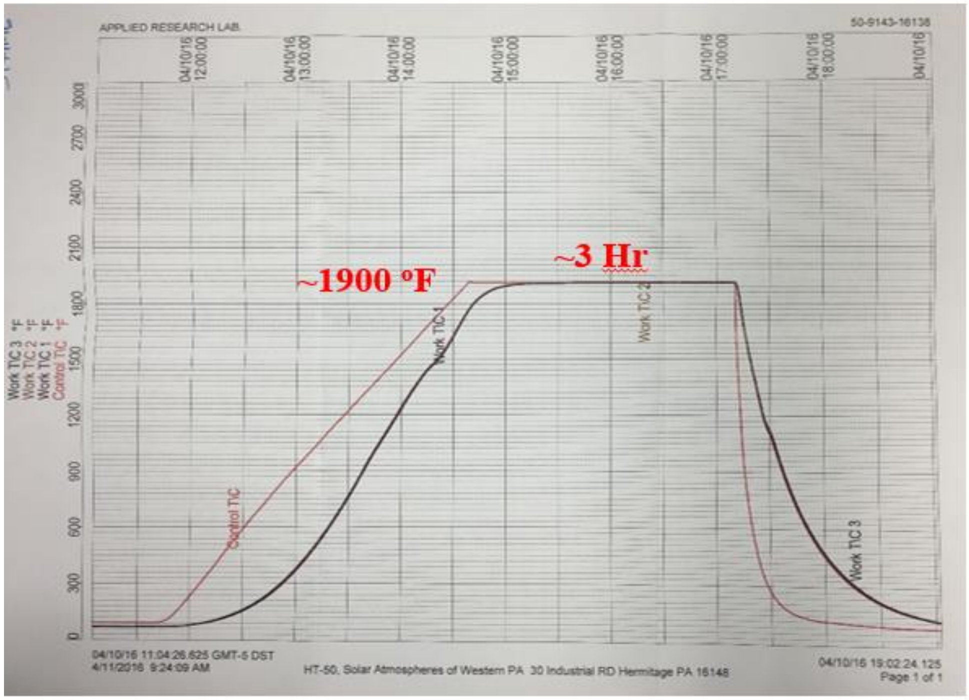
4.6. Post-processing

Due to the thermo-mechanical nature of the metal AM process, the manufactured part accumulates residual stresses during the build. Hence, it is important to perform stress- relief before separating the part from the base plate. In addition to stress-relief, heat treatment is also required to enhance the mechanical properties of the built part to meet the functional requirements. The part is heat treated by Solar Atmospheres, Pennsylvania, USA using the following heat treatment method (slightly modified from procedure in [80] to meet the functional requirement of the part).

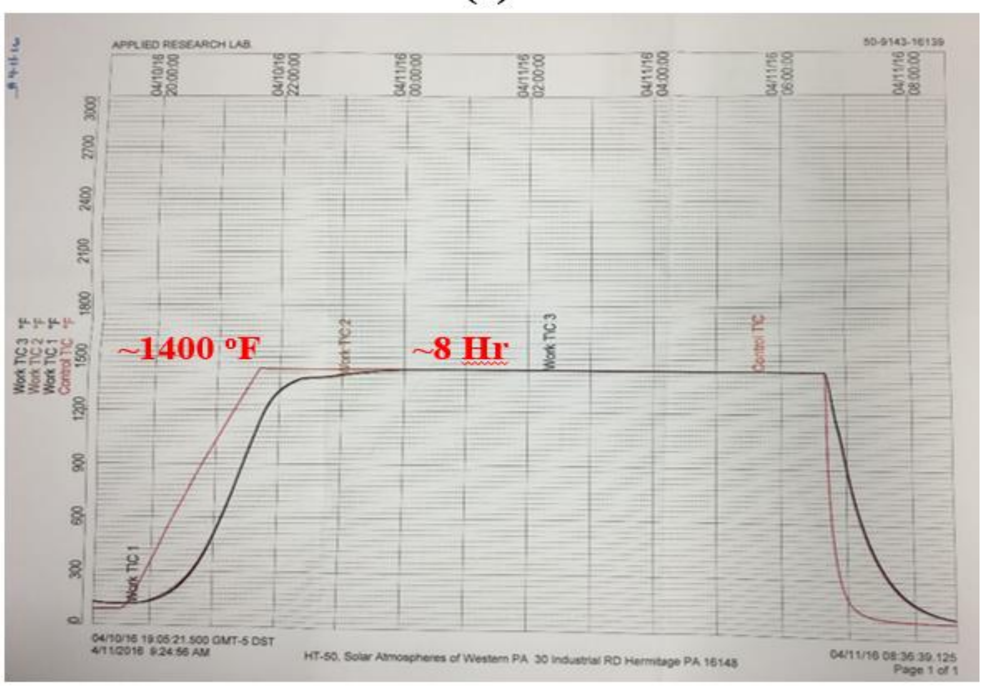
1) Solution annealing: at 1925+/-25F for 2 hours, water quench or air cool

2) Aging: at 1450F+/-25F for 7+/-1 hour, air cool

The next step in post-processing of this part include separation of the part from the build plate and machining to get the intended dimensions as per design.



(a)



(b)

Figure 4-9: Temperature profiles used for the actual heat treatment process: Solution annealing (a); aging (b)

4.7. Inspection and Testing of the Parts

For understanding the process and its effect on manufacturing of lattice structures, it is important to inspect the part from dimensional accuracy and structural integrity aspects. A Coordinate Measuring Machine (CMM) is used to measure the dimensional accuracy of the part. Metrology of the as-built part indicates that the fabricated part is undersized compared to the design dimensions (see Table 4-3 and Figure 4-10). Furthermore, to understand the effect of the heat treatment process on the additive manufactured part, dimensions are again measured after heat treatment and stress-relieving. The results clear show that the part shrunk during the heat treatment process. In addition, the flatness of build plate is affected during the heat treatment, resulting in warping of the build plate (see Table 4-3). The results also indicate that the alignment of the holes on the top surface is also affected in this process. Movement inside the lattice structure is also observed as a result of heat treatment. Separation of the stress-relieving and heat treatment procedures may reduce this distortion in the build plate.

Table 4-3: Results of dimensional analysis using CMM machine (accuracy 0.00004 in)

Dimensional Analysis (in inch)					
Measurement	Design	Build 1		Build 2	
		Pre-Heat Treatment	Post-Heat Treatment	Pre-Heat Treatment	Post-Heat Treatment
Build Height (H)	5.3500	5.3391	5.3335	5.3404	5.3317
Diameter (ϕ)	3.2000	3.1922	3.1920	3.1906	3.1887
Cylindricity	-	0.0053	0.0063	0.0068	0.0071
Perpendicularity	-	0.0020	0.0017	0.0027	0.0024
Flatness (Top)	-	0.0030	0.0023	0.0023	0.0027
Parallelism (Top)	-	0.0028	0.0040	0.0031	0.0055
Inner Circle (Right/C_1)	0.1900	0.1885	0.1895	0.1890	0.1894
Inner Circle (Left/C_2)	0.1900	0.1893	0.1896	0.1895	0.1888
Build Plate Flatness	-	-	0.0030	-	0.0073
Cylinder axes parallelism	-	-	0.0008	-	0.0020

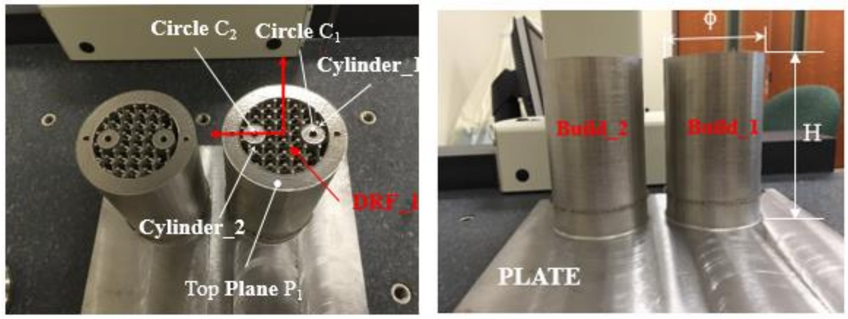


Figure 4-10: Illustration of the features measured as in Table 4-3

In the next step of inspection, the part will be CT scanned to check the integrity and porosity in the part. One part will be sectioned to access the lattice structure and for further investigation of the structural integrity of the individual struts. The other part will be machined to get the intended dimensions and will be pressure tested to verify the structural performance in real-world application.

4.8. Workflow

For CAD interpretation, each individual strut is a combination of surfaces; therefore, CAD modeling of lattice structures involves modeling a large number of surfaces. Many commercially-available CAD software packages lack the ability to handle large numbers of surfaces; therefore, they are unsuitable for designing lattice structure design. Meshing these lattice structures and FEA further intensifies the computational load on the software. In this work, different commercial software are explored to work with lattice structures, for example, SOLIDWORKS, RHINO (with GRASSHOPPER Plug-in), FORMZ, and SIMPLEWARE. Of all the software, only SIMPLEWARE allows designers to create internal lattice structures with different unit cells with different cell parameters and shell thicknesses. For creating components with engineering applications, a CAD model is required for further analysis using FEA as well as for manual redesign to meet the design requirements (machining allowances, internal tubes, interfacing features, dimensions etc.). However, the software failed to export the lattice structures as a CAD model due its large file size. From these experiences, a workflow (see Figure 4-11) to create lattice structure designs is developed. The workflow starts by creating a workable 3D model in SOLIDWORKS using the 2D drawings of the part. To determine the load paths as well as the scope for weight reduction, topology optimization of the design is performed using ALTAIR's OPTISTRUCT. The topology optimized designs (see Figure 4.2) give insight into where material is necessary in the design to efficiently resist the loading. This insight can be used to approximately define regions that require dense lattice structures as well as coarse lattice structures. This differential lattice density approach may further reduce the material requirement compared to using a lattice structure with uniform density. However, to avoid unnecessary complexity in this design, the lattice structure is designed with uniform density in this example.

As mentioned in Section 4.4, the important parameters in this design are the strut thickness, length of the strut (or effective cell size), and wall thickness of the cylinder. The 3D model from the SOLIDWORKS is simulated in FEA to calculate the mechanical stresses and deflection due to the loading shown in Figure 4-1. Based on the FEA results, the wall thickness of the cylinder and strut thickness are modified in the CAD model, and this process is repeated until an acceptable factor of safety is achieved. Then final design is analyzed for thermal deflections during metal AM using CUBES® (now an Autodesk product) software. The last phase in the workflow involves prototyping and actual manufacturing using the EOS system.

