特集：ガスタービン・航空宇宙分野におけるAdditive Manufacturing適用の最前線

Advances in Build Plate Design to Reduce Additive Manufacturing Cost and Development Time

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Key words：DMLM, Additive Manufacturing, Support Structures, Gas Turbines

1. Introduction

GE Gas Power is committed to creating world class, lower-carbon solutions for the energy transition. Additive manufacturing (AM) enables the delivery of affordable, reliable, flexible, and sustainable products for power providers around the world(1). GE Gas Power has over thirty Direct Metal Laser Melting (DMLM) printers for development and production at our campus in Greenville, South Carolina (USA) and is in volume production of over fifteen combustion and hot gas path components to reduce emissions, lower fuel consumption, and increase power output(2). The value of AM is achieved through increased component performance, reduced cost through parts combination and process elimination, and faster speed-to-market product introduction. For example, GE recently introduced the AM produced 9HA.02 DLN2.6e advanced pre-mixer combustion system that expands fuel flexibility on both rich and lean fuels, accommodates 50 % hydrogen capability, and extends turndown, the load range possible while in low emissions mode, to a park mode below 15 % load(3). On the 7HA.02, GE introduced an additively produced, high performing stage 2 turbine shroud that helped achieve world class 64 % combined cycle plant output and efficiency(4). These are high impact, high customer value driven applications that will positively impact gas turbine power production for the next twenty years.

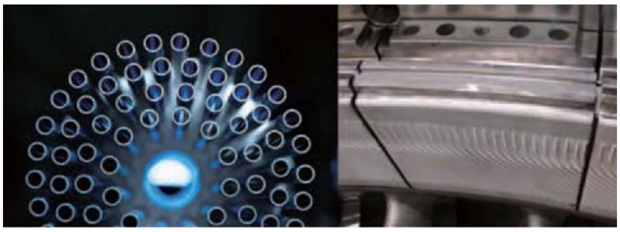

Fig. 1 Additively produced 9HA.02 DLN2.6e advanced pre-mixer and 7HA.02 stage 2 turbine shroud for superior gas turbine emissions and performance.

To strengthen the value proposition for future products, GE Gas Power partnered with the Mechanical Engineering department at Clemson University to innovate new and creative AM build plate techniques. The ability to improve support structures to reduce residual stress deformation drives increased yield and decreases product cost. Traditionally, support structures were minimized to save material and print time. However, applying support structures with an understanding of geometric feature behavior allows them to decrease build-induced part deformation, thereby reducing cost and development time while increasing the overall quality of the component.

2. Materials and Methods

2.1 Study Objective

In a short initial trial, two ad hoc support strategies were applied to a small, concave component with thick-to-thin transitions and the resulting effect on displacement was measured(5). The resulting reductions in distortion served as the basis for the current study. Four common part features were identified through employee interviews and support structure guidelines were generated to support the part features regardless of their position in components. Rather than basing design decisions on purely process-driven limitations, the design of the novel supports instead took into account the mechanical requirements of the part and the need to prevent distortion arising from repeated thermal expansion and compression that is known to occur as layers are printed during the build process(6). The design guidelines were generated to help standardize the application of supports to reduce development time and costs while delivering consistent and successful prints.

2.2 Features of Interest

While AM enables many complex geometric opportunities, four common geometries were initially selected for study of displacement behavior and for design of support solutions. Interviews with eight engineers and technicians at GE Gas

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原稿受付 2022年1月12日

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Power identified the most challenging part features to print. This pool of interviewees provided a holistic understanding of DMLM challenges from both the design and manufacturing points of view. Analysis of the interviews allowed for the selection of four features based on number of times identified and for the naming scheme based on the language used by the interviewees.

The selected features were modeled into testable geometries that allowed for lightweight simulation and effective test prints while remaining representative of feature behavior in end-use parts. The first feature, the bottom surface (Fig. 2a), was created as a 72 x 12 x 9 mm part based on an existing geometry commonly used to calibrate part simulation software. The roof feature (Fig. 2b) was defined as having an opening surrounded by three vertical walls. Its dimensions were 45 x 43 x 27.5 mm with a 25 mm deep recess surrounded by 1.5 mm thick side walls and a 2.5 mm rear wall. The overhang feature (Fig. 2c) was built with 5 mm thick horizontal surfaces but with only one 1.5 mm thick vertical wall. The overall size was 40 x 25 x 30 mm. The build of the hole feature (Fig. 2d) produced a 15 mm hole with 3.5 mm of material at the horizontal edges and 7.5 mm of thickness at the top, for a total envelope of 26.25 x 22.5 x 15 mm.

