DIGITAL INDUSTRIES SOFTWARE

Industrialized AM for aerospace and defense

Providing a pragmatic, end-to-end solution for designing and producing parts at scale

Executive summary

Aerospace and defense spend $2.897 billion annually on additive manufacturing (AM) equipment, materials and services. This includes ground, air, space and launch systems for both structural and nonstructural applications for commercial and military use. Aerospace and defense is the largest additive manufacturing sector and the use of AM as a production tool in that industry continues to expand. Aerospace and defense's increased reliance on AM for print production is demonstrated by several applications, including Rolls-Royce's compressor case, spacecraft heat exchangers and wing structures. Other examples include Saba using AM for printing an exterior hatch and Relativity Space's plan to produce reusable launch vehicles. These applications are evidence of the efforts to scale production with AM.

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Abstract

This paper explores the challenges aerospace and defense face when using AM at scale and how an end-to-end software solution lowers program risk, delivering new avenues of innovation in the industry.

Benefits of AM for the aerospace and defense industry

The aerospace and defense sector was an early adopter of AM. Boeing started to use it in the mid1990s to print nonstructural components. Now SpaceX, NASA, Honeywell Aerospace and Lockheed Martin all use AM. AM is an excellent tool for aerospace and defense applications such as reducing weight, enabling small series production, lowering fuel cost and consolidating parts. At the same time, using AM can satisfy the higher standards of aerospace and defense for strength, temperature, lifecycle and dynamics.

Some examples of this include a NASA test engine that utilized cryogenic liquid hydrogen and liquid oxygen to withstand the extreme environment inside a flight rocket engine where the fuel is burned at higher than 3,315 degrees Celsius. In the U.K., BAE Systems has a target to produce 30 percent of the parts for the Tempest fighter jet with AM. In the U.S., the Marine Corps and Defense Innovation Unit partnered with ICON to print a structure for hiding military vehicles from air reconnaissance. Figure 1 shows an analysis of the maturity of aerospace and defense applications.

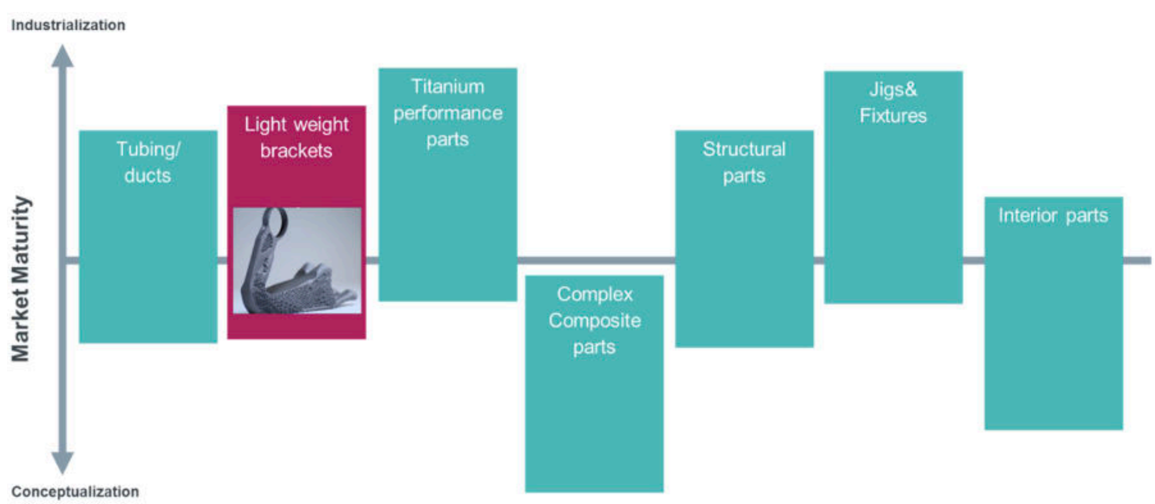

Figure 1. AM application maturity in the aerospace and defense industry.

