Computational Engineering and Design Tools for Additive Manufacturing

Ryan H. Carter, Drew P. Seker, Steven M. Storck, Li Ma, and Sam Sheppard

ABSTRACT

This article describes Johns Hopkins University Applied Physics Laboratory (APL) capabilities in computational engineering and design for additive manufacturing. Because additive manufacturing's selective deposition of material and energy enables the ability to produce new and novel geometries, designers and fabricators need new design software and validation methods to take full advantage of this new fabrication technology. APL employs an immense range of modeling, optimization, and finite element modeling software to unlock the true potential of additive manufacturing. By combining these AM-specific computational engineering design tools with its diverse expertise in areas such as rapid material development, the Lab can fabricate novel components with unprecedented properties for its sponsors' unique missions.

INTRODUCTION

A fourth industrial revolution is upon us, enabled by additive manufacturing (AM). This fabrication technology differs from conventional subtractive fabrication because it is a layer-by-layer process that selectively deposits material and energy. Because of these differences, AM is changing how the world and APL produce advanced prototypes and fielded hardware. The selective deposition of material and energy enables the ability to produce complex parts. Today, advancements in design and optimization software take advantage of AM's selective deposition nature to facilitate the design of new cellular solids (e.g., foams and lattices) and visually organic-looking, optimized structures. Although design and optimization software leverages the selective nature of AM, new simulation tools are required to enable an understanding of the impact of the complex thermomechanical conditions caused by AM. This article describes APL's use of AM-specific software tools and the need for further development in this area.

AM evolved from rapid prototyping.[1] The American Society for Testing and Materials (ASTM) defines it as the "process of joining materials to make parts from 3-D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies."[2] The desired geometry is "designed in a computer-aided design (CAD) software essentially broken down into a series of 2-D cross-sections of a finite thickness"[1] through specialized slicing software. These finite thicknesses are then stacked on top of each other to achieve the final part geometry.

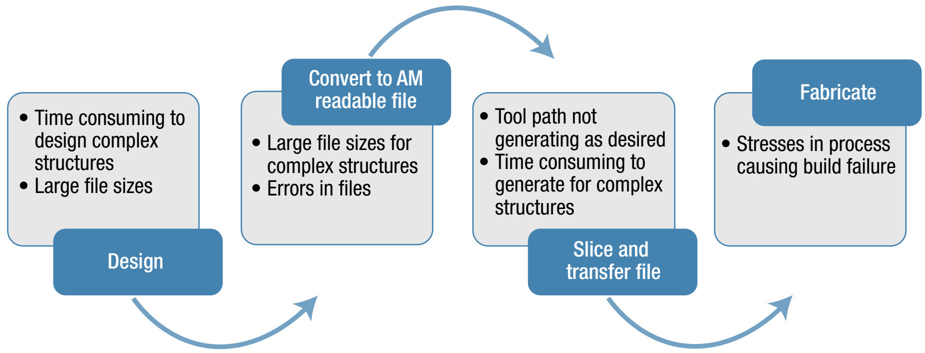

Figure 1. AM challenges. The AM workflow is a feedback loop, so a challenge at any one stage could require a part redesign, a change in processing, a different method of modeling entirely, or all of these. Such time-consuming changes negate the main benefits of AM—rapid iterations and quick turnarounds.

NEED FOR AM-SPECIFIC SOFTWARE TOOLS

AM enables the fabrication of parts with novel shapes, structures, and functionalities. Because of the relative newness of the technology and the still-evolving knowledge of how to best use it, process challenges (Figure 1) must be overcome before AM is adopted widely. The AM workflow is a feedback loop, so a problem at one stage could require a part redesign, a change in processing, a different method of modeling entirely, or all of the above. For example, for lattices to be readily used in the AM workflow, they must be designable in a relatively short time frame and have a file size that processes in hours, not days. If complex structures take significant time to design and process, fabricating them with AM might not be worthwhile since the technology's full capabilities—rapid iterations and quick turnarounds—cannot be leveraged. Using AM to its fullest potential and overcoming these process challenges requires the use of AM-specific software tools.

