SAVING WEIGHT WITH METALLIC LATTICE STRUCTURES: DESIGN CHALLENGES WITH A REAL-WORLD EXAMPLE

S. N. R. Kantareddy[1], B. M. Roh[2], T. W. Simpson[1, 2, 3],
S. Joshi[2, 3], C. Dickman[3], E. A. Lehtihet[2]
[1]Department of Mechanical & Nuclear Engineering
[2]Department of Industrial and Manufacturing Engineering
[3]Center for Innovative Material Processing (CIMP-3D)
The Pennsylvania State University, University Park, PA 16802

Abstract

Lattice structures are structurally efficient yet complex designs that enable high stiffness and reduce weight. While lattice structures are traditionally difficult to manufacture in metal with conventional fabrication processes, AM is a viable solution to manufacture such complex geometries to achieve lightweight designs. However, there is relatively little information available in the literature about designing large-scale lattice structures, particularly concerning computer-aided design tools, structural analysis, and post-processing for functional metallic components. In this study, we investigate and discuss these aspects in the context of a real-world problem for an oil and gas application. The lattice structure is designed and fabricated with IN 718 powder using an EOS M280 laser-based powder bed fusion system. A weight reduction of 42.4% is achieved while obtaining the desired mechanical performance. Results and challenges, particularly with the design workflow, are discussed along with future research directions.

1. Introduction

Lattice structures are open cellular structures with a continuous network of truss-like members (slender beams) [1]. These trusses 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 [2]-[4]. These open cellular structures have large surface area exposed to the external media; therefore, they are also efficient for improving the heat transfer from a structure [5]. Lattice structures are also useful as deployable structures that can be stored initially in compact configurations and later deployed [6]. Furthermore, the cross-section of the trusses can be designed to be hollow, circular, square or any desired shape to achieve different strengths suitable for specific applications.

Although lattice structures offer much potential to serve as structural members, their use has been limited due to the challenges in manufacturing such structures, particularly in the case of metal lattice structures. Since these structures are networks of slender beams, the final components often have a complex topology, which are difficult or impossible to fabricate using conventional subtractive manufacturing methods such as machining. Investment casting, drawing, constructed trusses and assembly methods have been explored to manufacture these metal lattice structures of different shapes [7], [8].

While drawing is feasible on sheet-like structures, it is difficult to draw networks of thin truss members to fabricate lattice structures. Assembly methods are susceptible to de-bonding and delamination; thus, they are not promising for structural applications. In constructed truss approaches, metal sheets with 2D ordered hexagonal holes are deformed to create a tetrahedral truss structure [8] such as a tetrahedral Alumninum lattice [9]. Although this process is affordable, it is feasible only for structures patterned in a planar fashion; moreover, the perforation of sheets leads to significant material waste.

Investment casting with sacrificial polymeric patterns can be used to manufacture metallic lattice structures [8]. 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 the intended lattice structure. Unlike previously discussed fabrication 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 [10], a Ti-6Al-4V lattice block [11], and Cu/Be 3D Kagome [12] structures. However, low density structures with thin members are difficult to manufacture due to the high probability of casting defects. Since the molten metal has to flow through complex channels in the lattice patterns, the material must be highly fluidic; therefore, the process is feasible to only certain alloys such as Al/Si, Cu/Be, Ti-6Al-4V, and IN 718 [13].

Although investment casting has been used to demonstrate fabrication of metallic lattice structures with different materials, there are limitations with the design 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. Hence, the investment casting process does not allow for the design freedom required for using lattice structures in many applications. Moreover, it is also observed that the cast lattice structures lack the required mechanical robustness and are unsuitable for some structural applications [9], [13]. Therefore, no existing conventional manufacturing process is well suited for fabricating lattice structures for functional applications, and this provides an opportunity to explore new manufacturing methods for metal lattice structures.

Metal additive manufacturing (AM) offers unprecedented design and material freedom to manufacture complex geometries with different metallic alloys and is currently being explored to manufacture lattice structures. Different metal AM techniques have been investigated to fabricate metal lattice structures including Ni and Cr bi-metal on direct metal deposition [14], stainless steel on selective laser melting (SLM) [15], [16], Ti-6Al-4V on selective laser melting [17], Ti-6Al-4V on Electron Beam Melting (EBM) [18], and AlSi10Mg on Direct Metal Laser Sintering (DMLS) [3]. Although EBM was used to demonstrate different lattice structures and porous structures, the high surface roughness or surface texture of the parts is unsuitable for functional applications. The resulting dimensional accuracy in EBM is lower than that of laser-based powder bed fusion process due to the higher layer thickness and low resolution. Furthermore, the minimum possible feature is larger than that in laser-based process, making it difficult to

manufacture thin lattice features. The layer thickness in EBM is typically larger than that of laser-based powder bed fusion process; as a result, the dimensional accuracy is lower than what can be achieved in laser-based powder bed fusion processes. 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 powder bed fusion approaches to manufacture these lattice structures.

