Proceedings of the ASME 2021
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC-CIE2021
August 17-19, 2021, Virtual, Online
DETC2021-69818

EXPLORATION OF SUPPORT STRUCTURE DESIGN FOR ADDITIVE MANUFACTURING AT A MAJOR OEM: A CASE STUDY

Lucas Morand
Graduate Research Assistant
Mechanical Engineering
Clemson University
Clemson, SC 29634-0921
lmorand@g.clemson.edu

Joshua D. Summers
Professor
Mechanical Engineering
University of Texas at Dallas
Richardson, TX 75080-3021
joshua.summers@utdallas.edu

Garrett J. Pataky
Assistant Professor
Mechanical Engineering
Clemson University
Clemson, SC 29634-0921
gpataky@clemson.edu

ABSTRACT

The support structures required in many forms of additive manufacturing are often seen as waste that is tolerated as necessary. In metal additive processes, cost is frequently reduced by minimizing the amount of support structures needed to produce a part so that in turn, material use is decreased. However, there still exists the challenge of generating parts that are not deformed by the stresses created in the process. In this case study, support structures were leveraged to address deformation. A part was printed via direct metal laser melting with supports with a high grouping density in areas of high anticipated deformation in order to stiffen the part to prevent deformation. Then, they were printed again with a low grouping density to allow the part to relax and reduce stress. Combinations of support strategy and leaving supports on during post processing were used to investigate the effects of keeping or removing the supports in post-print operations such as surface treatment. The two optimized support strategies saw a lower deformation than the baseline approach to supports, and the releasing strategy was closest to the reference solid model with a 26% reduction in average deformation. The results suggest that the support structures in additively manufactured parts have a different impact on the part than the original intent of the supports to simply alleviate a process requirement. The support structures should be used to impact the final part geometry.

1 INTRODUCTION

Additive manufacturing (AM) holds unique production capabilities that unlock new possibilities in design while still being faced with process challenges [1]–[4]. Designers working with processes such as direct metal laser melting (DMLM) must remember to account for problems like residual stresses that lead to part deformation, creating expensive waste for the manufacturer [4]. Designers are constrained by restrictive guidelines and enabled by opportunistic guidelines [5]. The former comes from limitations of the process and the latter is based on the unique abilities. In this study, the support structures used in the AM process that are traditionally considered waste are leveraged as opportunistic to reduce the restrictive part deformation that affects additively manufactured parts.

1.1. Restrictive Guidelines in Design for Additive Manufacturing

Restrictive guidelines are derived from the weaknesses or limitations of AM. These can cover cost optimizations as well as general work arounds for the inherent requirements of a layer-based process. Some researchers recognize the financial barrier commercial metal AM may pose and offer the variables a company must consider in order to successfully adopt AM, such as material expenses [6]. Not only does the equipment carry a high price, but the metallic powders are another area where cost is prohibitive, and waste must be controlled. It is important to reduce the waste associated with each print, but it is especially crucial to prevent failed prints.

Restrictive guidelines also look at developing mathematical optimization approaches in order to minimize the support structures required in order to have a successful print. The supports are traditionally sacrificial structures not part of the component geometry and thus do not add value to the end product [7]. They simply serve as intermediate structures necessary for printing certain features in specific orientations. As such, they require material, energy, and time and traditionally have been minimized to further drive down AM costs [8]. This can be extended to include considerations on ease of removal (and therefore post-processing costs) [9].

Parts that are deformed can sometimes be repaired, but this adds time and labor. Further restrictions can include the minimum wall thickness, maximum ledge length, and smallest hole diameter, as found experimentally to prevent unsatisfactory prints with stress concentrations [10], [11]. Some researchers create something resembling an instruction manual for their machines, discussing specific ratios and process parameters that set the limits for successful prints that they have found through bracketing and iteration [12], [13]. A further restrictive guideline for designers is based on the AM process in powder bed fusion being similar to welding and creating thermal concentrations leading to residual stresses. Others have studied the impact that these guidelines have on designed solutions through designer studies [14], [15]. Similar work has focused on developing design guidelines for creating meso-structures or non-sacrificial support structures [16]–[19]. Authors also offer solutions, tested experimentally, for designers to implement to reduce the stresses that usually lead to deformation [20].

1.2. Opportunistic Guidelines in Design for Additive Manufacturing

Opportunistic approaches to guidelines look at the unique opportunities available in the AM process and seek to inform designers of the best way to leverage them. This is often done post factum once the researchers have successfully used AM in a novel way and now seek to share. This can be in the hope of moving away from design fixation of using only the traditional subtractive manufacturing processes [21]. These tools are not meant to alter the design process, but instead are helpful guidelines to be implemented whenever the designers need them; tools in the toolbox [22], [23]. For example, a matrix was constructed to tie specific design requirements to micro-, meso-, and macro-structures available in the AM environment to allows designers to see what resources to use based on their design needs [24]. Topology optimization often generates structures too complex for the traditional subtractive manufacturing methods. AM has become a large test bed for these complicated structures, with researchers showing case studies and examples of successful implementations of topology optimization, offering best-practices and lessons-learned [25]–[28]. Other researchers have sought to keep the engineer in the loop by providing approaches to meso-structure design using verified guidelines instead of optimization [16], [17]. Similar approaches may be applied to the sub-problem of support structure design. The challenge of deformation in DMLM can be addressed with some of the capabilities afforded by these sorts of structures.