Support structures were leveraged to reduce part displacement. First, a process-limit defined support strategy was used as a baseline. This was based on the traditional approach to supporting parts for print, addressing DMLM process restrictions while using the minimum amount of volume to reduce print time and costs(7). This baseline was constant across all four geometries and is shown in orange in Fig. 2. All supports used in this strategy were thin plates with toothed attachments to the part. The dimensions of the plates were based on machine capabilities, and the toothed ends maximized ease of removability of the supports.

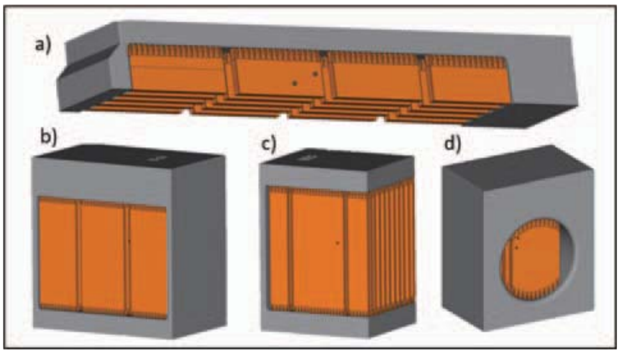


Fig. 2 The four geometries with their baseline supports shown in orange: a) Bottom Surface; b) Roof; c) Overhang; d) Hole

2.3 Hardware Solutions

Commercial dual-laser, high-volume DMLM machines with customizations were used to print the test geometries. Print parameters defined by GE Gas Power were held constant during the prints, and all parts were printed on the same build plate. The operating requirements of power generation parts demand unique properties, so a high γ', nickel-based superalloy was used. The use of DMLM allows for components to be made with the design freedoms associated with AM while also creating very low porosity parts that, after heat treatment, rival the density of wrought parts(8).

In order to quantitatively compare the printed parts to the nominal CAD models, a blue-light scanning method was employed. Rather than making contact with the part like in many traditional tribology approaches, this process uses light reflected back to the camera from the part to create a 3-dimensional surface representative of the printed parts(9). The measured point-cloud was then overlaid onto the original CAD file used in the print to evaluate distortion at specific points on the printed part. This direct comparison between support approaches determined their effectiveness in reducing undesirable shape change.

2.4 Software Solutions

Because of the expensive nature of a print-and-check approach to DMLM, simulation software has become an increasingly popular solution(10). With the ability to tune the software to match both machine parameters and material properties, the use of these software solutions can output a variety of results including stress experienced during the build and the resulting distortion amounts. For this work, the stress output was analyzed to design supports capable of addressing specific stress concentrations, and the distortion output was used to gain a better understanding of the effects the supports had on the resulting part. The displacement output is shown in Fig. 3 for the baseline hole feature in comparison with the printed part.

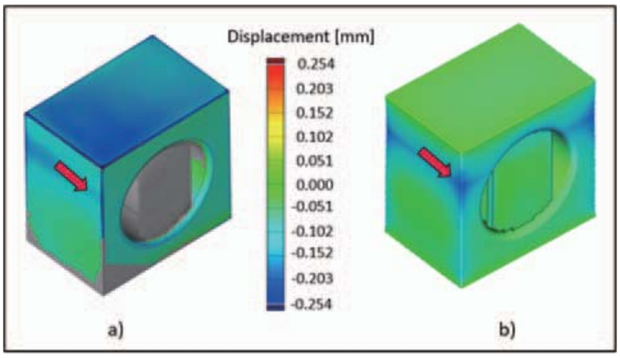


Fig. 3 Comparison between a) the blue-light scan of the baseline hole and b) the simulation prediction with their area of major disagreement shown with the red arrow.

3. Results

3.1 Support Design Guidelines

The design of support structures for each geometry needed to balance process limitations and mechanical strength. The traditional approach to applying support structures to parts was driven solely by process limitations and production objectives, including minimizing material and build time and maximizing removability(11),(12). The spacing of the supports at the maximum bridging distance allowed by the machine complemented these goals. However, this study introduced a novel approach to supporting, which was based on a need for mechanical reinforcement. Leveraging the results of simulations and an increased understanding of feature behavior, supports could be placed strategically to directly address movement by the part during build (e.g., from thermal growth). Fig. 4 shows supports placed in a roof geometry to balance the mechanical and the process needs according to anticipated deformation, shown by the dotted white lines.