There are some studies on laser-based metal AM of lattice structures, but most of them involve manufacturing a simple pattern as a test specimen rather than a functional component. For instance, the SLM process has been used to demonstrate different types of unit cells: cubic, diamond, truncated cube, truncated cuboctohedron, rhombic dodecahedron, and Rhombic cuboctahedron (see Figure 1) [19]. In the same study, the authors observed that the relative density is a significant property in determining the compressive load bearing capacity of the lattice structures; therefore, cell parameters such as strut thickness, strut length, and strut angle need to be determined based upon the structural requirements [20]. In addition to manufacturability of the structure, proper selection of the unit cell, unit cell orientation, build orientation, and applied heat treatment(s) is important because each of these choices influence the mechanical properties of the lattice structures to some extent [21].
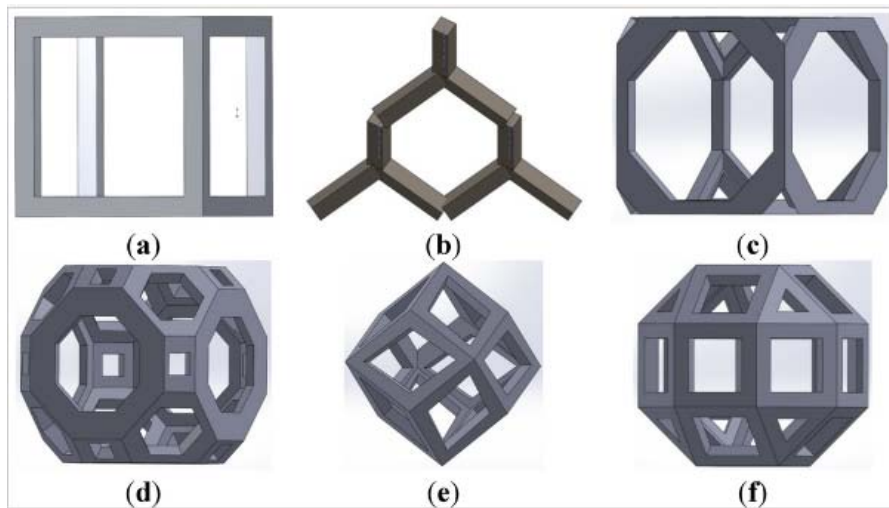

Figure 1: Different types of unit cells for open cellular structures made with Ti-6Al-4V EFI: (a) Cubic; (b) Diamond; (c) Truncated cube; (d) Truncated cuboctahedron; (e) Rhombic dodecahedron; (f) Rhombi cuboctahedron[19]

To understand the aforementioned aspects when designing metal lattice structures, the design process of lightweighting an industry-relevant part using lattice structures and metal AM is investigated in this work. Lightweight parts can also be realized using topology optimization [22]; however, topology optimized designs are not always easy to manufacture with metal AM [23]. The following section describes the design workflow used in this study for fabricating lattice structures for metal AM process. The subsequent sections summarize the details of the design and fabrication process, followed by a discussion on the challenges with the current workflow and future research directions.

2. Workflow

For CAD interpretation, each individual strut in a lattice is a combination of surfaces; therefore, modeling lattice structures involves modeling with a large number of surfaces in CAD, which is computationally intensive. Many commercially-available CAD software packages lack the ability to handle large numbers of surfaces, making them inefficient or unsuitable for designing lattice structures. Meshing these lattice structures and Finite Element Analysis (FEA) further intensifies the computational load on the software.

This work explores different commercial software to design the lattice structures, for example, SOLIDWORKS [24], RHINO [25], FORMZ [26], and SIMPLEWARE [27]. Of these software packages, only SIMPLEWARE, a voxel-based reconstruction software [27], allows designers to create internal lattice structures with different unit cells with different cell parameters and shell thicknesses. When creating components for engineering applications, a CAD model is required for further analysis using FEA and manual redesign to satisfy design requirements (e.g., machining allowances, internal tubes, interfacing features, dimensions etc.). However, SIMPLEWARE failed to export the lattice structures as a CAD model due its large file size and intense computational load when converting the voxel-based representation to a solid CAD model. Based on these experiences, the design workflow shown in Figure 2 was developed to create and analyze lattice structure designs. The workflow starts by creating a workable 3D model in SOLIDWORKS using the 2D drawings of the initial part that is being lightweighted.