DESIGN TOOLS FOR AM

Computer-Aided Design

All AM designs have to start somewhere, and one of the most powerful and common places to start is CAD. CAD software tools allow users to design in a digital space. Common examples include Creo, SOLIDWORKS, CATIA, and many more. These software packages are typically used to design a single part, assemble multiple parts, and create drawings. In addition, many CAD programs let users perform rudimentary testing and analysis. CAD is useful because it can turn an idea or a preexisting part into a virtual 3-D model in minutes. Then that model can be viewed, added to an assembly, converted into drawings, or tested without ever being manufactured. This gives designers much flexibility to be creative and try many iterations of the same part. In addition, the 3-D models and drawings allow designers to communicate their ideas with others effectively. Users can display impressive and orderly designs without ordering a prototype or creating drawings by hand. One of the most significant benefits of CAD is that it offers the ability to edit designs effortlessly. Parts can be modified or scaled in just a few clicks of a mouse, infinitely faster than remanufacturing a part from scratch. And when CAD is combined with the rapid speed of AM, a part can be conceived, virtually created, and manufactured all in one day. However, this form of modeling becomes obsolete when designs get overly complicated. A designer working with organic geometry can only get so far with simple 3-D features because of the time-consuming nature of creating such geometry and the fact that the geometries result in large file sizes that can push computers to their limits.

Implicit Modeling

Another modeling method used in AM is implicit modeling. This type of modeling differs from typical CAD because it uses continuous mathematical representations (implicit functions) to describe features instead of surfaces.[3] A surface representation, which uses a thin boundary to model the shape and is made up of vertexes, edges, and faces, is sufficient for conventional computer numerical control fabrication because work is being done on a solid billet of material.[5] There is no internal structure to be concerned with. However, such an assumption cannot be made in the case of AM since it is a layer-by-layer fabrication technology. Computers will quickly struggle to generate surfaces when designing a complex part with varying internal structures for AM. To fully define the surfaces and develop a usable component file, a large amount of data is required. The vast data required will cause the software to lag or crash, making it impossible to continue the design. On the other hand, modeling with implicit functions allows the ability to design complex parts with significantly less computing power. Not only does it require less computing power, but the fact that the mathematical distance function produces a mathematical value for all locations means that the designer can now model with fields.[4,5] The power of modeling with fields is illustrated in Figure 2, which shows that the geometry can vary as a function of the field.[6,7]

This benefit unlocks the true potential of AM to fabricate complex cellular solid structures that have improved structural, thermal, or acoustic properties. It is now possible to use implicit modeling to generate bioinspired designs. Evolution has "optimized" cellular structures to thrive for life (Figure 3).[9] A common example is a toucan beak. It has evolved into a complex cellular network that decreases the weight of the beak and serves as a thermoregulator. This example demonstrates that cellular structures can have multiple unique benefits within the same design.

APL uses nature as inspiration to design architected structures and metamaterials (where the structure of the part defines the macroscopic properties) and then applies them to sponsors' challenges. For example, the characteristics of the cellular structure (i.e., lattice) are varied throughout the bracket shown in Figure 4, enabling location-specific characteristics similar to those found in nature.

APL teams use implicit modeling to design complex cellular structures for various sponsor applications, combining them with novel APL-developed materials to fabricate components with unprecedented properties. For example, designing, predicting, and tailoring cellular structures' performance (structural, thermal, and modal) can profoundly impact the designs of aerospace vehicles and weapon systems. This capability will allow APL and the nation to pioneer a new era of aerospace vehicle and weapon system design that will ensure the nation's preeminence in the 21st century.