1.3. Gap in the Literature

From the previously discussed approaches to design for AM, a gap can be identified. The two guideline types are presented in mostly a mutually exclusive fashion as two paths. In painting the restrictions as burdens that exist until the process and parameters improve, they are left alone by designers as hard rules. However, the design freedoms and opportunities afforded by AM could be used to address the restrictive concerns of support structures and stresses. For example, this is just starting to be explored by using geometries such as lattices, impossible to create through other means, to act as heat sinks during the build [20]. However, there is much more work to be done leveraging the opportunistic to alleviate the restrictive.

One of the advantages of AM is the ability to customize parts without the need to amortize mold costs over large production runs. With that capability, parts are able to be uniquely altered for their print success. Support structures are a prime example of this. They are traditionally used to aid the process in depositing material. Because of the layer-by-layer nature, each layer needs something below it to be deposited onto as shown in Figure 1. Some geometries, such as overhangs, bridges, and holes, need support structures to fill the void and allow a layer to be deposited [8]. As such, each part's geometry, print orientation, and even specific print technology can require unique support structures. Traditionally, support material is placed based on known parameter limits. For example, a maximum allowable overhang ratio can be experimentally determined in order to then know the minimum allowable support spacing to successfully print the overhang feature [29]. This allows manufacturers to further reduce the problems associated with increased support structures, including the added finishing steps, material, and time, among other wastes [30].

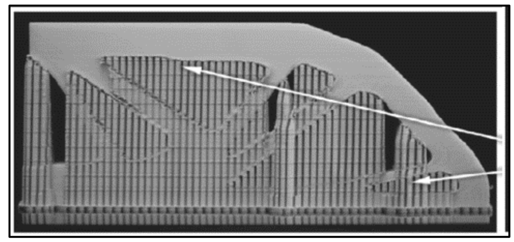

Figure 1: This part is shown with the support structures necessary to help the machine deposit material over gaps apparent behind the vertical supports. [31]

It is proposed to take support structures, traditionally sacrificial components of AM restricted by the process, and leverage them to address the process weaknesses. In other words, taking the opportunistic to alleviate the restrictive. Support structures, which already will be required, can have their grouping density varied to improve a part's deformation post-print. This utilizes support structures beyond their original task and employs them in a novel manner. This is shown by comparing both post-print deformation and deformation after post-processing between baseline constant grouping density supports and supports with varied grouping density.

2 CONTEXTUALIZING THE CASE STUDY

In powder-bed fusion processes (utilizing powder material and an energy source such as a laser or electron beam) that behave similarly to welding, the temperature changes and exotic materials present challenges such as residual stresses that often lead to part deformation [32]. DMLM is a subset of powder-bed fusion that uses a high-powered laser to fully melt each layer of powdered metal [33]. It introduces a higher amount of build and residual stress because it fully melts the metal, unlike sintering processes. This can cause a variety of challenges in the print as different areas of a part in production face large temperature gradients [32], [34]. These can lead to stress concentrations that develop into deformation or shifts that lift the part from the build plate and collide with the machine's re-coater. While manufacturers attempt to lessen waste by reducing things like support structures, the larger issue is that of failed prints because of these stress concentrations that are not addressed. In DMLM, the powder is fully melted to create the part, further exacerbating this issue. However, the ability to have the increased part density of up to 99.9% through melting keeps the DMLM process appealing enough to continue to develop [34].

There exist many variables to consider in DMLM printing from the gas flow in the chamber to scan patterns of the laser. Values such as these are often set by the manufacturer, but research is being conducted on optimization of these variables [35]. Instead, the process can be treated at as a black box model. The prepared print file that holds the geometry to be printed is one input, with the various print parameters being the second. These combine in the black box to output the print result as it appears on the build plate. The print parameters are deemed out of scope, and the geometry of the prepared file becomes the input of interest of this paper.

2.1. Case Study

Case studies have been previously successful and have been validated for use in design research [36]–[40]. They focus on describing a real, specific case [41]. They are especially useful when the context cannot be disassociated from the phenomenon, such as in the case of this paper. Here, the workflow of an ordinary part is followed at a major energy OEM and the results, while expected to be tied to the specific situation, are still applicable in a broader design and manufacturing environment as relevant lessons learned.