Figure 2: Illustration of software workflow from preparing 3D model of lattice structures to metal fabrication of final parts

The important parameters in this lattice design are the strut thickness, strut length (or effective cell size), and shell thickness. The 3D model from SOLIDWORKS is simulated in INSPIRE (FEA software) to calculate the von Mises stresses and the displacements. Based on the FEA results, shell thickness and strut thickness are modified in the CAD model, and this process is repeated until an acceptable factor of safety is achieved. Then the final design is analyzed for thermal deflections during metal AM using CUBES® (now an Autodesk product) software [28]. The last phase in the workflow involves prototyping using a Fused Deposition Modeling (FDM) machine before actual fabrication using the EOS M 280 system. The prototyping phase helped identify issues

that went unnoticed during the design iterations. Additionally, prototyping with plastic helped quickly communicate the design concept of such a complex network of struts with the different stakeholders. The final design was then exported to MAGICS to create any required support structures, and prepare the necessary files for the metal AM build.

3. Lightweighting a Metal Part using Lattice Structures

This section describe the design requirements, lattice structure generation, fabrication (plastic and metal), and post-processing of a metal lattice structure. Figure 3 shows a functional component used in high pressure applications. The objectives in this design process were to leverage the capabilities of metal AM to create lattice structures and explore options to lightweight the part. The part in its intended application is loaded with 10,000 psi pressure on the outside of 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 goal is to lightweight the part as much as possible while meeting the aforementioned performance requirements. Additional design requirements include: (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 interface surface; (4) interface features on the ends of the cylinder are fixed; (5) the dimensions (Φ 0.125 inch) of the autoclave features are standard; and (6) any voids created in the cylinder will experience atmospheric pressure.
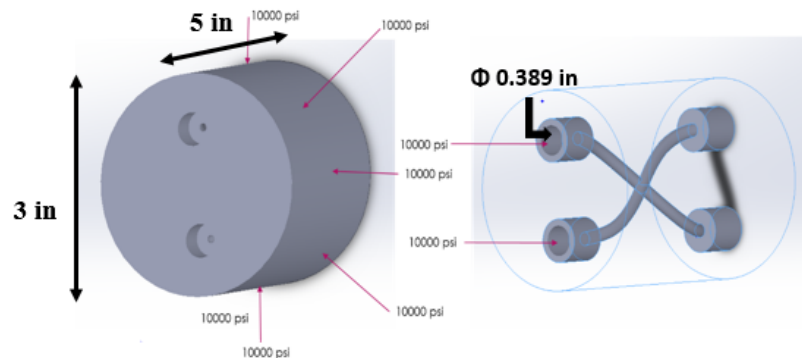

Figure 3: Shows pressure loads on the original design of the part. Internal tubular features are highlighted in the picture on the right side.

3.1 Lattice Design

The design of lattice structures starts with selecting a unit cell. Since the intended lattice structure should be manufacturable with the DMLS processes available for use, the unit cell cannot have overhangs above a certain limiting value (0.0118 inch for IN718 [29]). First, a linear pattern (in the X-direction) of 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

'extrude-cut' to create a lattice structure bounded by a cylindrical shell. Third, two spline curves that are always at an angle more than 45° 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. Finally, minor features are made at the interfaces to complete the design requirements according to the original 2D drawing.

The 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. There is currently no systematic way of determining these parameters using current software tools; therefore, these parameters are iteratively selected by manual adjustments based on trial-and-error and FEA simulations. The thickness of the struts and wall thickness of the cylinder are manually changed until the FEA results yielded a 'safe design' with a minimum factor of safety of 1.5. For minor adjustments, only wall thickness is altered because changing the dimensions of unit cells is computationally intensive. The finalized design is analyzed in MAGICS for manufacturability with the DMLS process. A prototype of a promising design was manufactured with 'ABS plus' using STRATASYS Fortus 250mc FDM machine. The prototype took 61 hr 48 mins, and consumed 22.8 in^3 of model material and 9.66 in^3 of support material.