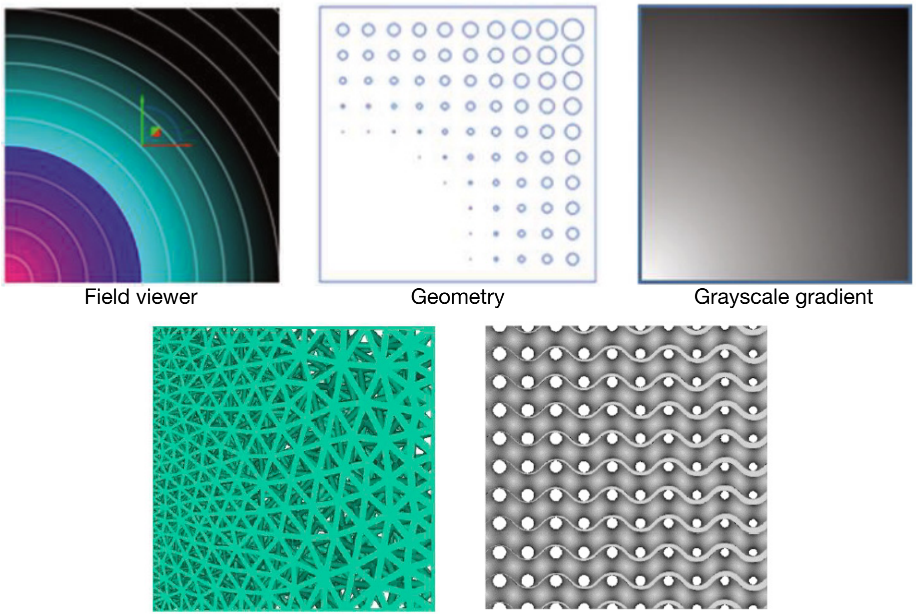

Figure 2. Example of distance fields computed with implicit functions. With this modeling technique, a mathematical distance function produces a mathematical value for all locations rather than a cumbersome surface. The values are used to understand where the points are relative to the geometry (such as inside versus outside the volume) and the distance from the volume boundary. This technique is particularly useful for modeling complex parts. (Image reprinted with permission from Allen.[6])

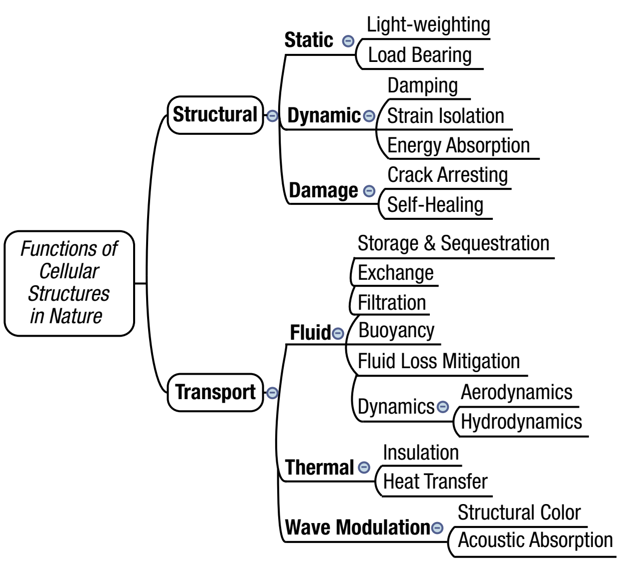

Figure 3. Functions of cellular structures in nature. Evolution has "optimized" cellular structures to thrive in many ways. Implicit modeling can be used to generate bioinspired designs. (Reprinted with permission from McNulty et al.[8])

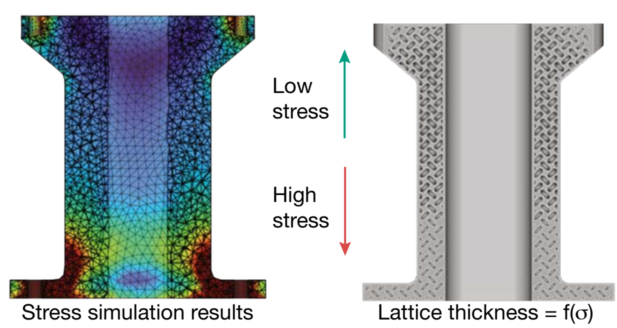

Figure 4. Example of architected cellular structures designed with implicit modeling. The characteristics of the cellular structure (i.e., lattice) are varied throughout the bracket, enabling location-specific characteristics similar to those found in nature.