The following are possible AM use cases for aerospace and defense companies driving the shift from conventional manufacturing to additive manufacturing:

- Optimized structures
- Elimination of expensive tooling
- Part consolidation
- On-demand manufacturing
- Shorten the lead times
- Lightweight parts
- Mass customization

Siemens Digital Industries Software believes additive manufacturing is reshaping the aerospace and defense industry. We are industrializing additive manufacturing so aerospace and defense companies can incorporate it into their product development and production operations – realizing the next level of product, manufacturing and business performance. There are three ways Siemens believes additive manufacturing can disrupt the aerospace and defense industry: by reimagining products, reinventing manufacturing and rethinking business.

Figure 2. A lightweight printed bracket.

Reimagining products

- Optimizing performance of parts with new materials
- Reducing weight of parts and components significantly while maintaining or increasing performance
- Creating complex structures and components (for example, bionic shapes, lattice structures, internal cavities)
- Customizing interior plastic parts at no additional cost

Reinventing manufacturing

- Decreasing costs for low volume, complex parts in production (for example, elimination of molds and castings)
- Reducing material waste leading to lower costs
- Simplifying complex assemblies by printing one part rather than multiple components
- Creating complex tooling faster and at lower cost
- Lowering the number of manufacturing steps and thereby reducing production errors

Rethinking business

- Providing faster repair in the field and increased availability of parts at point of use
- Integrating vertically to produce parts faster and on demand
- Accelerating innovation by speeding up design iteration cycles, production and time-to-market cycles

Barriers to industrializing additive manufacturing

Many organizations face barriers as they begin pushing the limitations of additive manufacturing and exploring how the latest technologies can help industrialize it.

As we can see in figure 3, economics is one driver of the current adoption of additive manufacturing. We can also see in this figure how AM compares financially with conventional manufacturing. Based on the AM capabilities available today and design complexity and volume, additive manufacturing may be more economical compared to more conventional methods. But the technology is advancing so quickly that even if it is not economical today, it may be tomorrow or in the near future. For example, in many cases today's HP Multi Jet Fusion technology can be used to print tens of thousands of small plastic parts more economically than injection molding. Metal AM printer companies are also rapidly adding additional lasers and automation for significantly enhanced production efficiency and throughput, further reducing overall cost.

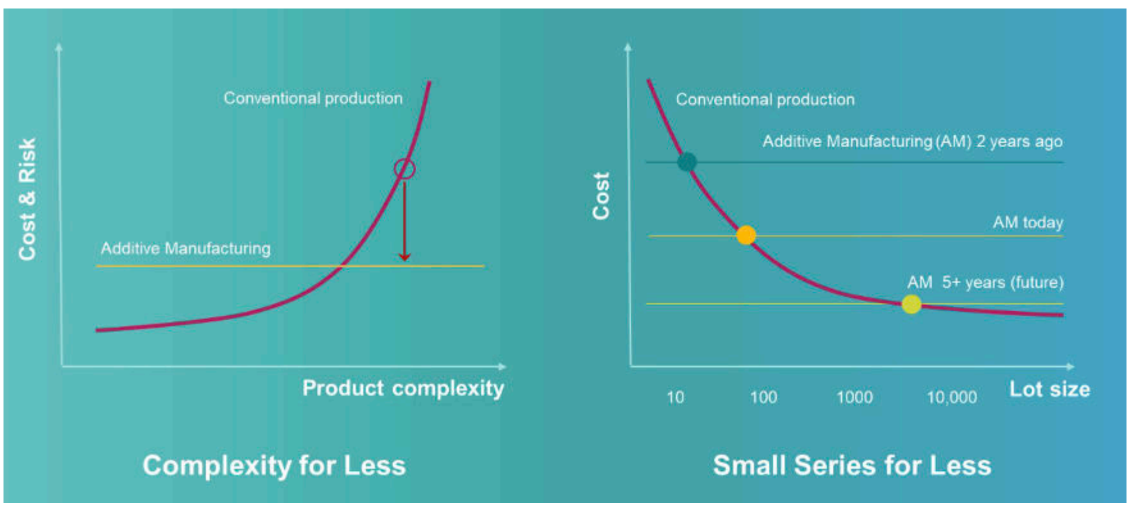

Figure 3. The cost of AM and conventional production.