The prototype (see Figure 4) helped to identify several design issues such as blockage of autoclave features, which were missed during CAD development. In addition, the prototype helped in discussing the design idea with experienced DMLS engineers as well as with other stakeholders. From the evaluation of the prototype, although there is evidence of manufacturing overhangs at this length scale, the design did not look promising to be successfully manufactured in metal due to possible distortion of horizontal struts. Furthermore, the experience of manufacturing these structures at Penn State's Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) suggests avoiding overhangs to improve manufacturability, particularly for internal components that cannot be easily accessed for support removal. As a result, the unit cell was modified to remove any remaining overhangs, and the redesigned unit cell shown in Figure 5d is used to populate the design. The final design, internal cross-sections, and the unit cells are shown in Figure 5 (a), (b)-(c), and (d), respectively. FEA results corresponding to the final design are shown in Figure (6); the estimated von Mises stresses and maximum deflection were determined to be acceptable for the intended function of this part.
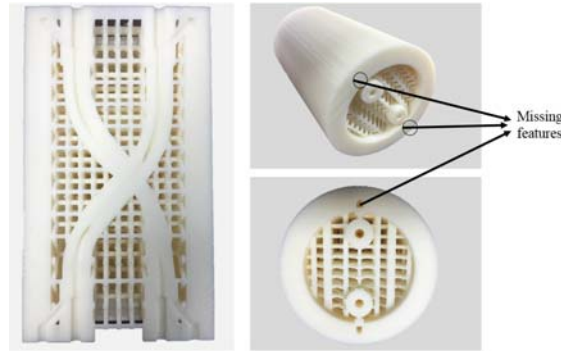
Figure 4: Shows the plastic prototype of the lattice structure. Visual inspection of the prototype helped in identifying missing features as highlighted in the figure.
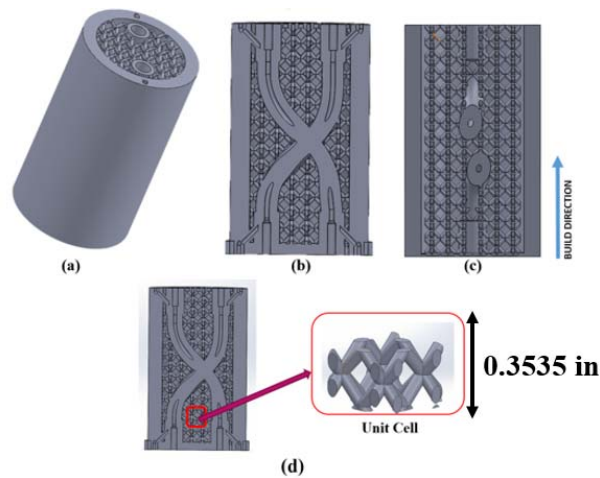

Figure 5: Final design of the lattice structure: (a) complete model with interface features; (b) cross-section showing the internal tubes; (c) cross-section showing the lattice structure around internal tubes; (d) unit cell used in the lattice structure
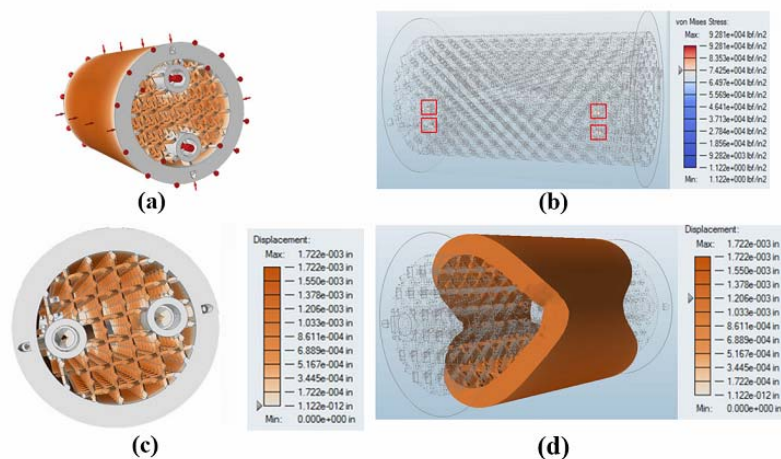

Figure 6: Finite element analysis of the lattice structure: (a) Boundary conditions showing pressure loads as well as displacement constraints; (b) von Mises stress map showing 4 critical regions with stresses higher than 74.25 ksi; (c) Deflection map showing deformation during pressure loading; (d) Displacements higher than 0.0012 in.