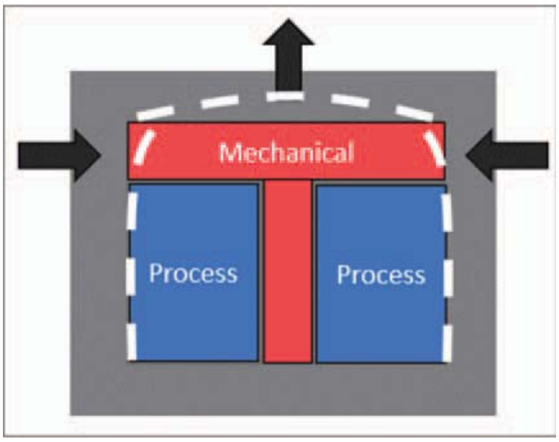


Fig. 4 Behavior of the print addressed by mechanical supports, with the remaining part supported by process-based supports.

The two different approaches were explored for each of the four geometries in order to create support design guidelines that would minimize the amount of costly print-and-check steps needed and that would eliminate subjective understanding of part displacement based on engineer experience. Instead, the guidelines would standardize the practice of support design, regardless of engineer's experience level.

3.1.1 Bottom Surface The bottom surface featured a geometry often used to stress-test materials and machines in order to calibrate simulation software. Its long horizontal surface was susceptible to the uneven cooling of thick-thin transitions leading to tension in the top layer creating a bowing of the part. For guideline design, the bottom surface was described as having two vertical walls connected by a raised horizontal surface. For support design, the entirety of the part was susceptible to curling, making mechanically driven supports necessary along the entire length. The supports span from the part to the build plate (Fig. 5a). Based on these needs, two example supports were created. They alternated checkered columns and plates along the length of the bottom surface in order to have one of the shapes in tension and one in compression. Initial simulations showed that only the plate-majority supports improved part displacement, so the column-majority support was not further utilized.

3.1.2 Roof The roof geometry had a horizontal member supported by three vertical walls. As the horizontal portion was deposited on top of the vertical members, the vertical walls pulled inward, and the least restricted end furthest from all three vertical walls curled upwards. This was a result of the cooling of the top of the geometry creating inward movement of the lower portions. Supports spanned within the cavity created (Fig. 5b). Because of the inward movement of the top of the vertical walls, a mechanical support was needed to bridge between them and provide resistance to the inward compression. The lifting of the center of the upper horizontal portion was also to be mechanically addressed with a support conducive to bracing tensile loads. Remaining areas of the geometry could be supported based on process limits as those were areas of low mechanical need (Fig. 4).

Two approaches were taken for example supports. A first configuration with solid material in the shape of a Y was employed to brace the inward compression and vertical tension. In a second approach, a beam was added across the top of the roof cavity to resist the compression orthogonally and to keep the upper horizontal member from curling. The remaining volumes were supported based on process limits to minimize print time and material use. In a similar effort, both the "Y" and beam approaches were modified and attempted with volume reducing holes and/or plates. This would not only reduce the volume of material needed to print the supports but also aid in the removability of the supports after print. Only the "Y" configuration is depicted in Fig. 4b.

3.1.3 Overhang Overhangs were described as a single vertical wall connecting bottom and top horizontal members at or near a 90° angle. In a manner similar to the bottom surface, the top unrestricted member of the overhang was susceptible to curl as the uneven cooling rate of the part created a top surface in tension. To combat the curling phenomenon, supports spanning part-to-part were needed to address the tensile mechanical need at the free end of the overhang and a process limit need closest to the vertical wall. In attempting to satisfy these needs, two examples were developed (Fig. 5c). In the process limit half of the support design space, thin plates similar to the baseline were used.

At the free end, one approach used a checkerboard pattern of circular cross-section columns (named “cylinder”) and the other used a square cross-section (named “box”). Both were equal in volume and spaced according to process limits.

3.1.4 Hole Finally, the hole geometry was simplified as Kirsch’s solution(13). The hole geometry was defined as a circular cavity extending completely through the body. This shape resulted in an alternating tension-compression pattern around the 90° marks of the circle. The shrinking of the top layer of the geometry as it cooled conflicted with the bottom of the hole constrained by the build plate. This created tension at the horizontal 0- and 180-degree areas and compression at the vertical 90- and 270-degree areas. It was determined that mechanical supports were needed at the vertical and horizontal edges of the hole. In the central portion, the large volume could be filled with process-limit based supports instead. As an example, a box and a cross approach were taken (Fig. 5d). The box connected the vertical and horizontal portions of the circle through vertical and horizontal members, with plates in the middle. The cross instead connected them through diagonal members joining in the center, with empty space allowed by process limits at the diagonal portions of the hole.