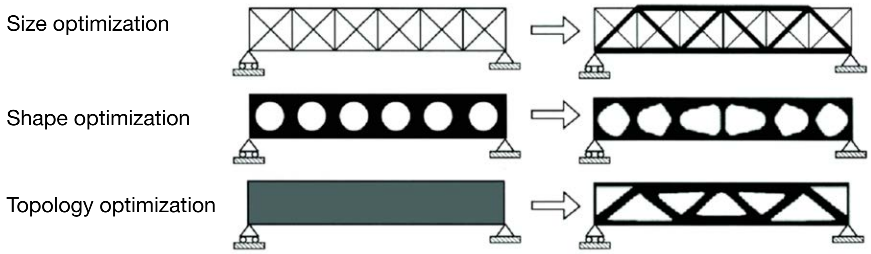

Figure 5. Comparison of optimization methods. As the terms suggest, size optimization involves optimizing an object's size, and shape optimization involves identifying the optimal shape of the object or its openings. Topology optimization involves optimizing the object's geometry and therefore encompasses size and shape optimization. (Image reprinted from Gebisa and Lemu, Attribution 3.0 Unported, CC BY 3.0, https://creativecommons.org/licenses/by/3.0/.[9])

OPTIMIZATION DESIGN TOOLS FOR AM

Optimized designs are becoming more common as engineers seek to make the most of technological advancements in manufacturing capabilities and computational power. Gone are the days of an engineer hand-drawing designs to deliver to a machinist who will turn the part on a manual lathe. Design optimization tools have been around since the birth of computers; however, their usefulness was constrained by the computational power and fabrication technologies available. While computers were able to generate optimized organic structures, most of these structures could not be fabricated with conventional fabrication technologies. With advancements in AM, the modern engineer can use massive computing resources to efficiently optimize designs for specific uses and turn these complex, organic geometries into reality. Different types of design optimization exist, including size, shape, and topology. Figure 5 compares these optimization methods. Because topology optimization involves optimizing the object's geometry, it encompasses size and shape optimization.

Topology optimization and *generative design* have become buzzwords for describing automated design optimization. Although they are often used interchangeably in the industry, there are important distinctions. Topology optimization is an enabling technology of generative design and one of many design optimization algorithms. *Topology optimization* specifically refers to a process of material removal through iterated simulation. This process results in the single most efficient material layout within a set volume to meet the prescribed loading, boundary conditions, constraints, and optimization goals. *Generative design* is a more broad term for design optimization. A computer algorithm, artificial intelligence, or higher machine learning generates many design solutions that pass a set of requirements with minimal user interaction. Generative design is not limited to one optimization algorithm, as with topology optimization. Instead, generative design has an artificial intelligence backbone that uses a variety of CAD, finite element analysis (FEA), and optimization algorithms to arrive at the best set of solutions that solve the defined problem. Generative design's most powerful benefit is its ability to simultaneously compare hundreds, or even thousands, of design options while considering everything from part performance to manufacturing costs.

Topology optimization has two common uses available in many commercial FEA and even CAD packages today: maximum stiffness and minimum mass optimization schemes run in a static structural analysis. In maximum stiffness optimization, the user must input a target mass, and the software will optimize to the stiffest design given the loading constraints. For minimum mass optimization, the user must input a maximum stress or deflection constraint so that the solver can find the minimum mass capable of withstanding the loading constraints. The optimization algorithm takes over once the engineer inputs all the necessary information. The entire design volume is meshed at this point, and the first FEA simulation runs. The topology optimization scheme then uses an algorithm for density penalization to modify the geometry. There are many approaches for how this can be done, but in general, the algorithm forces elements within the mesh that are not carrying any of the load to go to 0 density and therefore be removed from the geometry.[10] Figure 6 shows an example of a component whose topology has been optimized.