Once a final design with acceptable maximum stress and displacement results from FEA simulations was created, the design was analyzed for manufacturability. For example, several features still needed supports as highlighted in Figure 7 (a) and Figure 7 (c). These features are redesigned with modifications shown in Figure 7 (b) Figure 7 (d), respectively. This part is oriented vertically on the build platform for the DMLS processes. As the part is manufactured via layer-by-layer deposition of metallic powder, 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 [30]. However, since this structure is self-supporting, there are no support structures to help conduct the heat during the build, 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 build plate. The final design shown in Figure 5 (a)-(c) has a thick cylindrical shell that is supposed to attach directly to the build plate. 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. Meanwhile, machining allowances are added to the final design so that the dimensional accuracy and smooth surface finish can be achieved by machining the exterior surface during post-processing. Machining allowances are required to accommodate the shrinkage, distortion, surface defects, etc. in a metal AM part. The radius of the outer cylinder was increased by 0.1 in as an allowance for machining. Additionally, a 0.078in allowance was added at the base of the part for the wire EDM (Electric Discharge Machining) cut to separate the part from the build plate. An allowance of 0.1 in is also provided in the length for facing operations on the ends of the cylinder.
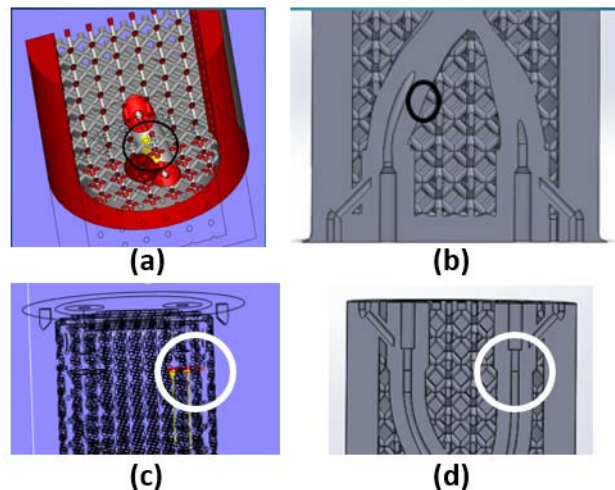

Figure 7: Examples of features needing supports
identified during manufacturability analysis

With the design finalized, the part was analyzed using CUBES® software to estimate the distortion in the build. The results in Figure 8 illustrate the magnitude of displacements due to the residual stresses occurring in the build. Average displacement is 0.274 mm, and maximum displacement is 0.569 mm; both were deemed acceptable.
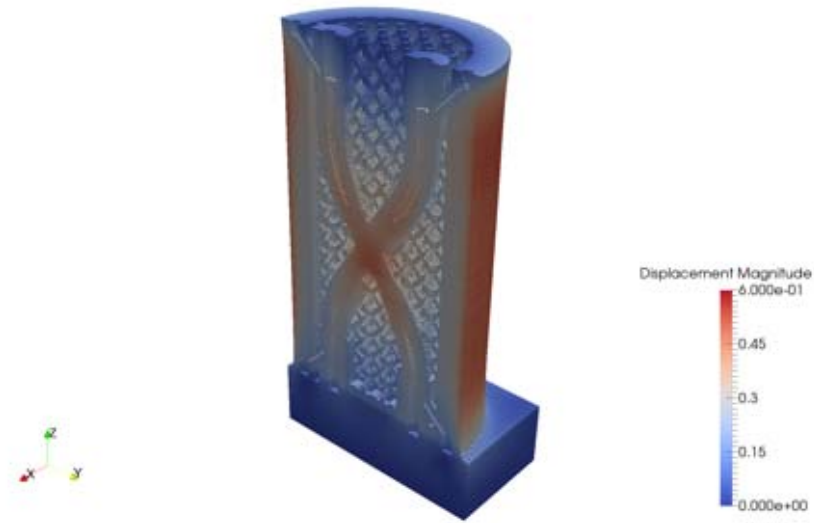

Figure 8: Results from thermal-deflection analysis showing magnitude of displacement

3.2 Fabrication

The part is manufactured with EOS IN 718 material with material properties listed in Table 1. The process parameters used in this build are presented in Table 2. Two parts, one for pressure testing and the other for inspection, are successfully manufactured as shown in Figure 9. The final weight of each part is 5.95 lbs; therefore, a 42.4% reduction in weight is achieved. The total build time was 122 hours with laser-on time of 92 hours. The struts were manufactured successfully with good surface finish, and there are no obvious defects (see Figure 10). However, a ring of material (see highlight box in Figure 9) is observed around the part, which is a result of unexpected machine restart during the build due to an electrical power outage. The structural integrity at this region was investigated during the inspection phase.