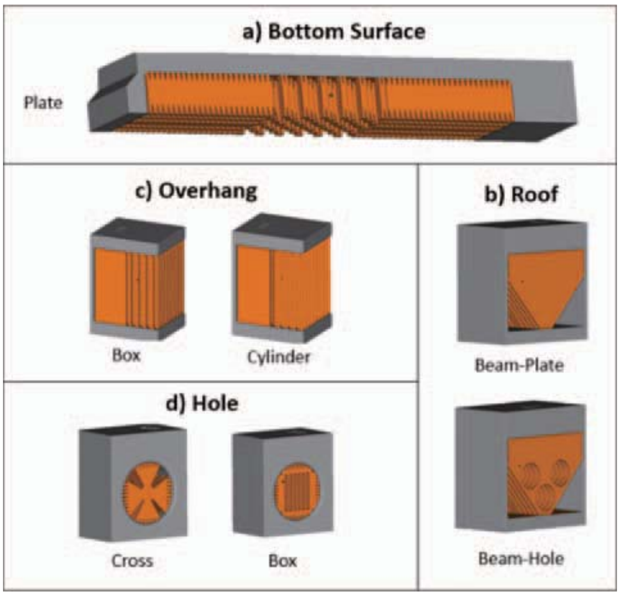


Fig. 5 Successful, innovative support strategies (in orange) of the four geometries.

3.2 Deformation Reduction The parts were all printed and measured to assess the impact of the support structures on the distortion. For the bottom surface geometries, the parts were partially cut from the build plate using wire electrical discharge machining (EDM). The resulting vertical displacement was measured from the build plate with a vertical gauge. The support strategy using a plate-majority approach with columns in compression in the middle reduced the vertical curl compared to the baseline by 0.95 %.

Subsequently, the remaining parts were all removed from the build plate using wire EDM, and the supports were removed by hand. Blue light scanning was used to quantitatively measure the distortion of each printed part compared to the baseline and to yield maximum and average values. Each part was printed twice, and the average of the maximum distortion for each pair was compared to the baseline. These results are summarized in Table 1.

The average distortion was lower than the baseline for all advanced support strategies. The maximum distortion was reduced in all cases except one - the boxed overhang supports. The bottom surface showed a 6.06 % reduction in maximum distortion with an 11.10% increase in support volume. In the roof geometry, the beam support with holes reduced maximum distortion by 58.59 % while only increasing material volume by 23.90 %. The cylinder overhang support reduced average distortion by 11.21 % and increased support volume by only 10.90%. The best hole support result was a 24.59 % reduction in average distortion but with a 51.50 % increase in material use. The removability of the supports was also compared, and the results are summarized in Table 1. Supports without an entry for a change in distortion were not able to be removed, emphasizing the importance of manufacturability in support design.

Table 1 Summary of results for the printed parts in comparison with the baseline support strategies.

Geometry	Support	MAX	AVG	Volume Change	Removability
Bottom Surface	Baseline			-	🟠🟠
	Plate	-6.06%		11.10%	🟢🟢🟢
	Block			-13.40%	🟢🟢🟢
Hole	Baseline	-	-	-	🟢🟢🟢
	Box	-15.15%	-24.59%	51.50%	🔴
	Cross	-24.24%	-21.31%	96.40%	🔴
Overhang	Baseline	-	-	-	🟠🟠
	Box	11.93%	-5.71%	9.50%	🟢🟢🟢
	Cylinder	-3.67%	-11.21%	10.90%	🟢🟢🟢
Roof	Baseline	-	-	-	🟢🟢🟢
	Y			37.30%	🔴
	Y-Plate			-23.30%	🔴
	Beam			52.40%	🔴
	Beam-Plate	-49.49%	-13.65%	3.60%	🟢🟢🟢
	Beam-Hole	-58.59%	-32.10%	23.90%	🔴