One of the most common approaches, solid isotropic material with penalization (SIMP), was developed as

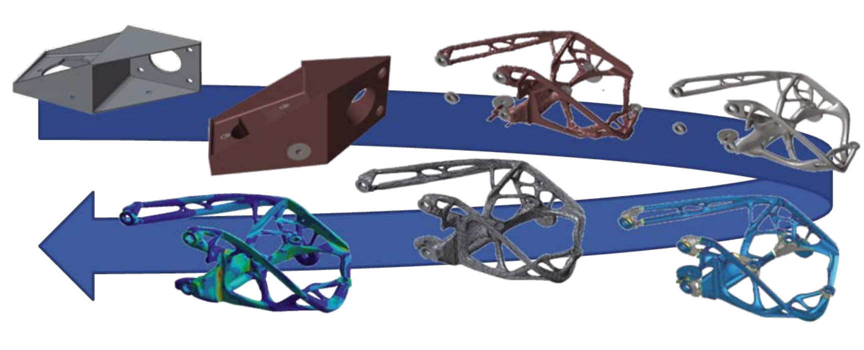

Figure 6. Example of topology optimization cycle. The bracket design evolved from a simple CAD drawing to a fully optimized design.

early as 1992 and is still widely used today.[11] The optimization software has additional constraints that can be applied to the resulting geometry to aid fabrication. The most common types include symmetry, minimum member size, draw directions, extrusion, and overhang angles. Each new constraint applied to the model, be it physical loading or manufacturing, reduces the level of optimization that can be accomplished. The manufacturing constraints become a trade-off between the level of optimization and how easily a part can be fabricated (which will drive cost and schedule).

The software industry currently offers many options for topology optimization. Most can be split into two distinct categories, one targeting designers and one targeting engineers. The most recent technology advancements have seen simple versions of topology optimization being brought right into SOLIDWORKS and Creo, two of the most common design software packages. An engineer will need to use a package with a stronger FEA backbone for more capable optimization software. Many of the most widely used FEA packages are beginning to implement topology optimization capabilities, including those from Ansys, Livermore Software Technology (LS-DYNA), Dassault Systèmes (Abaqus), COMSOL, and Altair Engineering (HyperWorks). In the FEA versions of topology optimization software, the user has more controls and capabilities, especially in the areas of meshing control and nonlinear behavior. Several FEA packages can perform dynamic simulations, handle nonlinear materials and assemblies of parts made from different materials, and control convergence criteria. Design software capabilities are generally limited to simple static structural optimization of single components. One commonality between all topology optimization software is that postprocessing results and reconstructing geometry make up the majority of the manual labor involved in the optimization process. Most software finishes the last optimization loop and terminates as soon as convergence is found. This means that the user is left with the resulting mesh of elements that survived the optimization process. Turning this mesh into a usable CAD part with parametric features and traditional nonuniform rational b-spline (NURBS) surfaces can take some time, depending on the software used.

The first successful use of topology optimization at APL was for a 2018 independent research and development grant to optimize a structural bracket from NASA's Parker Solar Probe (PSP) spacecraft built and operated by APL. Parker Solar Probe launched in 2018 to study our sun, its corona, and space weather. The bracket shown in Figure 7 was originally designed as a simple aluminum bracket; it was lightweight since its center was hollowed out and stiff because of its tube-like shape. It was a good candidate for optimization because several brackets were used to mount different sensors around the spacecraft, so any weight savings realized by optimization would be multiplied fourfold. Another factor in favor of optimizing this bracket was the well-defined loading conditions. Topology optimization reduced its weight by 65% (Figure 8). The final geometry was built additively and tested to flight specifications, showing an impressive correlation between test results and random vibration analysis of the optimized shape. While the bracket passed mechanical testing, it was not flown because of timeline restrictions.

The field of topology optimization is still evolving, with tens of papers published every year on topics ranging from new interpolation schemes to the optimization of new physics altogether. Recently, there has been significant interest in thermal optimization and multiphysics capabilities that consider thermal and structural loading conditions and performance metrics. Both industry and academia are also pouring a lot of effort into developing lattice optimization capabilities, which is at least in part driven by the advancements in AM capabilities and the demonstrated ability to fabricate components with complex lattice structures.