As explained in Section 4.4, the prototyping phase helped identify issues that went unnoticed during the design phase. Additionally, prototyping, even in plastic, helped in communicating such a complex network of struts with the manufacturing experts. The final design is then exported to MAGICS to create any required support structures and subsequent file preparation for metal AM build.

Figure 4-11: Illustration of software workflow from preparing 3D model of lattice structures to metal fabrication of final parts

4.9. Future Work

One part will be machined to the intended dimensions and will be pressure tested to validate the structural performance in a real-world application. The other part will be CT scanned to investigate the structural integrity and porosity in the part. Finally, the part will be sectioned to access the lattice structure and for further investigation of the structural integrity of the strut members.

Different materials may perform differently during the manufacturing of lattice structures; therefore, other materials with different properties from Inconel, like AlSi10Mg and Ti6Al4V, can be investigated in a similar way. Additionally, this case study only examines the manufacturability of two unit cells, but other self-supporting unit cells can also be examined.

Chapter 5

Leveraging AM Capabilities through Topology Optimization

In the earlier chapters, design challenges in leveraging AM capabilities at different complexities, by addition of new functionalities and by creating cellular structures, are discussed. In this chapter, the challenges in design and fabrication of lightweight design of the upright obtained by topology optimization will be investigated. The design workflow and fabrication process followed for this part are different and complex than those followed in earlier chapters. Additionally, weight of the part is not the sole decision making criterion for this design, but the final design is selected considering the manufacturing cost and amount of support material, along with weight of the part. This design process will be compared and contrasted with design process observed in Chapter 3 & 4 in Chapter 6. The following sections present the design requirement, topology optimization formulation, modifications on topology optimized designs, and design workflow.

5.1. Introduction

In this case work, topology optimization is applied to redesign an upright (see Figure 5-1). The upright, which transfers loads from the ground to the chassis, is an important component of the SAE Formula student racecar. To improve the performance and maintain low weight, new upright designs through topology optimization and AM are explored to efficiently utilize light-weight and strong materials.

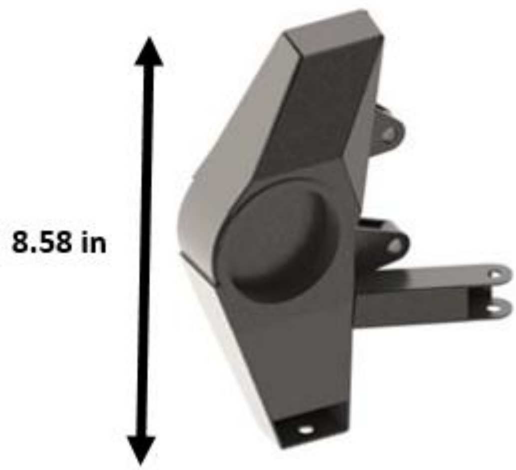


Figure 5-1: Box welded upright designed and used in SAE formula student racecar [18]

5.2. Initial Design & Problem Formulation

The first step in topology optimization is to identify the design and non-design regions in the design space. The design region is defined as the domain in the design layout in which the material density distribution needs to be optimized. Non-design region is the fixed or non-optimizable region in the design layout. Non-design region usually includes bolts, hinges, and regions that interact with neighboring parts in the assembly. In this case, assembly of upright along with other suspension components (e.g., tie rod, upper and lower A-arms, brake calipers) is shown in Figure 5-2. Maranan [18] formulated the initial topology optimization study for this upright. The optimization study was carried out using 3D COMPLIANCE DESIGN (also called 3D TopOpt) software [18,81]. This optimization software allows the user to define the design space (see Figure 5-3) of the problem in terms of non-design region (blue), void space (gray), loading (red), and supports (green). Table 5-1 shows the maximum loading cases for this optimization problem. Each of these loading cases pertains to different physical conditions that the suspension is subjected to during vehicle maneuvering (see Figure 5-4). A different variation of loading conditions on the upright is present in [82].

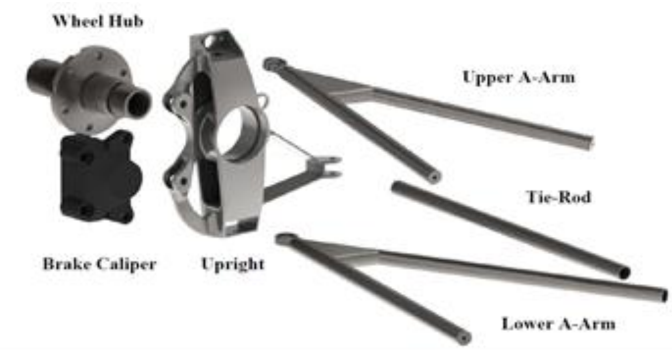


Figure 5-2: Upright (lightweight design) assembly with upper and lower a-arm, tie-rod and wheel hub [18]

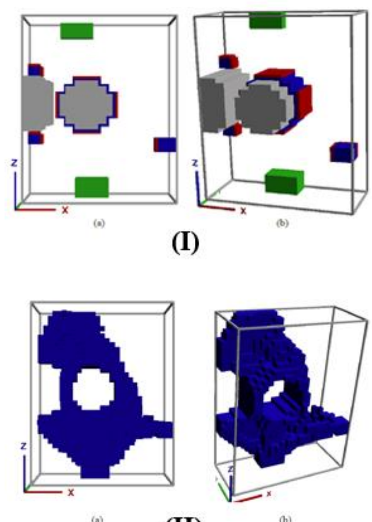


Figure 5-3: Design space setup in optimization problem (i); optimized design layout (ii) [18]

Table 5-1: Maximum allowable forces for each loading cases [18]

Inside Cornering	Outside Cornering
Upper Fore AA = -11.14 lbf Upper Aft AA = -31.36 lbf Pull Rod = 85.48 lbf Low Fore AA = 8.68 lbf Low Aft AA = 25.47 lbf Tie Rod Force = -11.79 lbf Bearing Lat Force = 132.2 lbf	Upper Fore AA = 29.39 lbf Upper Aft AA = 144.46 lbf Pull Rod = 430.3 lbf Low Fore AA = -389.81 lbf Low Aft AA = -589.57 lbf Tie Rod Force = 55.35 lbf Bearing Lat Force = -262.50 lbf
Forward Braking	**Rearward Braking**
Upper Fore AA = -547.32 lbf Upper Aft AA = 382.06 lbf Pull Rod = 485.23 lbf Low Fore AA = 1006.21 lbf Low Aft AA = -1457.35 lbf Tie Rod Force = 174.69 lbf Bearing Load = -448.6 lbf Brake Caliper Torque = 4082.54 lbf-in	Upper Fore AA = 86.27 lbf Upper Aft AA = -73.85 lbf Pull Rod = 80.47 lbf Low Fore AA = -227.68 lbf Low Aft AA = 175.54 lbf Tie Rod Force = -32.88 lbf Bearing Load = 77.80 lbf Brake Caliper Torque = -707.7 lbf-in

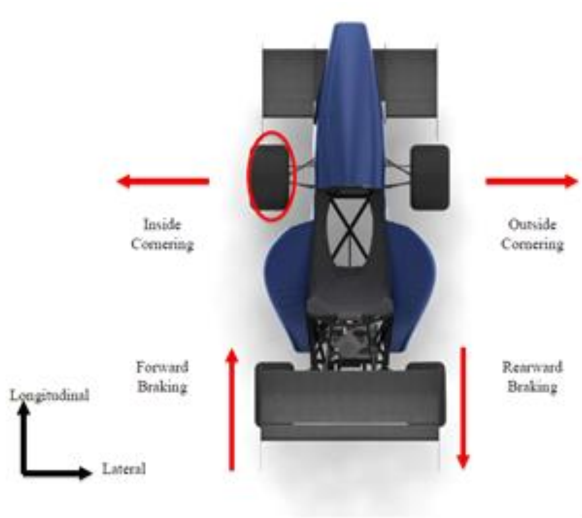


Figure 5-4: Terminology of load cases [18]

The optimized design layout shown in Figure 5-3 (II) was used as a reference to develop a solid model in SOLIDWORKS [17]. The initial optimized design is shown in Figure 5-5. The theoretical weight of the part is 1.62 lbs. The .STL file of the model is imported into MAGICS v19 [21] to generate supports for the EOS M280 DMLS machine that is used to manufacture it. The model is analyzed for two build orientations: (1) flat on the platform as shown in Figure 5-5a and (2) on the side as shown in Figure 5-5b. The build oriented flat on the platform (see Figure 5-7) requires support material equal to 202.4% of the material required for just the model. However, the amount of support material required for the build with part oriented flat on the side (see Figure 5-7) is 98% of the material required for just the model. That is, the part oriented flat on the platform requires 106.5% more material than what is required in side orientation.

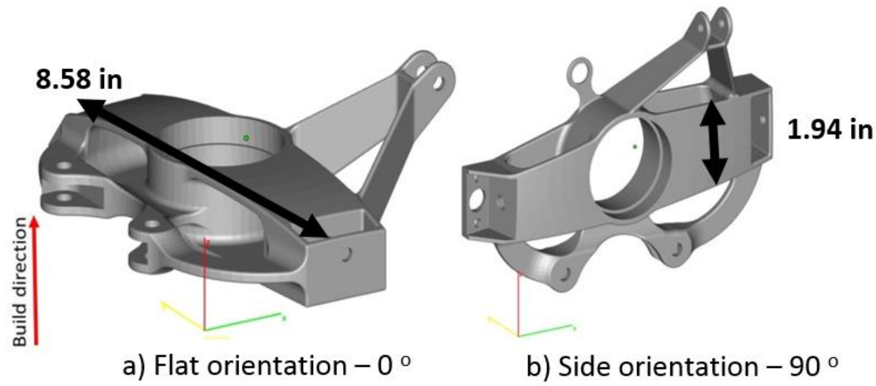


Figure 5-5: First optimized design (design 0) of the upright: (a) laying flat on the platform (b) orientation for ease of support removal

Figure 5-6 shows the support generation for the build with part lying flat on the platform. Figure 5-7 shows the support generation in the side build orientation. Support removal in the flat orientation is more difficult than in the side orientation as there are many supports generated between the top and bottom complex profiles in the flat orientation. The side orientation is used to fabricate the upright in Ti-6Al-4V using EOS M280 machine. The total weight of the actual component produced is 1.70 lbs, and the total amount of material used for supports is 4.80 lbs. The total amount of support material also includes the loose powder (0.8 lbs) trapped in the part between the supports; thus, it is more than the actual weight of the supports.