The study of the part occurred at a major energy OEM that designs and manufactures products from components to power generation systems and assemblies for worldwide markets. The tools used in the study are commercially available, enterprise solutions occasionally with customizations. The case study explores how the OEM designs support structures for DMLM part printing in a typical scenario at their manufacturing validation facility. This industry site creates production prototypes and manufacturing plans that are validated before being pushed to a larger AM facility. The parts produced range from tooling to parts of larger subsystems and are on a production scale in the 1000's per year. Broadly, there is a five-step process model (Figure 2): (1) Model Generation, (2) Additive Validation, (3) Additive Preparation, (4) Additive Manufacturing, and (5) Post Processing. This process model was derived from a series of informal interviews with AM engineers at the OEM over the course of a year.

Model Generation involves solid modeling of a geometry for print. This is usually performed by various teams in the company that design a part and expect it to be additively manufactured. They design the part internally to their team before communicating to a team of AM engineers their part geometry and design goals.

This moves into Additive Validation where the printability of the geometry is evaluated. The AM team, composed of engineers on site at the production validation facility, reviews the design and intent with the design team. This is based on restrictive guideline considerations previously discussed, specific to the intended DMLM machine, material, and application. Here, decisions are made on geometric features the AM team predict to be problematic in production. This spans from minor tweaks to part redesigns that can stretch from five days to forty days of iteration.

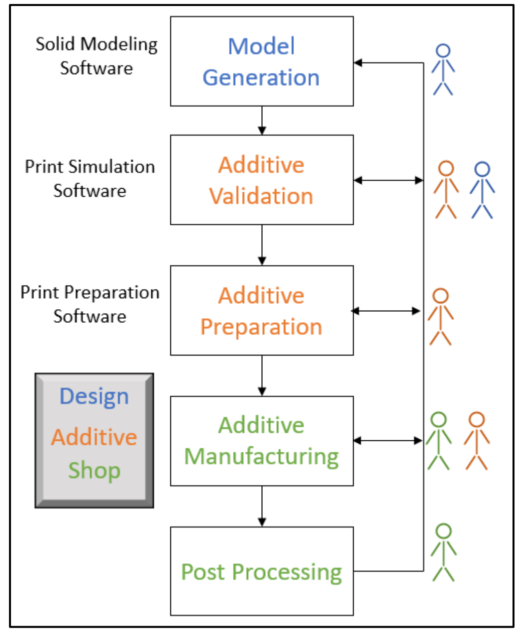

Figure 2: The OEM's process model for additively manufactured parts. The primary team is shown closest to the arrows, with the secondary next to them.

Once predicted to be successful, the part moves into Additive Preparation, where the appropriate orienting, supporting, and slicing occurs over three to seven days. These decisions are made by the AM team still in communication with the design team in order to decide what will satisfy the design requirements encompassing functionality, time, and cost.

The output is sent to the machine for printing that takes one to five days, which upon successful print then goes through various post-processing stages as dictated by the design requirements by a shop team of technicians on-site at the validation facility. Depending on these necessities, the post-processing can take five to forty days. The machines used are direct metal laser melting printers from a commercial company with modifications done by the OEM. The post-processing available for these parts includes support removal, surface treatment, heat treatment, and non-destructive testing. Some post-processing portions are done internally by the OEM while others are contracted out to vendors depending on time, cost, and needs.

Much iteration is expected in this process as requirements change and feedback is communicated between the three teams (design, additive, and shop), as highlighted by the arrows in Figure 2. The individuals representing each of the teams might change between the steps. For instance, one design individual might be focused on model generation while a second design team member might be working with the additive team representative during the additive validation step.

The OEM uses three main software packages in the additive process model. A commercial solid modeling solution is used to generate the part and create an STL file in the Model Generation phase. A second tool is a customized commercial AM simulation software used to simulate the print of the part and make decisions in the Additive Validation phase. Finally, an AM specific tool that allows for preparation, analysis, and modification of the STL as well as support generation is used in Additive Preparation.

3 EXPLORATION OF SUPPORT STRATEGY

For the test part, a simple geometry shown in Figure 3 was chosen and held constant to test varying support structure grouping densities. This shape was oriented as an A-frame and features varying thicknesses with fillets between them. The commercial solid modeling solution was used to generate the part and then create the STL file shown in Figure 3.

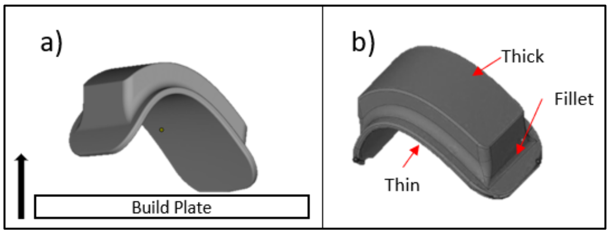

Figure 3: The test part in its print orientation. a) The arrow signifies the build direction relative to the build plate. b) The arrows show the areas of change in the geometry.

Then, print simulation software was used to analyze the print of the part. Two support strategies were identified in connection with the predicted deformation areas from the simulation software: strengthening and releasing. The strengthening strategy was to strengthen the areas of highest anticipated deformation by increasing the support grouping density. This bracing may stiffen the print and prevent the part from moving, yielding an end geometry that was truer to the original STL file and CAD model. The strengthening strategy is shown in Figure 4. The releasing strategy was based on the opposite idea: allowing the relaxation. To combat the high stresses of the DMLM process, the areas of anticipated deformation should be allowed to naturally relax as needed with a less-dense support grouping while the other remaining areas can have the higher density support grouping.