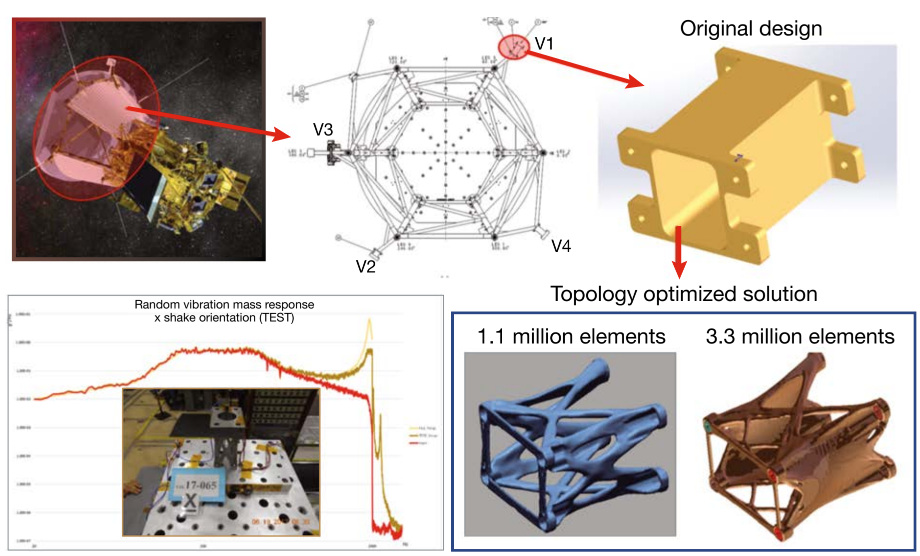

Figure 7. Optimization cycle of the PSP bracket. Top (left to right), rendered image of PSP, locations of the bracket of interest on a drawing of the spacecraft truss system, and bracket design that flew (unoptimized). Bottom (left to right), the vibration test setup overlaid on a simulation and measured response plots and CAD images of topology-optimized solutions.

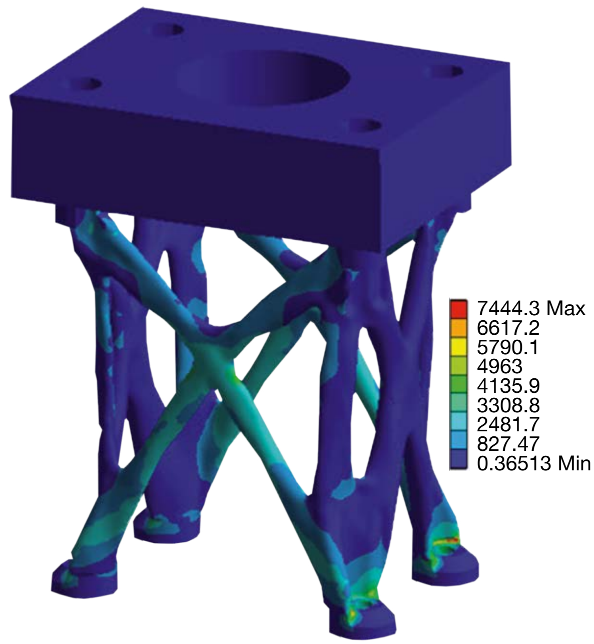

Figure 8. FEA results validating the PSP bracket optimization. Topology optimization reduced the bracket's weight by 65%.

SIMULATION TOOLS FOR AM

In addition to considering how to take advantage of AM to optimize the design of complex geometries, engineers need to consider build shape imperfections during the design process. AM processes' highly complex thermomechanical conditions lead to high gradients and high temperatures that cause deviations between nominal and actual parts.