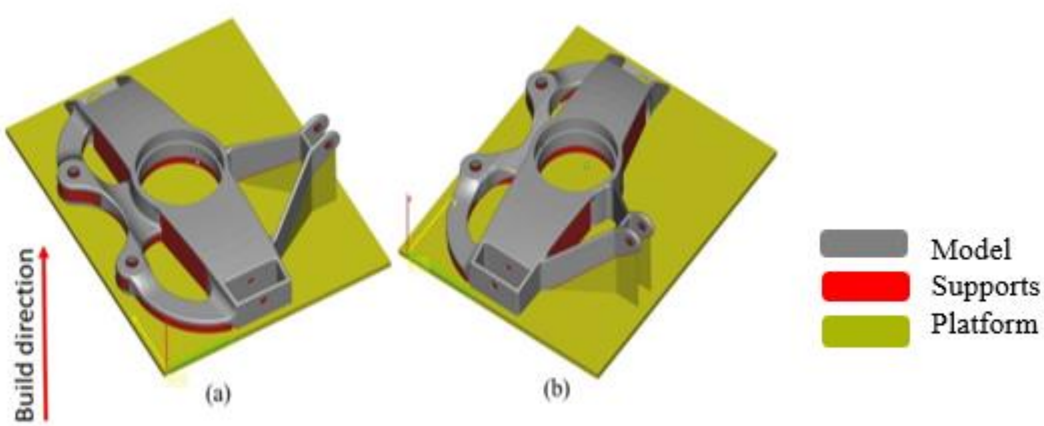


Figure 5-6: Shows the support generation if the part is oriented lying flat on the platform

A costing tool developed for additive manufacturing [23] is used to calculate the overall manufacturing costs of the build. As calculated, the overall manufacturing costs of the part in the flat and side orientations are $2015 and $2995, respectively. FEM simulations (see Figure 5-8) on the part are performed to ensure that the mechanical performance of the final part satisfies the loading conditions.

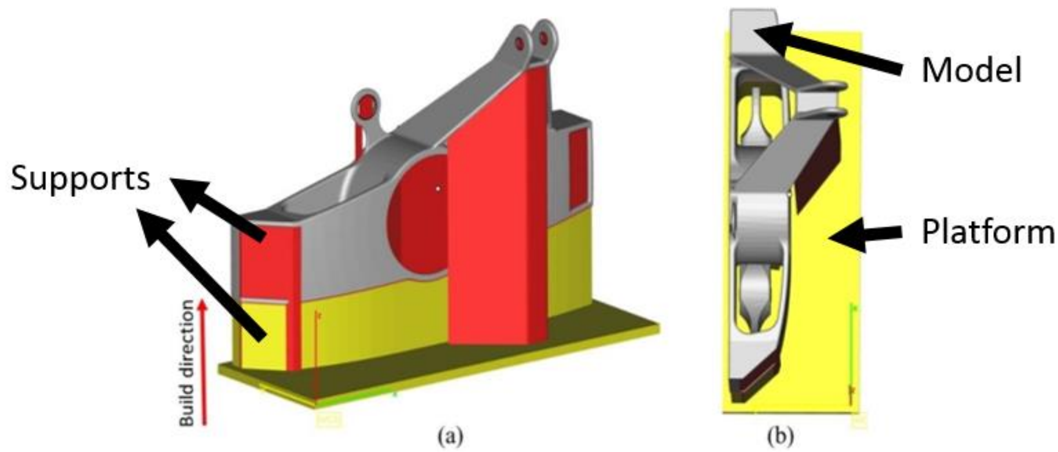


Figure 5-7: Shows the support generation if the part is oriented on its side

Properties used in these FEM simulations are presented in Table 5-2. Load cases for each of the simulation are presented in Table 5-1. The results show that the stresses developed in the forward brake loading case are very high compared to other load cases. Hence, for subsequent comparisons, only forward brake loading cases are presented. The yield strength of the heat-treated material is 145 ksi, and the maximum stress developed is estimated to be 65 ksi. This shows that the design satisfies the mechanical performance constraints, and there is scope for further weight reduction while ensuring an adequate factor of safety.

In order to further lightweight the design, using the design shown in Figure 5-5 as a reference, a new topology optimization problem is setup in OPTISTRUCT (see Figure 5-9). The loading cases and boundary conditions are the same as that of the optimization problem setup in 3D COMPLIANCE. OPTISTRUCT's optimization solver is widely used in industrial applications and rerunning the design with OPTISTRUCT helps to determine further scope for weight reduction, if any. Green shows the fixed or non-design space, and blue shows the design space in Figure 5-9. Since the optimization problem involves multiple loading cases, a weighted compliance approach is used to determine the optimized layout while considering four different loading cases.

Table 5-2: Summary of material properties of Ti-6Al-4V used in fabrication and modeling

Material Property	Value
Density	0.159 lb/in^3
Yield	145 ksi
Tensile	152 ksi
Young's modulus	116 GPa
Elongation at break	10%

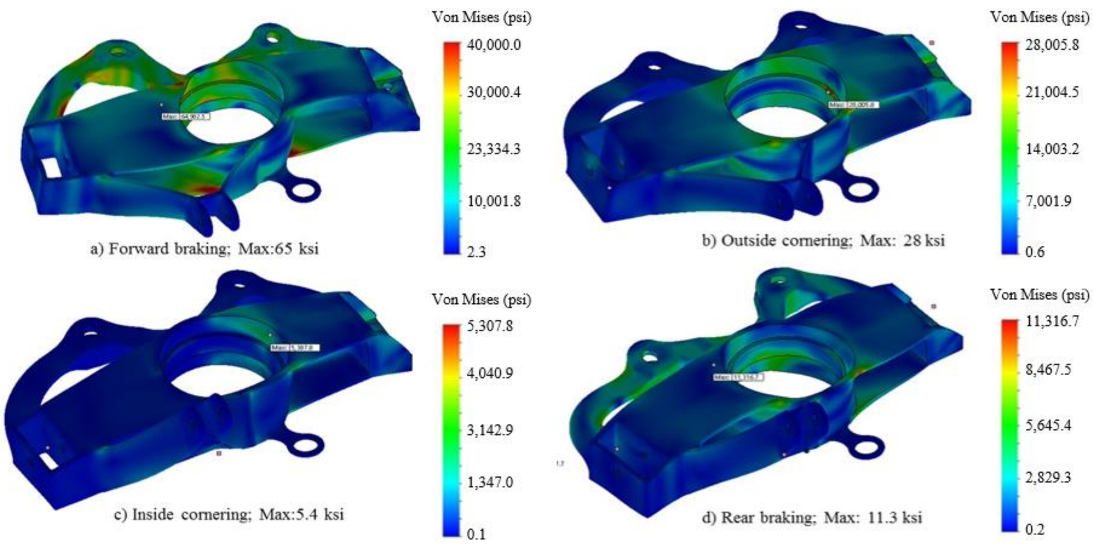


Figure 5-8: Results of FEM simulations for each of the loading cases for initial design

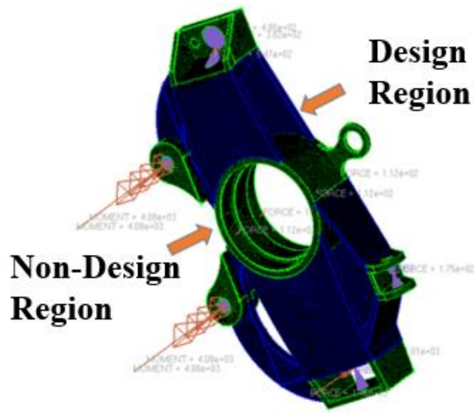


Figure 5-9: Design space setup for redesign

The objective function is defined as minimize compliance response subjected to 20% volume fraction as the optimization constraint. OPTISTRUCT solves this based on the Solid Isotropic Material with Penalization (SIMP) algorithm approach, a gradient-based optimization method; the details of the SIMP algorithm are presented in [83].

5.3. DfAM Guidelines and Redesigned Upright

As summarized in the previous section, data from the actual build shows that the exposure volume of the part is 10.68 in^3, and the exposure volume of the supports is 25.16 in^3. In addition, 5.03 in^3 of loose powder is trapped between the supports. As a result, only ~26% of the total material consumed is used in building the actual component. The remaining ~74% of the material is consumed in the form of support structures and loose powder. Furthermore, more than half of the build time is utilized to build the support structures. Thus, there is a need to reduce the support structures in order to reduce total material consumption and build time.

The upright is redesigned by applying the DfAM rules discussed in Section 2.2 to the topology optimized design layout. First, the unsupported surfaces that require support structures are identified. Taking 45° as the minimum build angle (see Table 2-1), surfaces requiring support structures are identified. These regions are modified such that the surface angles are increased above 45°, wherever possible. Second, additional features are designed at an angle more than 45° to support horizontal overhangs that otherwise require support structures. Third, sharp corners or intersecting curves of different surfaces are filleted to reduce stress concentration. The resulting model is checked for maximum stresses arising due to the forward brake loading case. The surface modifications and additional features resulted in an increase in the maximum stress. Therefore, the surfaces and additional features are manually redesigned by adding fillets, rounded corners, extra thickness, etc., to contain the stresses. These modifications reduce the need for support structures or in some regions, totally eliminate supports. The resulting design after DfAM modifications is shown in Figure 5-10. The new design is analyzed for manufacturability and support requirements (see Figure 5-10b). However, support structures could not be completely eliminated as fillets are required to avoid sharp corners and edges; therefore, resulting design still requires some support structures in the filleted regions.

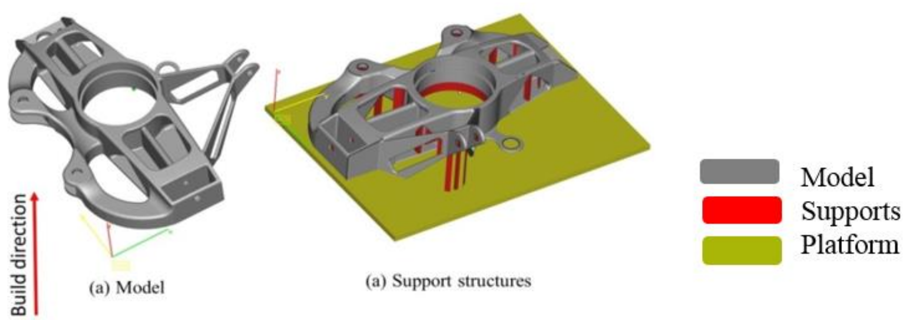


Figure 5-10: (A) Model of first redesigned upright (B) Generated supports

The support requirement has been considerably reduced compared to the initial design such that supports are only required for the fillets and non-design space. The model is analyzed using FEM simulation to determine the stresses due to the loading (see Table 5-1), and the results are presented in Figure 5-11. The overall manufacturing costs are estimated at $1495 using our manufacturing costing tool [23].