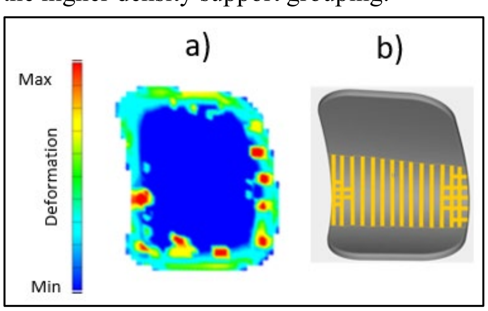

Figure 4: Comparison between the print simulation results and the supports modeled from the simulation results in the print preparation software. a) The color scale shows areas of deformation. b) The supports modeled here are with the strengthening strategy.

In the print preparation software, the baseline supports were added based on process restrictions found experimentally by the OEM based on variables such as material, process, and machine, as is found similarly in the literature [29]. The attachment point to the part was made into a toothed connection in order to more easily be able to remove the supports in the post-processing stage of the workflow. This decision was made based on a manufacturability consideration. The three strategies, including the baseline approach, are shown in Figure 5. The results of the simulation runs were used to determine the placement of the varied density supports in the print preparation software.

Figure 5: The three strategies viewed from the bottom showing the differing support structures in yellow.

Once the files were ready for print, they were sliced in the print preparation software and the resulting file sent to the machines for print. The parts were printed via DMLM from a nickel-based super alloy on the same machine. The machine is a commercially available, multi-laser, high-volume option.

An experimental plan was developed to further compare the effects of keeping supports on through the post-processing steps. The two variables of interest were the support strategy and the presence of support structures during post-processing. This would allow a better understanding of when was the best time in the process model to remove the supports in order to minimize part deformation. Their serialization is shown in Table 1.

Table 1: Matrix of test prints with their associated variables.

Support Strategy	Part S/N	Supports During Post-Processing
Baseline	A1	X
	A2	-
Strengthen	B1	X
	B2	-
Release	C1	X
	C2	-

The parts were printed and post-processed in accordance with a serial number approach. The three support strategies each were given two prints:

- one with supports on through the post-processing (#1) and
- one with supports off through the post-processing (#2).

For example, A2 had supports removed after the print while A1 did not. The parts each went through print, surface treatment, heat treatment, and non-destructive testing. These steps are shown in order in Figure 6. Post-processing steps like surface treatments are shown to improve operational characteristics without altering the design of the part [42].

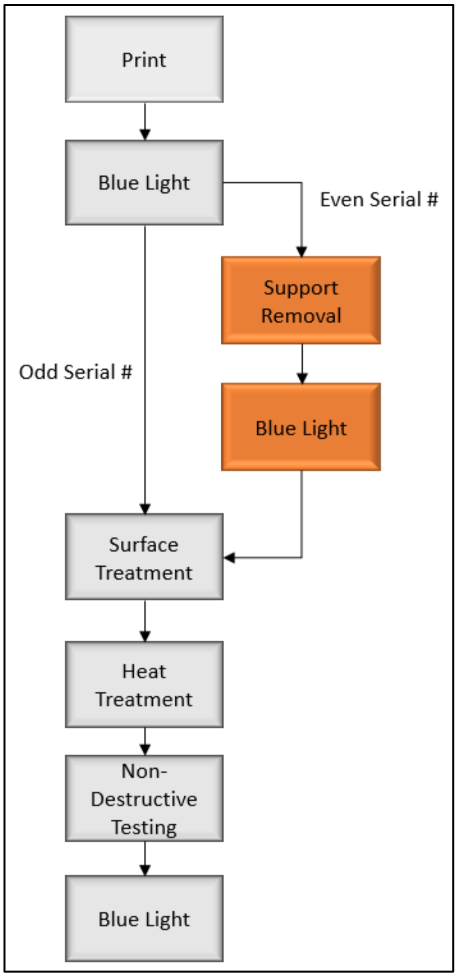

Figure 6: Flow chart of possible post-processing steps. Parts with an even serial number diverted to support removal and an intermediary scan before completing the rest of the post-processing steps.

At multiple stages, blue light scanning was employed to compare the part to its original part file and measure the deformation at four common locations across the part shown in Figure 7. These values were used for average and maximum calculations. When a part needed supports removed, the baseline support strategy parts were able to be removed by hand tools, while the other two strategies required electrical discharge machining.