Table 1: Reported material properties of EOS 718

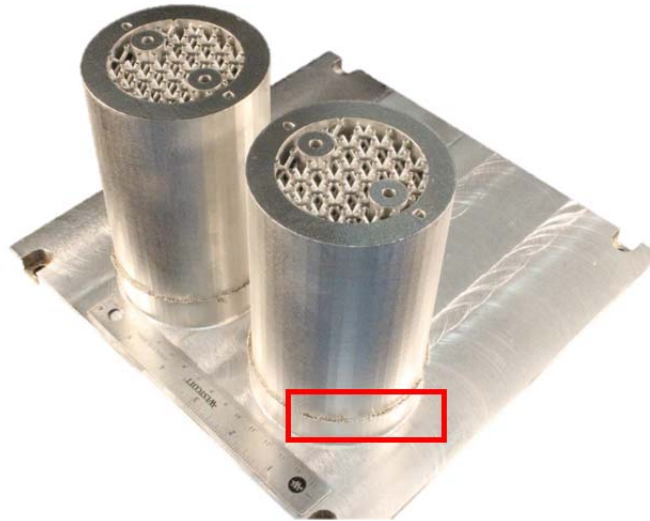| Material	Inconel 718
Modulus of Elasticity (E)	28.8 E+06 psi
Poisson's Ratio (Nu)	0.29
Density	0.289 lb/in ^3
Yield Strength (after heat treatment)	125 E+03 psi

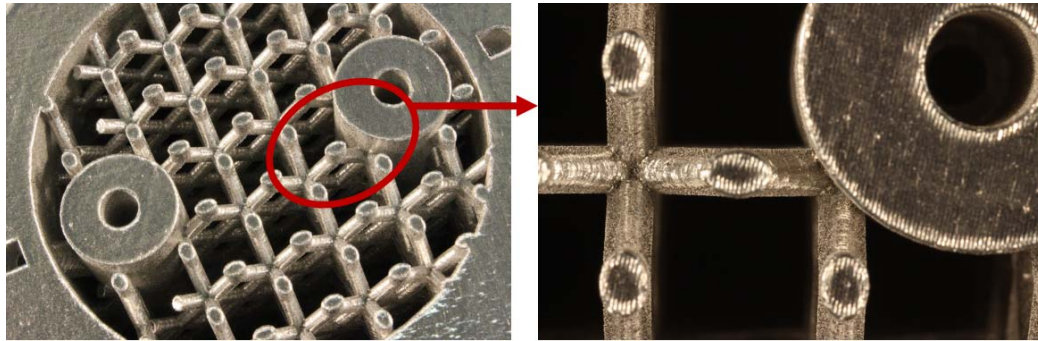Figure 9: Photograph showing as-built parts using IN 718 on the build plate

Figure 10: Photograph showing the details on the struts in the lattice structure

Table 2: Process parameters used in manufacturing of 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

3.3. Post-processing and Inspection

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 was heat treated by Solar Atmospheres, in Pennsylvania, USA using the following heat treatment method (slightly modified from procedure in [31] to meet the functional requirement of the part: (1) solution annealing: at

1925$\pm$25°F for 2 hours, water quench or air cool and (2) aging: at 1450F$\pm$25°F for 7$\pm$1 hour, air cool. To expedite post-processing, the parts were not stress-relieved prior to the prescribed heat treatment, which was performed while both parts were affixed to the build plate. After heat treatment, the parts were separated from the build plate using wire EDM and prepared for machining to achieve the intended dimensions as per the design.

To understand 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 Zeiss Eclipse 550 Coordinate Measuring Machine (CMM) with an accuracy of 60 micro-inch was used to measure the dimensional accuracy of the part before and after heat treatment. Metrology of the as-built part indicates that the fabricated part is undersized compared to the intended design dimensions (see Table 3 and Figure 11). Furthermore, to understand the effect of the heat treatment process on the additive manufactured part, dimensions are again measured after heat treatment. The results clearly show that the part shrunk during the heat treatment process. In addition, the flatness of the build plate was affected during the heat treatment, resulting in warping of the build plate (see Table 3). The results also indicate that the alignment of the holes on the top surface was affected by the heat treatment process. Movement inside the lattice structure is also observed as a result of the heat treatment process. Separation of the stress-relieving and heat treatment procedures in the future can likely reduce this distortion in the build plate.