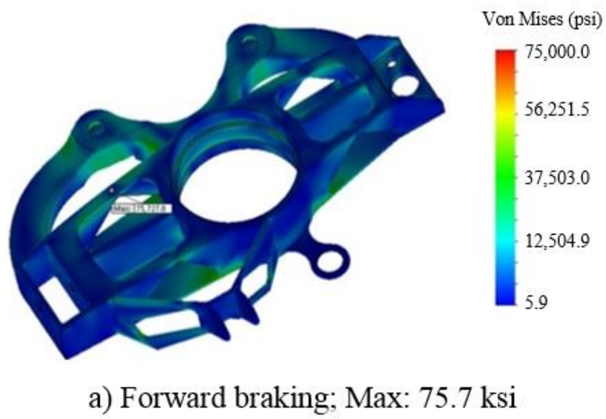


Figure 5-11: Estimated stresses of the first redesigned upright in forward loading case

Using the stress distribution in Figure 5-11 as a reference, the topology of the design is further modified to reduce the weight of the structure while not disturbing the surfaces modified with DfAM principles. The resulting design is shown in Figure 5-12. Supports for this second redesign are shown in Figure 5-13. Similar to the previous case, FEM simulation is performed to ensure that the design is safe in terms of strength (see Figure 5-14). This design requires 1.7 in^3 of support material, which is only 14.3% of the volume of the part. Fabrication cost is estimated to be $1448 using our costing tool [23].

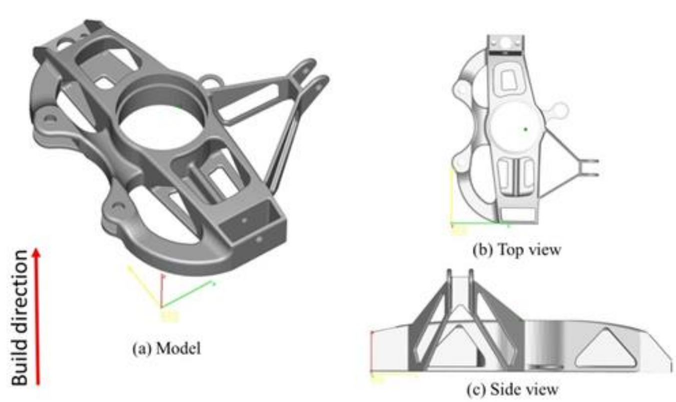


Figure 5-12: Second redesigned upright modified to reduce the weight

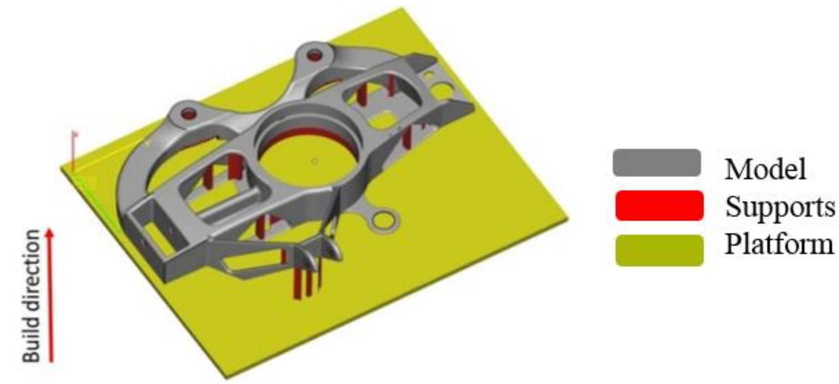


Figure 5-13: Supports generated in MAGICS for second redesigned upright

a) Forward braking; Max: 95.6 ksi

Figure 5-14: Maximum stress estimated during the forward braking in second redesigned upright

5.4. Comparison of Results

Part volumes, support structures, manufacturing costs, build times, and complexity of support removal for all three upright designs (see Figure 5-15) are summarized in Table 5-3. The volume of the support structures is calculated as a percentage of the volume of the model for comparison across the designs of different weights. The amount of support material required (see Table 5-3) in the side orientation is twice that of the horizontal orientation (see Figure 5-5b). Also, the cost of manufacturing is higher in case of the side orientation than in the horizontal (placed flat) orientation. However, for the actual fabrication, side orientation is preferred over horizontal orientation due to the ease of removing support structures in former case.

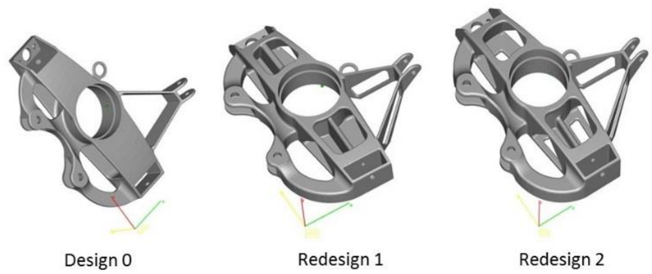


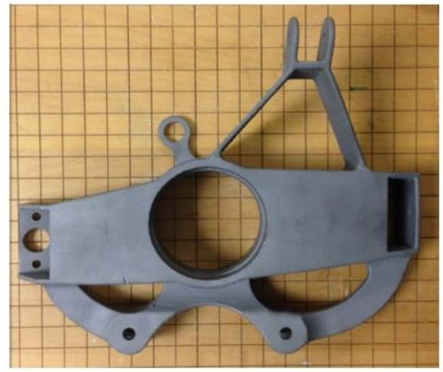
Figure 5-15: Summary of whole design process: shows design 0, redesign 1 and redesign 2

Figure 5-16 shows the actual fabricated part (Design 0) before removing the support structures and after removing the support structures. Using experience and suggestions in [84], support removal methods are classified in terms of complexity as presented in Table 5-4. Wire-EDM would require costly setup and higher operational costs. Support removal by hand, for example, with a chisel is easier but labor-intensive. Band saw and grinding based methods are categorized as medium complexity. Support removal in case of horizontal orientation would require wire-EDM, and it is particularly difficult to remove in Design 0. In the case of side orientation, support structures are built on the outside of the model, and such supports can be easily removed. Thus, it is very important to plan the support removal methods before actual fabrication of designs using AM.

Table 5-3: Summary of the designs with volumes, supports, build time, costs and complexity

Design	Volume of the model (in^3)	Volume of supports (in^3)	Volume of support as % volume of the model	Build time (Hrs)	Cost ($)	Complexity of support removal
Design 0 (Horizontal orientation)	10.2	10.0	97.6	14	2015	High
Design 0 (Side orientation)	10.2	20.7	202.4	28	2995	Med
Redesign 1	12.8	1.7	13.2	11	1495	Low
Redesign 2	11.8	1.7	14.3	11	1448	Low

a) Before removing supports



a) After removing supports

Figure 5-16: Fabricated design 0: before removing support structures (a) and after removing support structures (b) [18]

Table 5-4: Support removing methods classified into difficult levels based on experience and [84]

Manufacturing operations	Difficulty (Time/Labor/Cost)
Wire-EDM	High
Band Saw	Mid
Hand Removal	Easy
Grinding	Mid

Design for additive manufacturing (DfAM) principles mentioned earlier are implemented on initial design (Design 0) to obtain Redesign 1. By comparing Design 0 and Redesign 1, the weight of the part has increased, but the amount of support material required has been significantly reduced. The DMLS fabrication would now require extra material equal to 13.2 % of the volume of the model for building support structures instead of double the amount. Since sharp corners are to be avoided to prevent stress concentrations, filleting of the edges and corners is essential. These fillets require firm structures to support them during fabrication, and thus, support structures cannot be eliminated completely for this design. As seen from Figure 5-10, support structures are mainly supporting the filleted and corner regions, but the overall cost of manufacturing this redesigned upright has been reduced significantly compared to that of Design 0. Thus with a slight addition of weight, the manufacturing build time, material consumption, and ultimately manufacturing costs have significantly reduced.

Stress build-ups in Figure 5-11 hint at scope for further material reduction. Thus, Redesign 2 is created by modifying the topology of Redesign 1 while not disturbing the surfaces modified by DfAM rules in the previous design iteration. Thus, the volume of support material required in Redesign 2 is the same for Redesign 1, but the actual weight of the component has decreased from 2.04 lbs to 1.87 lbs.

Since manufacturing time is primarily dependent on the number of layers, the material removal is not affected much by reducing supports. Redesign 2 would still require 11 hrs to build, but the manufacturing cost has decreased due to savings in material consumption. The maximum stress estimated during the forward braking has increased in comparison to Redesign 1, but it is still significantly lower than the mechanical strength of the material. Since the fillets cannot be avoided to prevent the stress concentrations, support structures are required to support these fillets. Thus, a tradeoff exists between the part weight, stresses developed in the part, and the required support structures. This iterative design method can be applied in general to the other design problems as well, where topology optimization and additive manufacturing have to be used jointly. A Pareto chart (see Figure 5-17) can help to make the design decision based on the volume of the model, volume of the supports, and the mechanical performance. To the right end of the chart are the heavier designs with less amount of support structures, and to the left end of the chart are the lighter designs with substantial support structures. An ideal design would be the one located closest to the origin with good mechanical performance (small sized bubbles). However, the designer has to decide this tradeoff based on the intended function of the part.