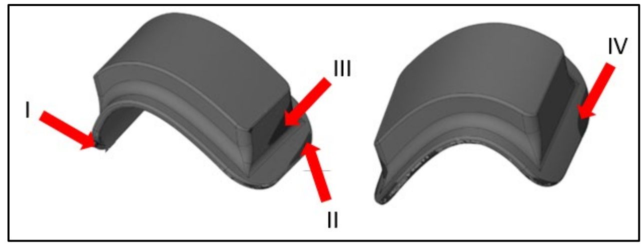

Figure 7: Blue light scan of common measurement points. These four points were compared to the original CAD model and the resulting deformation amounts were used in calculations.

4 SUPPORT STRATEGY EFFECTS AND OUTCOMES

The first result in the data is in the difference between the average deformation of the control baseline with constant supports kept on through processing, A1, and the strategized strengthen and release approaches (B and C). Figure 8 shows that there is a 16% reduction in average deformation between control (A1) and the strengthening parts (B) and a 16% reduction in maximum deformation. With respect to the control (A1) and the releasing parts (C), there was a 21% reduction in average deformation and a 24% reduction in maximum deformation.

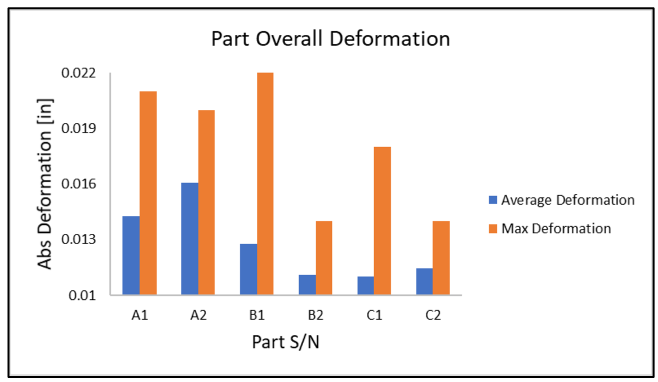

Figure 8: Part Overall Deformation. The strategized supports (B and C) have lower average and average maximum deformation than the baseline (A)

This trend is shown again in Figure 9 where the two baseline support prints (A), shown in blue circles, place higher on the average deformation axis than any of the other prints across all post processing steps and blue light scans.

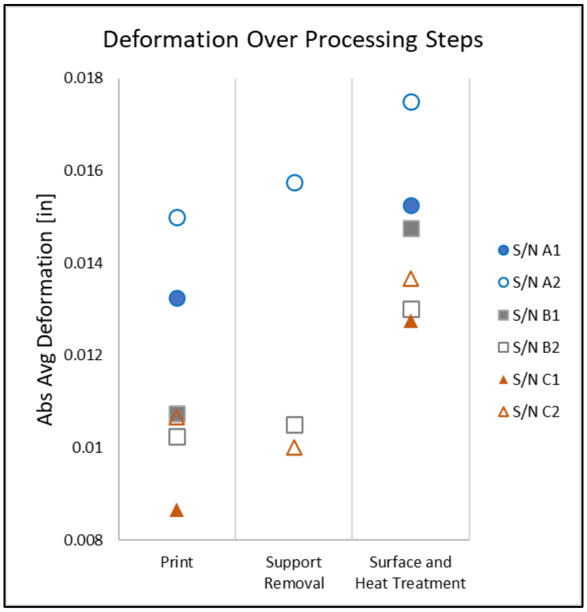

Figure 9: Deformation Over Processing Step. The operations increase deformation in the parts and the baseline support approach (A) yields a higher deformation at every scan.

This data shows that the supports used in the prints affect the overall part deformation. In this case, the strategized supports, B and C, both yielded less deformation in the part than the conventional control approach, A1. The releasing approach, C, was the most effective at preventing deformation and yielded a part that was truer to the original CAD geometry.

The second takeaway from the data is the effect of keeping support structures on through post-processing operations. The baseline approach (A) and the releasing strategy (C) both show in Figure 8 that keeping supports on through post-processing stages prevented average part deformation. The supported control baseline (A1) saw a 13% increase in average deformation when the supports were removed (A2). The supported release strategy (C1) saw a 4% increase in average deformation when the supports were removed (C2). However, the strengthening strategy (B1) average deformation decreased 13% when removing the supports (B2). This decrease in deformation by removing the support structures before post-processing is also shown when comparing the maximum deformation values. Across all three strategies, the maximum deformation was less when the supports were removed (the even serial number). In total, four out of the six comparisons showed less deformation when the supports were removed before post-processing steps.

The biggest consideration in the traditional application of support structures in metal AM is the added material use from the supports. Because of the cost of the metal powder, support volume is the target of minimization. Here, the volume of the supports can also be used to compare the deformation values of each strategy. Table 2 shows the volume of support material used in each part in comparison with the associated average and maximum deformation values.