4. Discussion

4.1 Implications of Reducing Distortion in Parts

Recent advancements in materials, methods, and machines have put AM on a pathway to directly compete on cost with traditional manufacturing methods. Build plate design and improved support structure techniques enable novel part combination for reduced assembly operations as seen in Fig. 6, and the reduced distortion directly improves yield and reduces cost. While each component has unique geometry requiring specific support geometry, the fundamental strategic approaches to design for bottom surfaces, roofs, overhangs, and holes combined with advancements in compensation modeling provide the AM engineer the tools necessary to quickly design initial build plate strategies. This increases dimensional quality earlier in the design-build phase of a development program and reduces the total development cost. Fast and effective dimensional control early in the design-build phase provides the AM engineer more time to focus on total part quality, throughput, and downstream finishing processes. High quality dimensional AM components that meet or exceed traditional forging and casting processes allow AM to directly leverage traditional downstream supply chain machining and tooling methods, thereby reducing development time and cost. Although the results from this study showed a net increase in the support structure material used for each build, the elimination of part-altering distortion results in a higher yield of AM components capable of service.

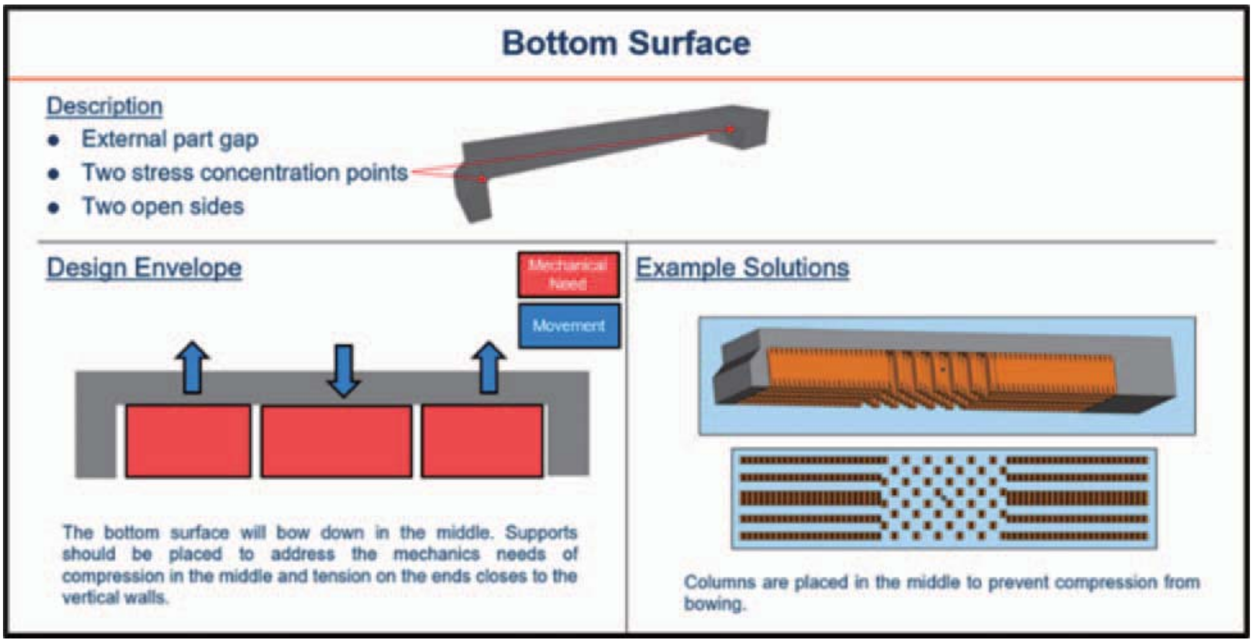
Fig. 6 GT26 lance injector demonstrating assembly reduction.

4.2 Implications of Creating Standardized AM Guidelines

Standardized AM support structure guidelines will result in long-term quality and consistency by implementing proven strategies to create high quality build-to-build and machine-to-machine dimensional results. Standards and design practices drive higher part quality in volume AM production and are important to drive consistency in AM development processes. This removes reliance on individual AM engineer expertise but does not fully eliminate it. Guidelines give the AM engineers a knowledge management-based foundation to enable them to quickly make necessary adjustments based on the component geometry and build plate requirements(14),(15). Design practices reduce the build plate design time for early career AM engineers and provide structure and consistency for new talent to enter the industry and make an impact as soon as possible(16). An example guideline generated in this research is shown in Fig. 7.