For the traditional injection-molded parts, CAD geometry must be adjusted to compensate for the anticipated shrinkage that occurs when the liquid cools down inside the model. Because AM is much more complex than traditional processes, compensating for part geometry distortion in AM parts is critical to the design process. Figure 9 shows an example of the differences between the original and compensated geometry.[12]

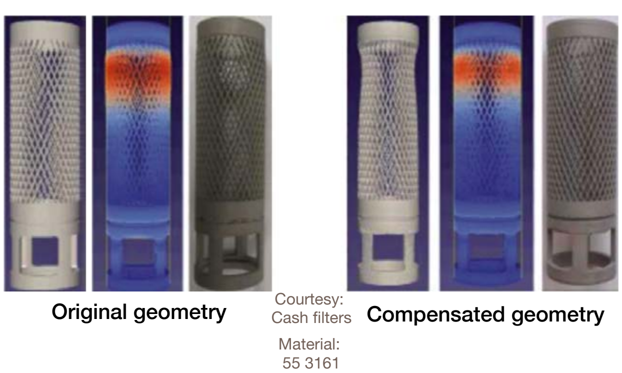

Figure 9. AM print process simulation of original and compensated geometry. Red shows locations of high distortion. (Image reprinted with permission from Ansys.[12])

In the AM process, the processing and materials and the way the part sits on the print bed while it is being printed affect the distortion. Several leading AM-specific simulation products, such as those from Ansys and Dassault Systèmes (3DEXPERIENCE), include automation tools to compensate for the AM geometry distortion. To predict the built part's thermal distortion and residual stress, a sequence of FEA models for AM processing must be run, including thermal, subsequent mechanical, and postprocessing models (such as one that removes the part from the build plate and applies heat treatment). Process parameters can be optimized, and strategies can be deployed to reduce build defects and distortion. Support optimization can be performed to determine the optimal amount of support necessary for manufacturing. The design is digitally morphed using the reverse shape optimizer to compensate for simulated part distortions with unchanged topology.

FUTURE OF DESIGN FOR AM

AM has revolutionized the manufacturing industry, from enabling the development of concept models to the creation of functional parts, and it is now driving the next generation of engineering design and innovation. AM may be transforming manufacturing; however, many limitations prevent further adaptation and the next innovation.

Whether AM machines are more capable than software is a chicken-and-egg problem. On the one hand, AM machines are more capable than software because they do not care about file size or geometric complexity. Most of the computational work has been completed by the time the build file is on the machine. The limitation is on the software side because of the difficulty in converting the designed file to a usable format that slicing software can read. Over the years, many file formats for AM have been created; however, no perfect solution has been reached to date. Stereolithography files (.STLs) are still common and can be used for geometrically simple components. However, for complex designs, the file size becomes overwhelmingly large to the point that it is unusable. Potential solutions have been developed, such as the 3D Manufacturing Format (.3MF), which drastically reduces the file size for strut-based lattices.[13] Even if a usable file for slicing can be generated, creating the tool paths of the AM machine still presents an issue. In some slicing software, the algorithm that generates the tool paths takes a great deal of time to create the paths for the entire part. At the same time, other slicer software packages struggle to generate a visual preview of the paths for the operator to review. In addition, to take full advantage of the design freedom AM processes offer, more design methods and tools are needed to address challenges such as multiscale structure design, multi-material design, and parts consolidation. To