Table 2: Comparison of support volume and corresponding deformation

Strategy	Support Volume in^3	Tot Avg Deformation in	Max Deformation in	Max Deformation Location
A1	0.217	0.014	0.021	IV
A2	0.217	**0.016**	0.020	II
B1	0.312	0.013	**0.022**	I
B2	0.312	0.011	0.014	I
C1	0.353	0.011	0.018	I, IV
C2	0.353	0.011	0.014	I, II

Depending on the application and tolerance requirements of the part, additive manufacturing engineers must consider the tradeoff between material use and deformation. If a goal of AM is to reduce cost, this can be done by fewer failed prints – defined either by complete print failures or parts that are out of design tolerance. As such, it is up to the engineers to decide between lesser support volume but higher deformation and hoping to be in tolerance or extra material used in the supports but less deformation and a higher chance of being in tolerance. This consideration is displayed in Table 2 where the C2 strategy, releasing strategy and supports removed in post-processing, had the lowest amounts of average and maximum deformation but a 63% increase in support volume compared to the baseline. This tradeoff between added material in the supports and the acceptable part deformation is at the discretion of the designers and engineers based on design specifications and allowable post-processing steps. More labor and tools used in the support removal process lead to increased cost, another compromise to be considered.

The blue light scans looked at common measuring points, shown in Figure 7. After the processing steps, the location of the maximum deformation was as displayed in Table 2. It is shown that the support strategy not only affected the amount of maximum deformation experienced by the parts, but also moved that deformation location around the part.

Overall, in comparing the maximum deformation results, the releasing strategy saw smaller values than the baseline and the strengthening strategies. In terms of support structure presence in post-processing, the removal of the structures before surface treatment, heat treatment, and non-destructive testing yielded less maximum deformation than keeping the structures on. This leads to combination C2, the releasing strategy with supports removed, being the strategy of choice for maximum deformation reduction in this part, even with the highest support volume.

While supports are traditionally used as a bypass to process limitations as described earlier, the data presented offers that supports used in prints have a different impact than their original purpose. The key observation is not the success of the C2 combination in this specific part geometry but that rather than simply helping the printer build on top of a vacancy in the part geometry, support structures actually affected the part's overall deformation in the print process, the part's resistance to deformation during post-processing operations, and the location of maximum deformation. Support structures are tools that should not be automatically applied in a consistent pattern. Rather, the support structure and therefore the support strategy should be customized to each part and geometry. Using tools such as the print simulation software enables designers and engineers to make informed and intentional decisions on the approach to supporting the part. This is done in order to address some of the challenges faced by DMLM such as part deformation as explored in this case study. Support structures are a way forward to alleviate DMLM process restrictions.

5 OBSERVATIONS

In this case study the support grouping density and therefore total support material volume were altered while the thickness, support shape, and specific attachment parameters were held constant. However, in changing the grouping density, supports were added along the longitudinal direction to create the strategized approaches rather than changing the latitudinal density. The orientation of these perpendicular supports could also have played a role in the improved deformation performance of the part.

Some parts were printed and processed not in accordance with the model laid forth in Figure 6 but still maintaining the case study support strategies. In this batch, no surface treatment occurred before the heat treatment. All of these parts developed cracks near locations II and IV shown in Figure 7 with the exception of one that only cracked in one location. The cracks sites are near the areas of highest deformation on the part. The simulation software also predicted these areas to be concentrations of stress during the build process. The variation in support strategies did not change the presence of the crack. While the deformation was investigated in this case study, the link between cracks and support strategies needs to be studied further.

6 FUTURE WORK

The work in this case study was based around DMLM, a nickel-based alloy, and the part geometry presented. The support strategies were uniquely designed and applied for these parameters. However, the larger observations stand: support structures influenced the deformation behavior of the part both post-print and through each of the post-processing stages, one of the key challenges faced by DMLM.

In order to apply custom support structures to parts, a nomenclature for the features of the part must first be derived. Defining what constitutes a part feature is already challenging and sometimes subjective with the nuances of language. This is further exacerbated by the different print orientations possible in AM. In one orientation a print may have an overhang but rotated 90-degrees it does not. There are many ontologies developed with AM in mind but there lacks a wide standard [20], [43], [44]. In Figure 2 it is shown that the five steps in the process model are divided between three teams. Without a robust standardized nomenclature, the communication between teams will suffer and details will be lost by the time the part has completed all of its process steps.

Once a standard is decided on to describe the part, an exploration into the relationship between part features and support structures in DMLM prints can occur. How to adapt supports with intent for individual part feature success is an open question. Applying customized support structures to parts will yield similar results to the reduced deformation quantified in this case study. Broadly, this study demonstrates the need for exploring the opportunities afforded by AM to alleviate restrictions on geometry no matter the process or material.

7 ACKNOWLEDGEMENTS

We acknowledge the support of General Electric Company in funding this project through a graduate internship and sponsor project #2014149. Any opinions, findings, and conclusions are those of the authors and do not necessarily reflect the views of the sponsor.

8 REFERENCES

[1] J. Barcus, "I Have Seen the Future, and It Is 3D Printing," *Forbes*, Feb. 2020.

[2] Y. Huang, M. C. Leu, J. Mazumder, and A. Donmez, "Additive manufacturing: current state, future potential, gaps and needs, and recommendations," *J. Manuf. Sci. Eng.*, vol. 137, no. 1, 2015.