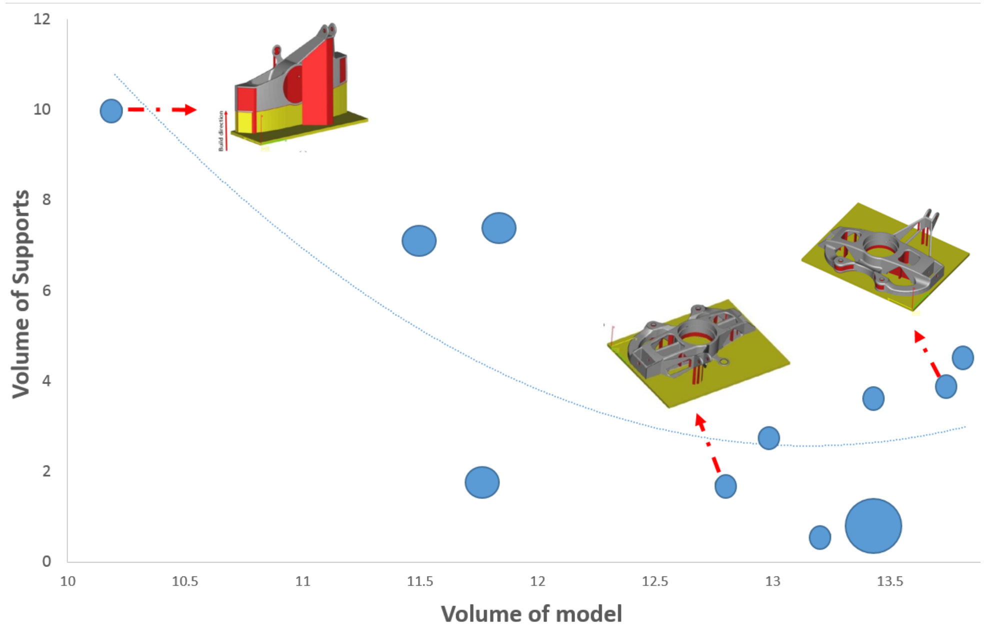


Figure 5-17: Pareto-front showing the interdependency among volume of the model, volume of the supports and von Mises stress. The size of the bubble refers to the von Mises stresses during simulation of the forward loading case

5.5. Workflow

The goal of the redesign process in this chapter is to leverage the advanced AM capability of producing optimized metal components. The design stages necessary to realize these design requirements such as topology optimization, costing, trade-offs between performance and weight, etc., are absent in the previous two cases. The workflow followed in redesigning for AM with topology optimization is illustrated in Figure 5-17. The process starts with understanding the design of the existing component and identifying a plan for redesign by answering questions such as what tools can be used for topology optimization, how to select designs considering weight, total cost, powder stock, etc.

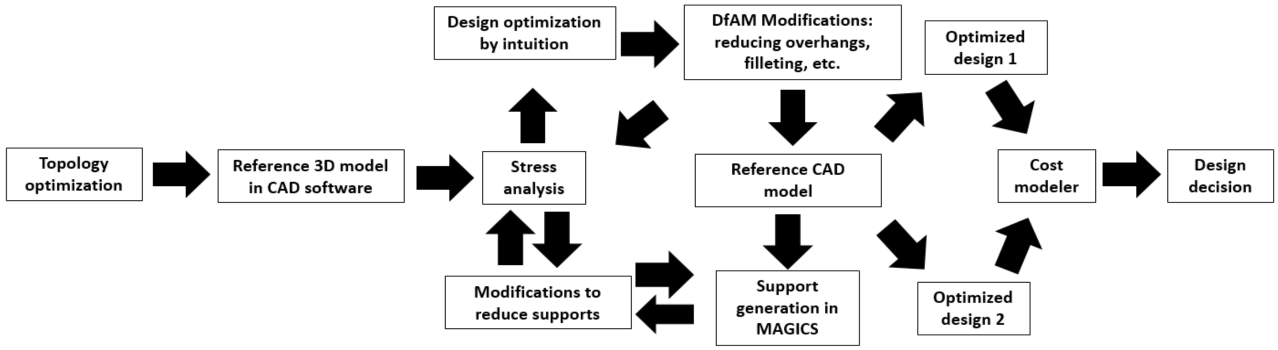


Figure 5-18: Design workflow for redesigning for AM with topology optimization

Topology optimized designs are difficult to modify in a CAD environment. For instance, filleting and modifying surfaces of the resulting design directly exported from optimization software is an arduous task. Therefore, topology optimized design layouts are used as a reference to manually modify the designs through a series of iterations. Stress analysis showed the regions of stress concertation and regions with scope for material removal. In each iteration, all of the sharp edges are filleted, and corners are rounded to avoid stress concentrations. The amount of support structures required for each of the designs is calculated using MAGICS software. Since reducing support structures is also one of the goals of the redesign process, modifications are made to reduce overhanging features. The addition of new features may affect the stresses in the design; therefore, the modified designs are again analyzed for stress distribution. This iterative process resulted in two optimized designs, one with more weight and a higher factor of safety, another with less weight and a lower factor of safety. Design decisions cannot ignore the cost of manufacturing; therefore, a cost modeler [23] is used to calculate the overall cost of manufacturing. The design workflow ends with a design decision-making step that requires stakeholders to select a final design based on cost, mechanical performance, weight of the part, and difficult level of support removal.

5.6. Future work

Future work entails formalizing an approach that integrates topology optimization, FEM, support design, and DfAM rules into a more coherent framework. We also plan to fabricate and test Redesign 2 using the EOS M280 machine and collect actual fabrication data similar to Design 0 to get a more accurate measure of the support requirement and trapped powder. Also, geometry affects the residual stresses and deflections caused by frequent heating and cooling cycles in a laser-based additive manufacturing process. Hence, for functional parts like this, it is important to know the performance of the design during the AM process. Thermo-mechanical simulations will be carried out to estimate the deflections in the part and this data will be used to redesign, if required.

Chapter 6

Comparison of Design Workflow among Three AM Adoption Methods

Many design problems are multidisciplinary and involve modeling and analysis of various scenarios to simulate the performance of the design in its intended function. There are different commercial tools available to individually simulate various engineering problems. The designer has to select these tools appropriately and integrate the use of these tools into the design process. Using multiple engineering tools and communicating the design information from one platform to other in an iterative fashion is a very complex and time consuming process. Designing for metal AM requires use of multiple different engineering tools, for instance, a CAD modeling software to create 3D designs, a support generation software to create support structures for the already created 3D design, a thermo-mechanical analysis software to determine the level of thermal distortions occurring during the metal AM process, etc. There is no single software currently available to perform all the design functions required for metal AM. In addition, these software tools cannot easily communicate with other posing a challenge of manual interpretation of the results at different stages and communicating them down stream. Thus, without an established workflow and streamed processes, it is not easy to implement the complex workflow comprising the various engineering tools necessary in designing for metal AM.

Furthermore, as presented earlier, there are different levels of AM adoption methods to leverage metal AM capabilities in industries. The problem requirements and design complexities are different in each of these levels. Some of these levels may require a different set of engineering tools and a higher number of design iterations that are not required in other design problems. As a result, the workflow suitable in one level of redesign may be different from the workflow used in other level of redesign. To understand some of these differences, the design process followed in the redesigning of three previously presented industry relevant components is discussed in this chapter.

6.1. Comparison of Design Workflow

The details of the design workflow for each of three parts analyzed in this thesis are compared and contrasted to identify the differences in the number steps and tools required to achieve the redesign process. Additionally, the different software used in each case are identified to compare the need of engineering tools in each of the levels of AM utilization. The use of different workflows and engineering design and analysis tools can differently affect the improvement in performance compared to the baseline components. Therefore, the change in a design or the ‘delta’ in design among the three components is also discussed in this chapter. Furthermore, some of the gaps observed while implementing the redesign process and potential strategies of tackling these problems are also discussed. A summary of this comparison is given in Table 6-1, and each aspect is discussed in the following sections.

Table 6-1: Comparison of design process for different levels of design for AM

Design aspect \ Level		Level 2 design for AM: New functionalities	Level 2/level 3 design for AM: Cellular structures	Level 3 design for AM: Topology optimization
Basis for design concept		Manual design of flow channels based on intuition	Design is populated by a self-supporting unit cell	Manual redesign based on topology optimized designs
Workflow		No mechanical performance simulations	No topology optimization	No prototyping
3D modeling		Oil channels are designed; modified by taking feedback from MAGICS	Cellular structures are created in SOIDWORKS; Lattice structure is simulated in INSPIRE; Unit cell size is modified	Unsupported features are modified to be self-supporting; features requiring support structures in MAGICS are modified to be self-supporting; stress-concentration regions identified through FEA are modified to remove stress-risers
Why FEA		No FEA component	Cell size is based on the deflection results from FEA	Manual material removal based on intuition and FEA results of forward loading case
TopOpt		No TopOpt component	Not possible with lattice structures due to large number of surfaces	Initially topology optimized, and manual removal of material at later stages
Tools	1. 3D modeling	SOLIDWORKS;	PTC CREO SOLIDWORKS, SIMPLEWARE	SOLIDWORKS
	2. Topology optimization	-	-	3D COMPLIANCE, OPTISTRUCT
	3. FEA	-	INSPIRE	SOLIDWORKS
	4. Thermo-mechanical	-	CUBES®	CUBES®
	5. Support generation	CUBES® MAGICS	MAGICS	MAGICS
	6. Prototype	-	INSIGHT	-
Change in design		Oil flow channels	1. Cellular structure replacing bulky material 2. Lightweight	1. Lightweight 2. DfAM optimized 3. Less support Structures
Gaps in the current design tools		Thermal-deflection analysis software does not communicate with 3D modeler	Lattice generation and exporting a workable CAD format file is very difficult	Topology optimization framework does not include additive manufacturing based constraints
Recommendations		Thermal- deflection analysis tools within in the 3D modelling environment	Need for lattice generation and simulation capabilities in single software platform	Topology optimization software with AM constraints, for instance, overhangs, surface orientation, etc.

First, the design conceptualization for each of the three cases is quite different. The oil cooling channels are based on intuition, and they are designed such that the channel is equidistant throughout its length from the surface of the piston bowl. This constrains the freedom to decide the placement of these new features. In case of cellular structures, the unit cell is conceptualized first and the whole design space is populated with these unit cells. Therefore, a significant portion of the total design conceptualization effort is spent in formulating the unit cell. In the SAE upright case, the design is based on the results from topology optimization.

Each of these design conceptualization methods depends on the designer's skills. Creating lattice structures takes less manual effort but demands high computational costs. Interpreting topology optimization software and creating a 3D model in CAD software requires significant human effort. In the piston redesign case, structural performance was not an important concern; therefore, there is no need for multiple iterations in the workflow to repeatedly check for stress-risers after each DfAM modification. In lattice structure design, FEA results determined the thickness of the struts and the outer cylinder. Any modification to the thickness of struts required the 3D modeler to rebuild the entire network of struts, taking long computation time. Topology optimization of lattice structures is desired, but it is very difficult with the current optimization software that is available. In the SAE upright case, the design workflow illustrates continuous back and forth iterations between DfAM modifications and corrections to eliminate stress-risers. Therefore, the three workflows differ in the requirement for FEA. As a result, the engineering tools required in the three cases are also different (see Table 6-1). Level 3 (SAE upright) case obviously requires more engineering design and analysis tools compared to that of Level 2. The number of engineering tools needed, affects the CAD data management as different software outputs different file types. The SAE upright case requires significant effort to organize different file types such as output from topology optimization, FEA, 3D modeling, support generation, etc., at each iteration level.