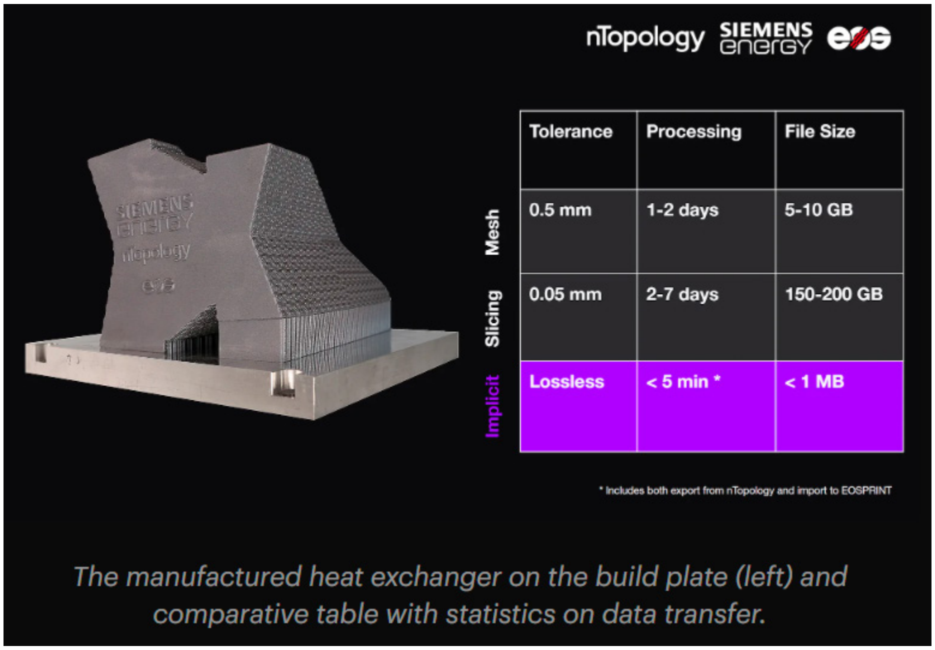

Figure 10. The heat exchanger produced with Implicit Interop capability demonstrates the capability of going from nTop to the EOS Slicer in under 5 minutes with under a megabyte of data. (Reprinted with permission from nTop.)

unlock the full potential of metal AM, it is essential to develop multiscale and multiphysics integrated computational materials engineering for computational linkage of process–microstructure–properties–performance.

On the other hand, the software is more capable than AM machines. For example, current design software can generate complex designs inspired by nature. To achieve fully optimized structures like many of those found in nature, the ability to print with multiple/graded materials and/or to tailor microstructure in specific locations is required. Currently, there are limitations to how multiple materials can be printed at once. To achieve graded materials, a directed energy deposition machine must be used. However, this type of machine limits the minimum feature size and surface roughness achievable. It is also possible to design with infinitely high precision and accuracy with unimaginably small features; however, the ability to additively manufacture fine features with minimal surface roughness and multiple materials is quite limited. In recent years, the excitement around complex structures such as lattices has fueled software and machine manufacturers to invest heavily in solving limitations. One such example is the bottleneck of “design to physical part.” EOSPRINT and nTop worked collaboratively to develop the “Implicit Interop capability.”[14] This new capability allows for “the direct transfer of implicit geometry between design, build preparation, CAD, CAE, PLM, and visualization software without any loss of geometric precision or design intent.”[15] To demonstrate the functionality of this new capability, EOS and nTop partnered with Siemens Energy to produce a heat exchanger (with a bounding box size of 220 × 150 × 160 mm; Figure 10).[15] Before Implicit Interop, meshing the file with such complexity and size took days. This capability reduced the processing time to five minutes or less.[15] This collaboration is an example of new capabilities that could be utilized by the AM industry.

Because the above example is such a success, we believe there will be an exponential increase in capabilities within the additive-specific software and for additive manufacturing machines. We hope that it is clear that the ability would not be possible without collaboration. For example, suppose humankind wants to fully develop the ability to print functionally graded materials in three dimensions in a design that has been topology optimized for both shape and material. We must realize that innovation occurs at the intersection of technical disciplines. Those from many disciplines, from material scientists to topology optimization experts, must be brought together to solve this problem. In conclusion, we foresee that the roadblocks described in Figure 1 will be solved soon through collaboration.

CONCLUSION

AM is enabling the fourth industrial revolution. Complex structures with unique capabilities can be realized by combining AM’s ability to selectively deposit material or energy layer upon layer with AM-specific software. These AM-specific software packages also overcome some of the challenges of additive technologies (such as designing complex components in a time-efficient manner). However, the ability to export the files to a format that is readable to AM slicer software without sacrificing minimum feature size has still not been addressed. It is clear that as the ability to design and optimize complicated parts continues to advance, the need for more computationally efficient methods of exporting the parts to slicing software grows. At the same time, to keep up with software capabilities, AM machines must continue to advance with the capability to print fine features while also being able to print multi-materials efficiently. APL uses its diverse expertise in combination with the latest AM-specific design tools to continually push the boundaries of what is possible and provide its sponsors with unique solutions to complex problems.

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