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

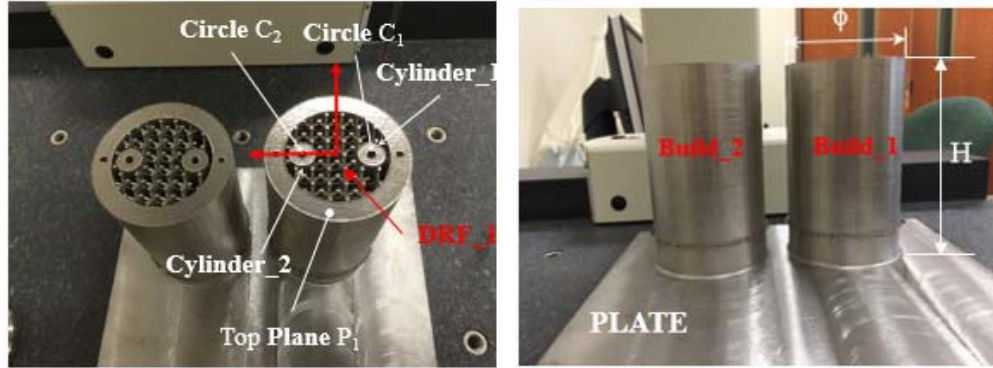| Dimensional Analysis (in inch)					
Measurement	Design	Build 1		Build 2	
		Pre-Heat Treatment	Post-Heat Treatment	Pre-Heat Treatment	Post-Heat Treatment
Build Height (H)	5.3500	5.3391	5.3335	5.3404	5.3317
Diameter (ϕ)	3.2000	3.1922	3.1920	3.1906	3.1887
Cylindricity	-	0.0053	0.0063	0.0068	0.0071
Perpendicularity	-	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 11: Illustration of the features measured as in Table 3

Finally, the part was inspected using a GE v|tome|x micro computed tomography (CT) scanning system to investigate the structural integrity of the internal lattice features. Figure 12 shows internal network of lattice structures and other features at different cross-sections. Analysis of the CT scan image stack confirms that there are no obvious defects in the structure or voids in the lattice structure or cylinder walls. The part is currently being machined to specification for pressure testing.
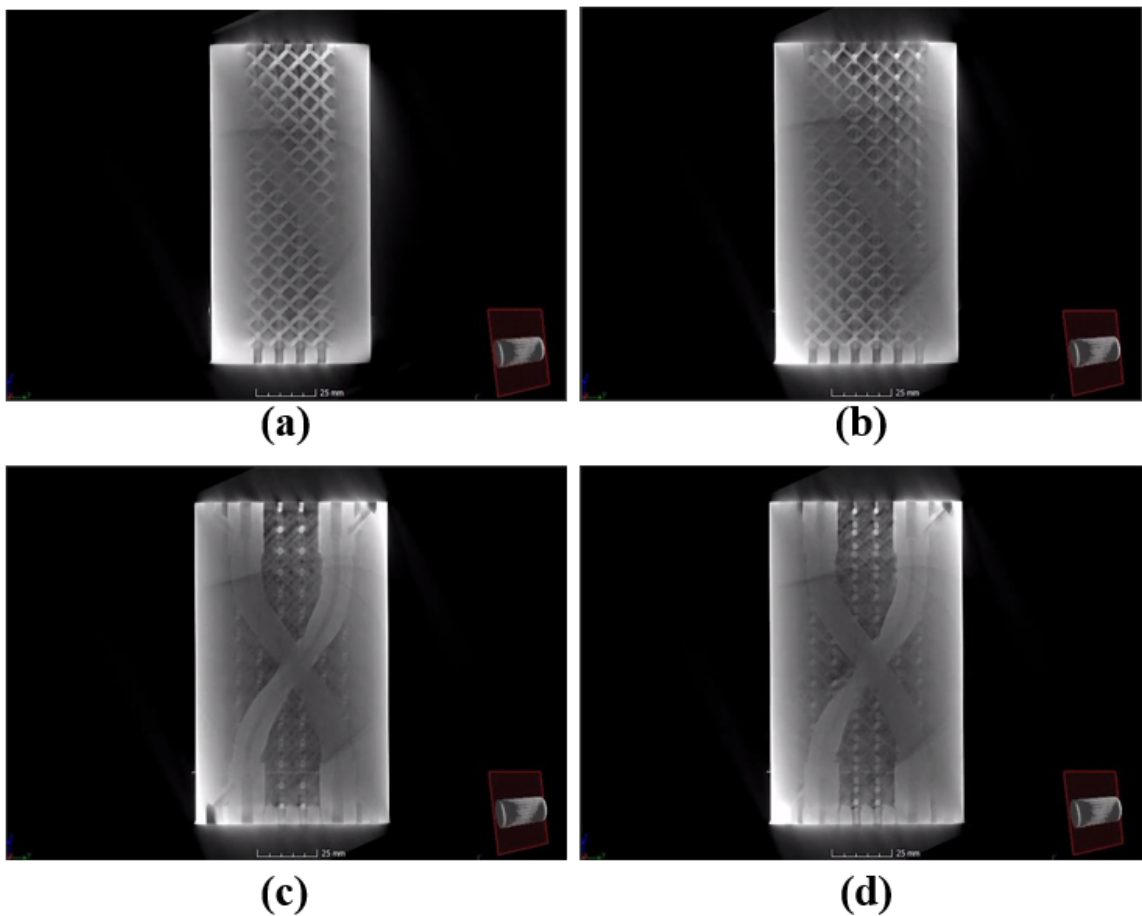

Figure 12: CT scan images of the part showing internal lattice features: (a) – (d) are the images taken at different cross-sections in the part.