The improvements in design compared to the current baseline components are also listed in Table 6-1. The lattice structure design had many improvements compared to the other components. The topology of the structure is completely changed, in addition to the reduction in the weight of the part. The new design is porous compared to the original design; as a result, the new design can significantly affect the heat transfer between the atmosphere and internal channels.

These workflows are developed based on the design process in three specific example cases; therefore, the workflows need to be validated by applying them to other components of similar complexities before generalizing. The sequence of the elements in the design workflow can be applied in general, but the specifics of each element can be case dependent. For example, the iteration loop between the design modifications to reduce supports and modifications to eliminate stress risers may be valid in general to other components, but the details of these modifications can be different from component to component. Additionally, some components may require new engineering design and analysis tools that can improve the exiting workflow. Validation with other components can help identify these 'generalizable' and 'case specific' parts of the workflows. Furthermore, identifying the existing gaps in the current workflow can help in developing a generalized workflow in the future. The following section explains the gaps in the current workflow along with few recommendations based on the insights from three cases.

6.2. Gaps and Recommendations

One of the common gaps observed in the design work flow in the three cases is the absence of support generation tools within the 3D modeling software. Availability of such tools can decrease the need for multiple iterations of file conversions and transferring the design from one software to another. Additionally, manufacturability analysis tools can also be integrated into the CAD software. For instance, SOLIDWORKS allows creation of automated and customized modules through its application programming interface (API). Designers can easily check the regions requiring support structures as well as control the way supports are generated without having to use another software. Such integrated modules reduces the part turnaround time between manufacturability analysis and design, allowing for multiple iterations on the design in much shorter time. As a result, overall computation time is decreased, and CAD data is easily organized and managed in the design database.

Topology optimization software currently lacks AM-specific manufacturing constraints within the optimization framework. Topology optimization software already contains some of the traditional manufacturing constraints such as draw direction, symmetry, member size, etc., but metal AM related constraints such as build angles, overhang lengths, support structure placement, etc. are yet to be implemented. Therefore, topology software outputs optimized designs without considering the AM considerations and such designs demand substantial manual intervention. Additionally, topology optimization software does not communicate well with the other 3D modeling software. It is currently difficult to convert a topology optimized design into a workable 3D model to manually edit the geometry to make it more suitable for metal AM. Furthermore, .STL files generated directly from topology optimized designs contain substantial errors and are difficult to be sliced and used for generation of g-code. As seen from the SAE upright case, topology optimization was just used as a reference to create the 3D model as the files directly exported from topology optimization software are not easy to edit. Soon, we may be able to manufacture multi-material components using laser based powder bed fusion systems, which will enable us to manufacture components with varying material densities. Manufacturability of metal components with multiple densities opens up new scope for further optimizing designs than what is currently possible. However, the current method of representing CAD models using triangulated meshes cannot store the required information such as materials, density, etc. Therefore, new ways of representing optimized designs with more detailed information can remedy this.

CAD models are converted into triangulated mesh (.STL format) for interpreting the designs in AM based support generation and pre-processing software such as MAGICS, Slic3r, Insight, etc. However, conversion of the original CAD file into a .STL format approximates the surfaces with triangles. Fine meshes are capable of capturing the details of the small features, but at the cost of file size. Large file sizes are not suitable in the downstream of the AM workflow. Additionally, fine meshing may not always capture the details on all of the features in a design. For instance, a fine meshing used in the lattice structure case captured the small details such as lattice struts, but the outer surface is visibly triangulated, and printed that way. Triangulated surfaces are clearly visible on the fabricated parts (see Figure 4-7). A different file format such as a voxel-based representation may remedy this as the voxels used in approximating the CAD format can be changed in unit size and orientation to minimize approximation errors. A voxel-based representation can also be used to perform manufacturability analysis on the designs and more details on this are given in following section.

6.3. Scope for Manufacturability Analysis Tools

AM is not always economical or the best process of manufacturing a part, and often traditional manufacturing of a part can be less expensive and fast [75–77]. Yet, many students and hobbyists have turned to AM as the preferred option for making parts, due to the simplicity in setting up the process and realizing their parts. If the part is designed with lack of foresight for AM machine capabilities, then the build may not be successful. As previously discussed, there are commercial manufacturability analysis tools to available to detect and identify defective or problem causing features. Many of these software are expensive and cannot be easily used by everyone designing for metal AM. Additionally, these are individual software platforms and require the ability to swiftly change from one software to the other. Therefore, it is difficult for everyone to have all the required software resources. Integrating manufacturability analysis tools into the modeling software can be helpful for anyone to easily analyze the manufacturability issues and make corrections to the design.

6.3.1. Voxel-Based Representation

First step towards developing a rapid manufacturability analysis tool for additive manufacturing involves identifying the design features that are difficult to be manufactured using AM. In this work, a MATLAB based manufacturability analysis module that can detect critical features is developed. First, CAD model in .STL format is imported into the MATLAB environment (see Figure 6-1) and converted into a voxel based representation (see Figure 6-2). Voxels or 3D pixels are [85] volume elements that constitute a notional 3D space in computed based design. CAD model in .STL format can be discretized into finite number of voxels based on the required resolution. In MATLAB, 3D array is constructed to completely fit in the 3D model in .STL format. All the elements of the arrays which are completely inside the model and on the boundary are assigned a value of ‘1’. Rest of the elements of the 3D array are assigned to ‘0’. The value ‘1’ represents the active elements and all of the active elements combined constitute the 3D model. Voxels can store much more information than just ‘0’s and ‘1’s, for example, voxels can be assigned two different numbers, each of which denote a different material. Thus, voxel based representation is also useful for multi-material 3D printing.

A STL file stores CAD data in the form of facet normals and vertices of the triangulated CAD model. 3D printing is advancing towards printing multi-materials, functional materials, and foam materials that can have different density distributions in a single body. However, .STL representation is not capable of storing and communicating this information along with the geometric data. Although modified versions of STL files are introduced to suit AM needs, the auxiliary data can only be stored for the triangulated surfaces, not the interior of a part. In addition, use of .STL for AM purposes introduces errors in two stages, one during triangulation and another when slicing into layers. CAD modelers visualizes the .STL data by surface smoothening; therefore, surface roughness or irregularities due to triangulation and slicing are not easily seen by the designer, whereas in a voxel-based approach, the surface irregularities can be easily observed, and a designer can use this feedback to improve the model or fine-tune the voxel resolution. In a voxel-based approach, the slicing algorithm does not need to deal with triangles in random planes, thus improving the slicing accuracy. High resolution .STL files are computationally difficult to be modified using Boolean operations on two or parts; however, voxels are easy to be used in Boolean operations. Lattice structures are difficult to be handled by current CAD modelers due to the large number of Boolean operations needed to use using lattice unit cells to construct a lattice structure. This increases the computation complexity, and limits the length scales on the lattice structures as well as their potential use in real-world due to difficulties in designing. In research conducted on computational time and number of struts that can be generated on a personal computer, the maximum number of struts using ACIS kernel on 512 MB RAM is 2400. Thus, voxel based approaches are being developed to easily design these lattice structures by reducing the computational load during Boolean operations [86,87].

Second, voxelized CAD data is easy to scan to detect critical features. To demonstrate, the MATLAB module is able to detect the thin walls and small gaps based on the minimum feature specifications for the AM process. The user can detect the thin walls and undersize holes either separately or in combined mode (see Figure 6-3 and Figure 6-4). The user can also change the minimum feature specifications within the module.

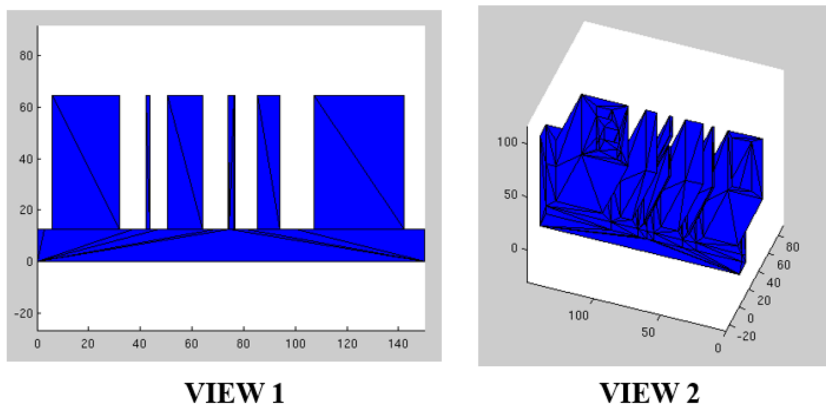


Figure 6-1: .STL visualization in MATLAB environment

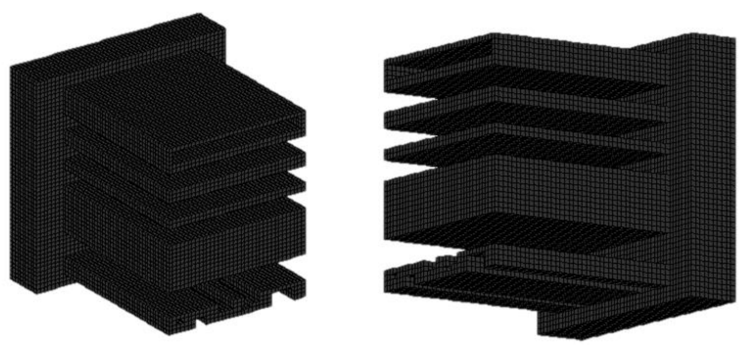


Figure 6-2: Voxel based representation of CAD model

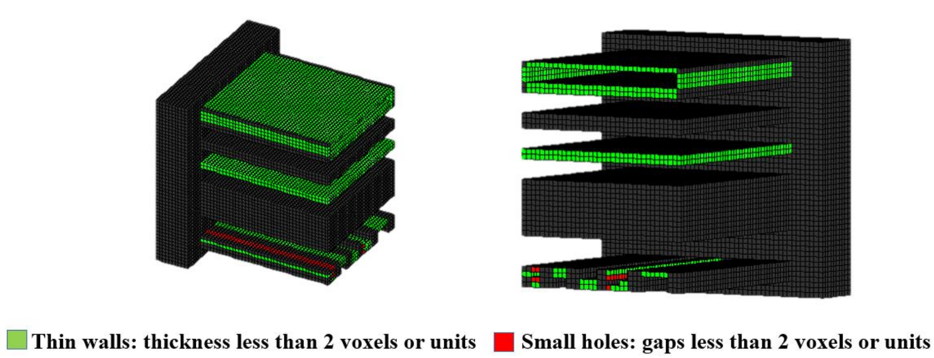


Figure 6-3: Shows identified thin walls and under size holes in the 3D model represented by voxels