5. Conclusion

GE Gas Power is industrializing additive manufacturing to create a new generation of lower carbon, high efficiency gas turbine products. Fundamental AM research and process improvements such as the build plate design example are small but important steps for the continued growth and industrialization of AM components such as the 9HA.02



Bottom Surface

Description
- External part gap
- Two stress concentration points
- Two open sides

Design Envelope

The bottom surface will bow down in the middle. Supports should be placed to address the mechanics needs of compression in the middle and tension on the ends closes to the vertical walls.

Example Solutions

Columns are placed in the middle to prevent compression from bowing.

Fig. 7 Example guideline generated for the bottom surface.

DLN2.6e advanced combustor and the 7HA.02 stage 2 turbine shroud. AM is also opening new pathways in research and design for engineers to create novel components capable of burning very high levels of hydrogen while managing the risk of burning such highly reactive fuels. The combination of highly efficient and low carbon burning gas turbine components enables GE Gas Power to create a new generation of lower carbon power generation products and allows power producers to adapt to a future decarbonized world.

References

(1) Ford, S., and Despeisse, M., 2016, Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges, J. Clean. Prod., 137, pp. 1573-1587.

(2) 2016, GE Power Opens First Advanced Manufacturing Facility, a $400 Million Digital Industrial Investment for South Carolina, Gen. Electr.

(3) Vandervort, C., Leach, D., and Scholz, M., 2016, Advancements in H Class Gas Turbines for Combined Cycle Power Plants for High Efficiency, Enhanced Operational Capability and Broad Fuel Flexibility, The Future of Gas Turbine Technology, 8th International Gas Turbine Congress.

(4) 2017, HA Technology Now Available at Industry-First 64 Percent Efficiency, Gen. Electr.

(5) Morand, L., Summers, J. D., and Pataky, G. J., 2021, Exploration of Support Structure Design for Additive Manufacturing at a Major OEM: A Case Study, ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection.

(6) Ding, J., Colegrove, P., Mehnen, J., Ganguly, S., Almeida, P. M. S., Wang, F., and Williams, S., 2011, Thermo-Mechanical Analysis of Wire and Arc Additive Layer Manufacturing Process on Large Multi-Layer Parts, Comput. Mater. Sci., 50(12), pp. 3315-3322.

(7) Strano, G., Hao, L., Everson, R. M., and Evans, K. E., 2013, A New Approach to the Design and Optimisation of Support Structures in Additive Manufacturing, Int. J. Adv. Manuf. Technol., 66(9), pp. 1247-1254.

(8) Yap, C. Y., Chua, C. K., Dong, Z. L., Liu, Z. H., Zhang, D. Q., Loh, L. E., and Sing, S. L., 2015, Review of Selective Laser Melting: Materials and Applications, Appl. Phys. Rev., 2(4), p. 41101.

(9) Xiao, G., Liu, S., Zhang, Y., Wu, Y., Chen, B., and Song, S., 2021, A Measurement Method of the Belt Grinding Allowance of Hollow Blades Based on Blue Light Scanning, Int. J. Adv. Manuf. Technol., 116, pp. 3295-3303.

(10) Peter, N., Pitts, Z., Thompson, S., and Saharan, A., 2020, Benchmarking Build Simulation Software for Laser Powder Bed Fusion of Metals, Addit. Manuf., 36(October 2019), p. 101531.

(11) Seepersad, C. C., Govett, T., Kim, K., Lundin, M., and Pinero, D., 2012, A Designer's Guide for Dimensioning and Tolerancing SLS Parts, Solid Freeform Fabrication Symposium, Austin, TX, pp. 921-931.

(12) Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., and Martina, F., 2016, Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints, CIRP Ann., 65(2), pp. 737-760.

(13) Kirsch, C., 1898, The Theory of Elasticity and the Needs of Strength Theory, J. Assoc. Ger. Eng., 42, pp. 797-807.

(14) Huang, G. Q., Shi, J., and Mak, K. L., 2000, Synchronized System for 'Design for X' Guidelines over the WWW, J. Mater. Process. Technol., 107(1), pp. 71-78.

(15) Edwards, K. L., 2002, Towards More Strategic Product Design for Manufacture and Assembly: Priorities for Concurrent Engineering, Mater. Des., 23(7), pp. 651-656.

(16) Fazelpour, M., Patel, A., Shankar, P., and Summers, J. D., 2019, Design Guidelines as Ideation Tools-a User Study on Exploring the Subjectivity of Unit-Cell Design Guidelines, Int. J. Des. Creat. Innov., 7(1-2), pp. 50-69.