[3] W. Gao *et al.*, "The status, challenges, and future of additive manufacturing in engineering," *Comput. Des.*, vol. 69, pp. 65–89, 2015.

[4] M. K. Thompson *et al.*, "Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints," *CIRP Ann.*, vol. 65, no. 2, pp. 737–760, 2016, doi: https://doi.org/10.1016/j.cirp.2016.05.004.

[5] B. Vayre, F. Vignat, and F. Villeneuve, "Designing for additive manufacturing," *Procedia CIrP*, vol. 3, pp. 632–637, 2012.

[6] T. H. J. Vaneker, "The role of Design for Additive Manufacturing in the successful economical introduction of AM," *Procedia Cirp*, vol. 60, pp. 181–186, 2017.

[7] J. Jiang, X. Xu, and J. Stringer, "Support structures for additive manufacturing: a review," *J. Manuf. Mater. Process.*, vol. 2, no. 4, p. 64, 2018.

[8] G. Strano, L. Hao, R. M. Everson, and K. E. Evans, "A new approach to the design and optimisation of support structures in additive manufacturing," *Int. J. Adv. Manuf. Technol.*, vol. 66, no. 9, pp. 1247–1254, 2013, doi: 10.1007/s00170-012-4403-x.

[9] Y.-H. Kuo, C.-C. Cheng, Y.-S. Lin, and C.-H. San, "Support structure design in additive manufacturing based on topology optimization," *Struct. Multidiscip. Optim.*, vol. 57, no. 1, pp. 183–195, 2018.

[10] D. Thomas, "The development of design rules for selective laser melting." University of Wales, 2009.

[11] G. A. O. Adam and D. Zimmer, "Design for Additive Manufacturing—Element transitions and aggregated structures," *CIRP J. Manuf. Sci. Technol.*, vol. 7, no. 1, pp. 20–28, 2014, doi: https://doi.org/10.1016/j.cirpj.2013.10.001.

[12] G. A. O. Adam and D. Zimmer, "On design for additive manufacturing: evaluating geometrical limitations," *Rapid Prototyp. J.*, 2015.

[13] N. Meisel and C. Williams, "An investigation of key design for additive manufacturing constraints in multimaterial three-dimensional printing," *J. Mech. Des.*, vol. 137, no. 11, 2015.

[14] R. Prabhu, S. R. Miller, T. W. Simpson, and N. A. Meisel, "But will it build? Assessing student engineering designers' use of design for additive manufacturing considerations in design outcomes," *J. Mech. Des.*, vol. 142, no. 9, 2020.

[15] R. Prabhu, S. R. Miller, T. W. Simpson, and N. A. Meisel, "Teaching design freedom: Understanding the effects of variations in design for additive manufacturing education on students' creativity," *J. Mech. Des.*, vol. 142, no. 9, 2020.

[16] M. Fazelpour, P. Shankar, and J. D. Summers, "Developing design guidelines for meso-scaled periodic cellular material structures under shear loading," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, vol. 50114, p. V02BT03A002.

[17] M. Fazelpour, A. Patel, P. Shankar, and J. D. Summers, "Design guidelines as ideation tools–a user study on exploring the subjectivity of unit-cell design guidelines," *Int. J. Des. Creat. Innov.*, vol. 7, no. 1–2, pp. 50–69, 2019.

[18] M. Fazelpour, A. Patel, P. Shankar, and J. D. Summers, "A user study on exploring the sequencing of unit cell design guidelines," 2017.

[19] M. Fazelpour, P. Shankar, and J. D. Summers, "A Unit Cell Design Guideline Development Method for Meso-Scaled Periodic Cellular Material Structures," *J. Eng. Mater. Technol.*, vol. 141, no. 4, 2019.

[20] L. Cheng, X. Liang, J. Bai, Q. Chen, J. Lemon, and A. To, "On utilizing topology optimization to design support structure to prevent residual stress induced build failure in laser powder bed metal additive manufacturing," *Addit. Manuf.*, vol. 27, pp. 290–304, 2019, doi: https://doi.org/10.1016/j.addma.2019.03.001.

[21] C. C. Seepersad, J. Allison, and C. Sharpe, "The need for effective design guides in additive manufacturing," in *DS 87-5 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 5: Design for X, Design to X, Vancouver, Canada, 21-25.08. 2017*, 2017, pp. 309–316.

[22] E. Gendreau, S. O'Shields, and J. D. Summers, "Developing a Method for Classifying Design Enablers," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2017, vol. 58110, p. V001T02A011.

[23] J. D. Summers, S. Anandan, and S. Teegavarapu, *Introduction of Design Enabling Tools: Development, Validation, and Lessons Learned*. Cambridge, MA: Oxford Press, 2009.

[24] Z. Doubrovski, J. C. Verlinden, and J. M. P. Geraedts, "Optimal Design for Additive Manufacturing: Opportunities and Challenges." pp. 635–646, Aug. 2011, doi: 10.1115/DETC2011-48131.