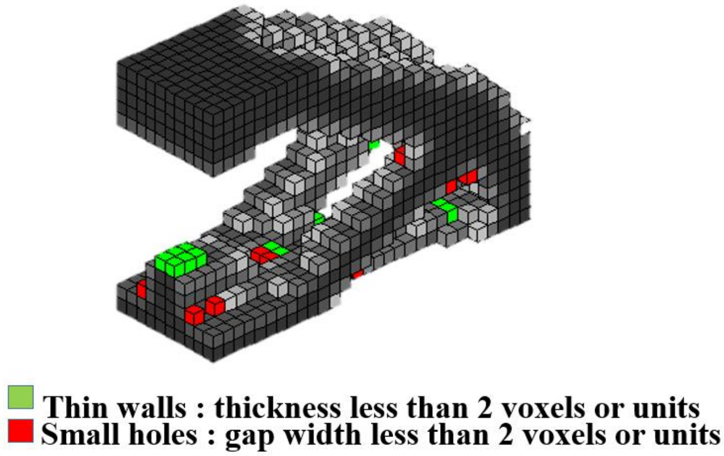


Figure 6-4: Shows identified thin walls and undersize holes in the 3D model of a topology optimized cantilever bear

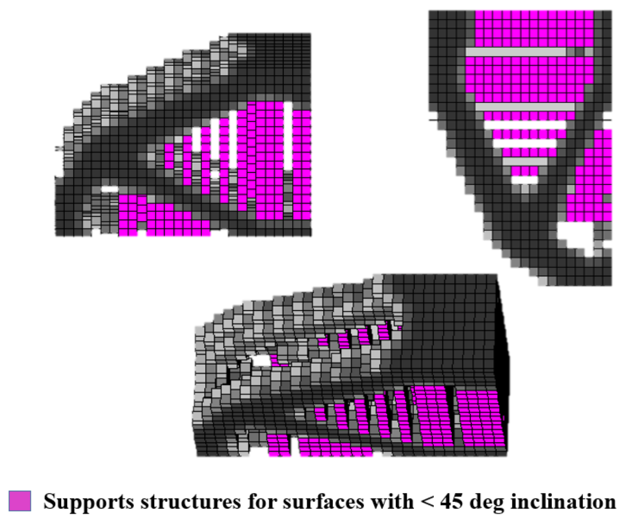


Figure 6-5: Supports structures (pink) generated, for a topology optimized cantilever design (gray), using MATLAB module

Third, support structures can be generated after identifying the unsupported surfaces in the model (see Figure 6-5). Metal AM requires support structures for surfaces oriented at angles less than 45^{o} with the horizontal (see Table 2-1). The overall workflow of this manufacturability analysis tool can be summarized as in Figure 6-6.

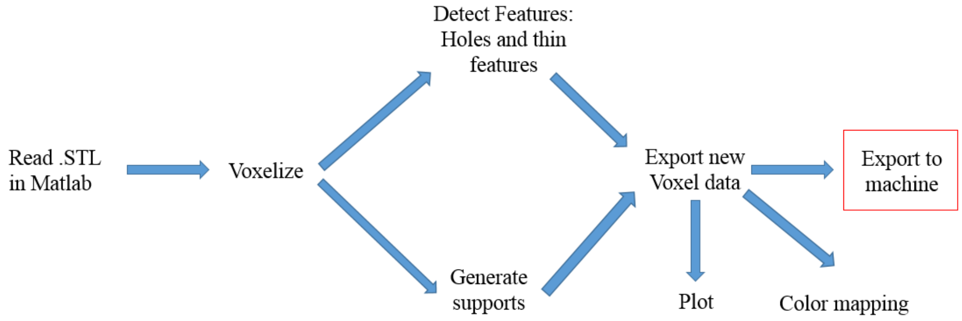


Figure 6-6: Shows overall workflow for voxel based representation developed in MATLAB module

6.4. Future Work

This voxel-based representation method can also be extended to improve topology optimization frameworks for AM [88]. A workflow concept of incorporating AM constraints within topology optimized framework is shown in Figure 6-7. Furthermore, a voxel-based approach can also be used to design and optimize support structures in AM [89]. Additionally, a voxel-based representation is useful in improving additive manufacture of lattice structures [90].

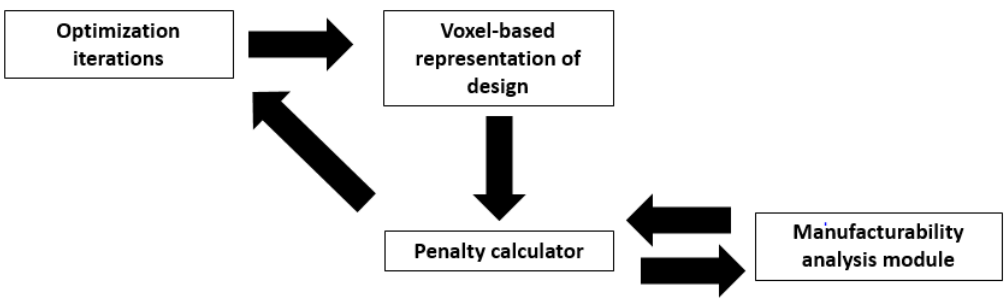


Figure 6-7: Conceptual workflow to incorporate AM constraints within topology optimization framework

Chapter 7

Closing Remark & Future Work

7.1 Summary of the Thesis

This thesis focused on investigating the design process for leveraging metal AM capabilities at different levels of design complexities. AM offers unprecedented design freedom and enables new design opportunities, but it comes with new design challenges. AM is an emerging technology that is capable of changing the way parts are produced and designed. Metal parts with complex designs are difficult to be manufactured by any traditional means; however, AM can be a potential solution to manufacture these parts. For instance, Figure 1-4 from NAVAIR's case study is an example of multi-component test equipment with 17 individual parts that are consolidated into a simpler assembly as shown in Figure 1-5. The original assembly was too complex and bulky to be portable, but part consolidation of this assembly reduced the number of individual parts as well as made the test equipment portable and lightweight. However, redesigning for AM is not straightforward and involves multiple manual design iterations to implement DfAM principles to make the part suitable for AM. Moreover, the strategies to implement DfAM principles are not generalized and may vary from part to part, process to process, and material to material.

These part-specific requirements may require modifications in the existing design workflow, and a single workflow may not be suitable for all the design cases. In this thesis, to understand some of these differences, three industry relevant components are redesigned for additive manufacturing. These three parts can be categorized in different levels of complexities as per Renishaw's staircase model [19]. In each case, the design conceptualization, workflow, design tools, DfAM principles, and resulting product performance are compared and contrasted against the current baseline component. The design conceptualization for each of the three cases is different. Significant effort in design conceptualization is spent on sketching the curves to follow the surface of the piston bowl in piston design case, designing the unit cell in lattice structure design case, and interpreting the topology optimized design in a 3D model. The workflow in the SAE upright case has challenging interdependencies between FEA and DfAM modifications.

7.2 Contributions

From these three cases, the obvious gap in the workflow is the need for multiple file conversions and strict CAD data management at each design iteration. For example, integrating manufacturability analysis tools into a 3D modeling software can enable easy DfAM modifications. Many software allow modules to be added using programming interface. For instance, SOLIDWORKS allows creation of automated and customized modules through its application programming interface (API). The MATLAB-based manufacturability analysis tool discussed in this thesis can be used to code the custom modules for software such as SOLIDWORKS. Additional recommendations are made for improving the design tools, and ultimately for improving the design workflow to reduce the computational time, improve the information flow, to swiftly change across the software platforms, etc.

7.3 Limitations and Future Work

The current design process is more suitable for laser-based powder bed fusion system and is not tested for other types of metal AM. This is a limitation on the versatile use of the current study across different metal AM systems. The workflow and the design process followed for all the three cases is not verified for repeatability. Therefore, repeating the design processes for components with similar complexities can identify additional hidden gaps, if any. Moreover, the current study does not consider the discussion on how the laser parameters are selected for building components with different levels of complexities.

The voxel-based representation discussed in this thesis may also form a new development platform to incorporate AM constraints into a topology optimization framework. The critical region causing build failure in piston design will identified to improve the design in next iteration. The lattice structure parts (see Chapter 4) will be separated from the build plate and subsequently pressure tested to evaluate the mechanical performance. The two final upright designs (see Chapter 5) can be further compared after actual fabrication for actual material consumption, manufacturing time, manufacturing defects, and easiness of removing supports.