3.4 Discussion of Lattice Design Workflow

This section discusses the gaps in the current design workflow and some of the challenges in design of the metal lattice structures. The unit cell is conceptualized first, and the whole design space is populated with these unit cells; therefore, a significant amount of the total design conceptualization effort is spent in optimizing the unit cell. A CAD software with a library of unit cells for lattice structures that can create editable CAD models, not just .STL files, can significantly reduce the computation time for creating functional lattice structures. FEA results determined the thickness of the struts and the outer cylinder; however, any modification to the thickness of the struts required the CAD software to rebuild the entire network of struts, taking long computation time.

Optimization of lattice structure parameters (e.g., strut thickness, strut length) is desired, but it is very difficult with the current lattice optimization software that is available. Developing optimization tools that can optimize the number of unit cells, type of unit cell, size of the unit cells, relative density, and spatial arrangement can significantly improve the design and analysis of lattice structures. Another gap observed in the design workflow 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, custom-made manufacturability analysis tools can also be integrated into the existing CAD software using their application programming interfaces.

Finally, conversion of the original CAD file into a .STL format approximates the surfaces with triangles (mesh). Fine meshes are capable of capturing the details of the small features, at the expense of file size. Large file sizes are not suitable for downstream in 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 this lattice structure case captured the small details such as lattice struts, but the outer surface is visibly triangulated (see Figure 9). 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 as well as in orientation to minimize the approximation errors.

4, Closing Remarks & Future Work

Lattice structures are lightweight and open cellular structures with high compressive load-bearing capacity; therefore, these structures can be good substitutes to solid structures in many applications. However, creating parts with lattice structures results in complex topologies that are difficult to make using conventional manufacturing processes. Laser-based metal AM processes that do not necessarily depend on the complexity of the geometry can be a potential solution to manufacture such lattice structures. The goal in this study was to investigate the design process in creating a lightweight part, with lattice structures, using laser-based metal AM process. Different software such as SOLIDWORKS, RHINO, FORMZ, and SIMPLEWARE were explored to create lattice structures. SIMPLEWARE offers a library of primitives for different lattice structures, but exporting an editable CAD model proved difficult.

In this work, design for the lattice structures is created in SOLIDWORKS by starting with selecting a unit cell and patterning in the X, Y, and Z directions. As each of the struts in the lattice structure is represented by an independent surface, creating the network of these struts is computationally intensive. Lattice parameters such as strut length, strut thickness, and wall thickness of the cylindrical shell are determined by finite element analysis. The final design was fabricated on EOS M280 machine with IN718 in 122 hrs (for 2 parts). The final parts were heat treated before separating them from the build plate. Dimensional analysis of the parts indicated that the heat treatment caused shrinkage in the lattice structure and distortion in the build plate. Separation of the stress-relieving and heat treatment procedures may reduce this distortion in the build plate. Analysis of the CT scan images taken at different internal cross-sections confirms that there are no obvious defects or voids in the lattice structure or walls of the cylinder.

The design workflow utilized in this study can be applied to lattice structures with similar complexities. Determining the unit cell parameters by trial-and-error takes significant design computation time; therefore, developing an optimization module to calculate the optimum unit cell would be a promising area of future research. Additionally, availability of a library of AM suitable primitives for lattice structures can significantly reduce the time required to conceptualize and model the design in CAD software. Current manufacturability analysis tools require the conversion of the CAD file into .STL format; however, these .STL files are large at fine resolutions and are difficult to process in other AM software. Integrating manufacturability analysis tools with CAD software can help designers quickly modify their designs based on the manufacturability results.

In continuation of this work, one part will be machined to the accurate dimensions and pressure tested to validate the structural performance in the real-world application. Finally, the part will be sectioned to access the lattice structure and for further investigation of the structural integrity of the strut members. Additionally, as this work only examines the manufacturability of a particular unit cell, other self-supporting unit cells can also be examined.

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