[25] S. N. Reddy K., V. Maranan, T. W. Simpson, T. Palmer, and C. J. Dickman, "Application of Topology Optimization and Design for Additive Manufacturing Guidelines on an Automotive Component." Aug. 2016, doi: 10.1115/DETC2016-59719.

[26] S. Liu, Q. Li, J. Liu, W. Chen, and Y. Zhang, "A Realization Method for Transforming a Topology Optimization Design into Additive Manufacturing Structures," *Engineering*, vol. 4, no. 2, pp. 277–285, 2018, doi: https://doi.org/10.1016/j.eng.2017.09.002.

[27] A. W. Gebisa and H. G. Lemu, "A case study on topology optimized design for additive manufacturing," in *IOP Conference Series: Materials Science and Engineering*, 2017, vol. 276, no. 1, p. 12026.

[28] P. Shankar, M. Fazelpour, and J. D. Summers, "Comparative study of optimization techniques in sizing mesostructures for use in nonpneumatic tires," *J. Comput. Inf. Sci. Eng.*, vol. 15, no. 4, 2015.

[29] E. Atzeni and A. Salmi, "Study on unsupported overhangs of AlSi10Mg parts processed by Direct Metal Laser Sintering (DMLS)," *J. Manuf. Process.*, vol. 20, pp. 500–506, 2015, doi: https://doi.org/10.1016/j.jmapro.2015.04.004.

[30] A. E. Patterson, S. L. Messimer, and P. A. Farrington, "Overhanging features and the SLM/DMLS residual stresses problem: Review and future research need," *Technologies*, vol. 5, no. 2, p. 15, 2017.

[31] M. Leary, L. Merli, F. Torti, M. Mazur, and M. Brandt, “Optimal topology for additive manufacture: A method for enabling additive manufacture of support-free optimal structures,” *Mater. Des.*, vol. 63, pp. 678–690, 2014, doi: https://doi.org/10.1016/j.matdes.2014.06.015.

[32] P. Mercelis and J. Kruth, “Residual stresses in selective laser sintering and selective laser melting,” *Rapid Prototyp. J.*, 2006.

[33] W. E. Frazier, “Metal Additive Manufacturing: A Review,” *J. Mater. Eng. Perform.*, vol. 23, no. 6, pp. 1917–1928, 2014, doi: 10.1007/s11665-014-0958-z.

[34] C. Y. Yap *et al.*, “Review of selective laser melting: Materials and applications,” *Appl. Phys. Rev.*, vol. 2, no. 4, p. 41101, 2015.

[35] W. T. Carter *et al.*, “Scan strategies for efficient utilization of laser arrays in direct metal laser melting (dmlm).” Google Patents, Oct. 2018.

[36] S. Teegavarapu, J. D. Summers, and G. M. Mocko, “Case Study Method for Design Research: A Justification.” pp. 495–503, Aug. 2008, doi: 10.1115/DETC2008-49980.

[37] M. Kayyar, F. Ameri, and J. D. Summers, “A case study of the development of a design enabler tool to support frame analysis for Wright Metal Products, a US SME,” *Int. J. Comput. Aided Eng. Technol.*, vol. 4, no. 4, pp. 321–339, 2012.

[38] M. Fazelpour and J. D. Summers, “Evolution of Meso-Structures for Non-Pneumatic Tire Development: A Case Study,” 2014.

[39] D. Stowe, S. Thoe, and J. D. Summers, “Prototyping in Design of a Lunar Wheel-Comparative Case Study of Industry, Government, and Academia,” 2010.

[40] E. J. Gendreau *et al.*, “Camels and Fennec Foxes: A Case Study on Biologically Inspired Design of Sand Traction Systems,” in *ASME IDETC/CIE*, 2015, pp. 2–11, doi: DETC2015-46286.

[41] R. K. Yin, *Case study research and applications: Design and methods*. Sage publications, 2017.

[42] D. A. Lesyk, S. Martinez, B. N. Mordyuk, V. V Dzhemelinskyi, A. Lamikiz, and G. I. Prokopenko, “Post-processing of the Inconel 718 alloy parts fabricated by selective laser melting: Effects of mechanical surface treatments on surface topography, porosity, hardness and residual stress,” *Surf. Coatings Technol.*, vol. 381, p. 125136, 2020, doi: https://doi.org/10.1016/j.surfcoat.2019.125136.

[43] S. Kim, D. W. Rosen, P. Witherell, and H. Ko, “A Design for Additive Manufacturing Ontology to Support Manufacturability Analysis,” *J. Comput. Inf. Sci. Eng.*, vol. 19, no. 4, Jun. 2019, doi: 10.1115/1.4043531.

[44] E. M. Sanfilippo, F. Belkadi, and A. Bernard, “Ontology-based knowledge representation for additive manufacturing,” *Comput. Ind.*, vol. 109, pp. 182–194, 2019, doi: https://doi.org/10.1016/j.compind.2019.03.006.