Appendix

MATLAB code for Voxel-Based Representation

```
MATLAB Code for Feature Detection:
% following code is the main program used to detect the thin features
and small gaps in the CAD model
grid = xPhys;

[elx,ely,elz] = size(xPhys); % extracting the grid size of the voxels

gridmix(1:elx,1:ely,1:elz) = 0;

gridhole = feature_hole(grid); % function to identify small gaps

gridthin = feature_thin(grid); % function to identify thin walls

count =0;
for i = 1:elx
    for j = 1:ely
        for k = 1:elz
            gridmix(i,j,k) = grid(i,j,k);
            if gridhole(i,j,k) == 3
                gridmix(i,j,k) = 3;
                count = count+1;
            end
            if gridthin(i,j,k) == 4
                if gridhole(i,j,k) == 3
                    gridmix(i,j,k) = 3;
                else
                gridmix(i,j,k) = 4;
                count = count+1
                end
            end

            end
        end
end

% following functions are called in the above code

function gridhole = feature_hole(gridX)
[elx,ely,elz] = size(gridX);
gridhole(1:elx,1:ely,1:elz)=0;
for k = 1:elz
    for j = 1:ely
        for i = 1:elx
```

```
            gridhole(i,j,k) = gridX(i,j,k);
        end
    end
end
%Detection of hole features

for q = 1:elz
    for p = 1:ely
        for j = 1:elx
            if gridX(j,p,q) < 0.3
 % Finding hole feature in X-direction
                if j>1 && j<elx-2
                 if gridX(j+1,p,q)<0.3 && gridX(j+2,p,q)<0.3
                 else if gridX(j-1,p,q) >= 0.3
                         gridhole(j-1,p,q) = 3;     %hole identifier

                     if gridX(j+1,p,q) >=0.3
                         gridhole(j+1,p,q) = 3;
                     else gridhole(j+2,p,q) = 3;
                     end
                     end
                 end
                end
              if j == elx-1
                if gridX(j+1,p,q) >= 0.3 && gridX(j-1,p,q) >= 0.3
                    gridhole(j+1,p,q) = 3;
                    gridhole(j-1,p,q) = 3;
                end

            end
 % Finding hole feature in y-direction
             if p>1 && p<ely-2
                 if gridX(j,p+1,q)<0.3 && gridX(j,p+2,q)<0.3
                 else if gridX(j,p-1,q) >= 0.3
                         gridhole(j,p-1,q) = 3;     %hole identifier

                     if gridX(j,p+1,q) >=0.3
                         gridhole(j,p+1,q) = 3;
                     else gridhole(j,p+1,q) = 3;
                     end
                     end
                 end
                end

            if p == ely-1
                if gridX(j,p+1,q) >=0.3 && gridX(j,p-1,q) >=0.3
                    gridhole(j,p+1,q) = 3;
                    gridhole(j,p-1,q) = 3;
                end
            end
  % Finding hole feature in z-direction
             if q>1 && q<elz - 2
                 if gridX(j,p,q+1)<0.3 && gridX(j,p,q+1)<0.3
                 else if gridX(j,p,q-1) >= 0.3
                         gridhole(j,p,q-1) = 3;     %hole identifier
```

```
                        if gridX(j,p,q+1) >=0.3
                            gridhole(j,p,q+1) = 3;
                        else gridhole(j,p,q+1) = 3;
                        end
                        end
                    end
                   end

            if q == elz-1
                if gridX(j,p,q+1) >=0.3 && gridX(j,p,q-1) >=0.3
                    gridhole(j,p,q+1) = 3;
                    gridhole(j,p,q-1) = 3;
                end
            end
            end
        end
    end
end
end

% *********************************************************************
% following functions is called in the main program

function gridthin = feature_thin(gridX)
[elx,ely,elz] = size(gridX);
gridthin(1:elx,1:ely,1:elz)=0;
for k = 1:elz
    for j = 1:ely
        for i = 1:elx
            gridthin(i,j,k) = gridX(i,j,k);
        end
    end
end
countinstance = 0;
%Detection of thin features

for q = 1:elz
    for p = 1:ely
        for j = 1:elx
            if gridX(j,p,q) >=0.3

 % Finding thin feature in X-direction
                if j>1 && j<elx-2
                 if gridX(j+1,p,q) >= 0.3 && gridX(j+2,p,q) >= 0.3
                 else
                     if gridX(j-1,p,q) < 0.3
                         countinstance = [j;p;q] ;
                         gridthin(j,p,q) = 4 ;     %thin wall
identifier
                     if gridX(j+1,p,q) >= 0.3
                         gridthin(j+1,p,q) = 4;
                     end
                     end
                 end
```

```
                end
              if j == elx-1
                if gridX(j+1,p,q) < 0.3 && gridX(j-1,p,q) <0.3
                    gridthin(j,p,q) = 4;
                end
              end
 % Finding thin feature in y-direction
              if p>1 && p<ely-2
                 if gridX(j,p+1,q) >= 0.3 && gridX(j,p+2,q) >= 0.3
                 else
                     if gridX(j,p-1,q) < 0.3

                         gridthin(j,p,q) = 4;     %thin wall identifier

                     if gridX(j,p+1,q) >= 0.3
                         gridthin(j,p+1,q) = 4;
                     end
                     end
                 end
             end
              if p == ely-1
                if gridX(j,p+1,q) < 0.3 && gridX(j,p-1,q) <0.3
                    gridthin(j,p,q) = 4;
                end
              end
% Finding thin feature in z-direction
              if q > 1 && q < elz-2
                 if gridX(j,p,q+1) >= 0.3 && gridX(j,p,q+2) >= 0.3
                 else
                     if gridX(j,p,q-1) < 0.3

                         gridthin(j,p,q) = 4;     %thin wall identifier

                     if gridX(j,p,q+1) >= 0.3
                         gridthin(j,p,q+1) = 4;
                     end
                     end
                 end
              end
              if q == elz-1
                if gridX(j,p,q+1) < 0.3 && gridX(j,p,q-1) <0.3
                    gridthin(j,p,q) = 4;
                end
              end

%end of thin feature detection
        end
    end
    end
end
assignin('base','countinstance',countinstance);
end
```

```
%*********************************************************************

MATLAB Code for generating supports:
Main program:
Input: xPhys

for k = 1:10
    for j = 1:20
        for i = 1:30
            tempX(i,j,k) = xPhys(j,i,k);
        end
    end
end

for k = 1:10
    count = 0;
        for j = 1:20
            count = 1 + count;
        for i = 1:30
            gridX(i,k,21-count) = tempX(i,j,k);
        end

    end

end
supportscal = supports(gridX);
gensupport(1:30,1:10,1:20) = 0;
for k = 1:20
    for j = 1:10
        for i = 1:30

            if supportscal(i,j,k) == 2
                gensupport(i,j,k) = 2;
            else gensupport(i,j,k) = gridX(i,j,k);
            end
         xPhyssup(j,i,k) = gensupport(i,j,k);
        end
    end
end

%*********************************************************************
%following function is called in the main program


function supports = supports(gridX)
[elx, ely, elz] = size(gridX);
  penalty(1:elx, 1:ely, 1:elz) = 0;
  supports(1:elx,1:ely,1:elz) = 0;
    for k = 1:elz
        for j = 1:ely
            for i = 1:elx

                 if (gridX(i,j,k)<= 0.3)
                    if k < elz
```

```
                        if gridX(i,j,k+1) > 0.3
                            if i > 1 && i < elx
                                if gridX(i-1,j,k) <=0.3 &&
gridX(i+1,j,k) <=0.3

                                                if j > 1 && j < ely
                                                    if gridX(i,j-1,k) <=0.3 &&
gridX(i,j+1,k) <=0.3
                                                        if gridX(i+1,j-1,k)
<=0.3 && gridX(i+1,j+1,k) <=0.3
                                                            if gridX(i-1,j-
1,k) <=0.3 && gridX(i-1,j+1,k) <=0.3
                                                                temp =
penalty(i,j,k);
                                                                 penalty(i,j,k)
= temp + 1;
                                                                    for m =
1:k
                                                                        if
gridX(i,j,m)<0.3
supports(i,j,m) = 2;  %support identifier
                                                                        else
supports(i,j,m) = gridX(i,j,m);
                                                                        end
                                                                    end

                                                            end
                                                        end
                                                    end
                                                end
                                                if j == 1
                                                    if gridX(i,j+1,k) <=0.3
                                                          temp =
penalty(i,j,k);
                                                          penalty(i,j,k) = temp
+ 1;
                                                        for m = 1:k
                                                           if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
                                                                        else
supports(i,j,m) = gridX(i,j,m);
                                                                        end
                                                        end

                                                    end
                                                end
                                               if j == ely
                                                   if gridX(i,j-1,k) <=0.3
                                                       temp = penalty(i,j,k);
                                                       penalty(i,j,k) = temp +
1;
                                                        for m = 1:k
                                                           if gridX(i,j,m)<0.3
```

```
supports(i,j,m) = 2;  %support identifier
                                                                        else
supports(i,j,m) = gridX(i,j,m);
                                                                        end
                                                    end

                                                end
                                            end

                                    end

                                end

                                    if i == 1
                                        if gridX(i+1,j,k) <=0.3

                                            if j > 1 && j < ely
                                                if gridX(i,j-1,k) <=0.3 &&
gridX(i,j+1,k) <=0.3

                                                temp = penalty(i,j,k);
                                                penalty(i,j,k) = temp + 1;
                                                    for m = 1:k
                                                     if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
                                                                        else
supports(i,j,m) = gridX(i,j,m);
                                                                        end
                                                      end

                                                end
                                            end
                                            if j == 1
                                                if gridX(i,j+1,k) <=0.3
                                                    temp = penalty(i,j,k);
                                                     penalty(i,j,k) = temp
+ 1;
                                                    for m = 1:k
                                                      if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
                                                                        else
supports(i,j,m) = gridX(i,j,m);
                                                                        end
                                                    end
                                                end
                                            end
                                           if j == ely
                                               if gridX(i,j-1,k) <=0.3
                                                   temp = penalty(i,j,k);
                                                   penalty(i,j,k) = temp +
1;
                                                    for m = 1:k
```

```
                                                        if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
                                                                    else

supports(i,j,m) = gridX(i,j,m);
                                                                    end
                                                      end
                                                  end
                                              end
                                            end
                                       end
                                       if i == elx
                                           if gridX(i-1,j,k) <=0.3

                                               if j > 1 && j < ely
                                                    if gridX(i,j-1,k) <=0.3 &&
gridX(i,j+1,k) <=0.3
                                                    temp = penalty(i,j,k);
                                                    penalty(i,j,k) = temp + 1;
                                                        for m = 1:k
                                                         if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
                                                                    else

supports(i,j,m) = gridX(i,j,m);
                                                                    end
                                                         end

                                                    end
                                               end
                                               if j == 1
                                                   if gridX(i,j+1,k) <=0.3
                                                       temp = penalty(i,j,k);
                                                        penalty(i,j,k) = temp
+ 1;
                                                       for m = 1:k
                                                         if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
                                                                    else

supports(i,j,m) = gridX(i,j,m);
                                                                    end
                                                      end
                                                  end
                                              end
                                              if j == ely
                                                  if gridX(i,j-1,k) <=0.3
                                                      temp = penalty(i,j,k);
                                                      penalty(i,j,k) = temp +
1;
                                                       for m = 1:k
                                                         if gridX(i,j,m)<0.3

supports(i,j,m) = 2;  %support identifier
```

```
                                                                  else
supports(i,j,m) = gridX(i,j,m);
                                                                  end
                                                  end
                                             end
                                         end
                                       end
                                  end
                              end
                              end

                          end
                      end
                   end
              end

end

%**********************************************************************
%following functions from math central are used to convert the .STL
format into voxel format, and to display CAD model in voxel based
representation
```

1. PATCH_3Darray
2. Display_model

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