One of the largest barriers for companies wanting to adopt AM today is the current state of the software for additive manufacturing. We have seen customers who use as many as five to eight products to execute the entire additive manufacturing workflow: a computer-aided design (CAD)/computer-aided engineering (CAE) system from one vendor, topology optimization from another, lattice structures from a third, print preparation software from the printer original equipment manufacturer (OEM) and other packages for machining or finished product inspection. This uncontrolled, disconnected process impedes the ability of companies to quickly iterate on 3D printed parts, breaks the digital chain of data and impairs traceability throughout the process as you can see in figure 4.

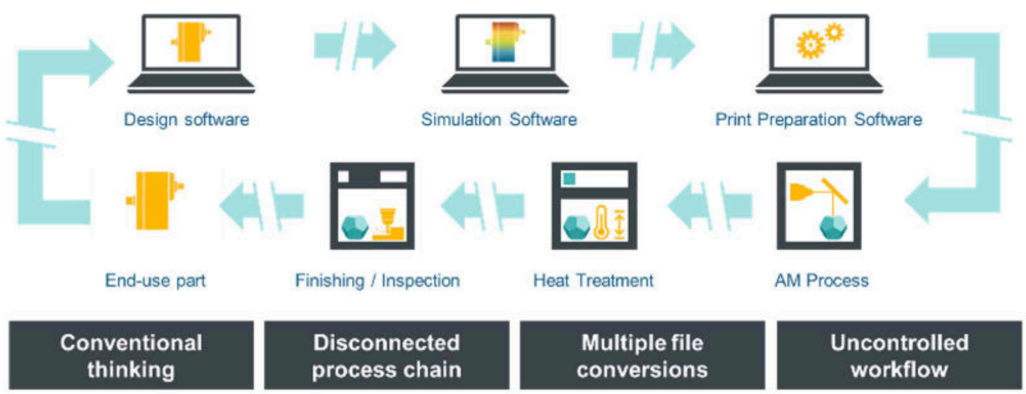

Figure 4. The normal disconnected AM software process.

The Siemens solution to AM challenges

Siemens AM value proposition
Siemens is a leader in industrializing AM for production parts. We offer a comprehensive end-to-end integrated software system for product development and production and drive a wide range of production 3D printing technologies in a single solution. We have an ecosystem of leading partners and together we are revolutionizing what's possible. We also help our customers to engage in AM by sharing our experience with consulting, engineering and printing services. Siemens' goal is to make additive manufacturing an industrial process. We believe that AM should be just another tool in the toolbox when it comes to manufacturing parts, but to achieve that goal, AM users need to have ability to execute all of the required software operations as part of a single, unbroken workflow from design to final part delivery. This is why Siemens has been investing heavily in that goal.

Streamline AM with an end-to-end solution

As we engage with customers, they articulate their challenges, like the disjointed software process for AM. We then use these as a springboard for developing our software solutions. By leveraging digital twin technology we have created an integrated, end-to-end software process for additive manufacturing that addresses these challenges as we see in figure 5.

Applying our knowledge of the entire additive process to the toughest problems our customers face means we can bring unparalleled value to our additive solution. We are investing across the board in designing solutions that address the most difficult issues facing companies today and the result is a single, integrated end-to-end system for industrial AM. With technologies like convergent modeling, integrated topology optimization, lattice structure generation and built-in build tray setup and print execution functions, the software workflow for additive manufacturing is managed from design to print.

We're fully committed to delivering this industrialized additive manufacturing solution and to provide our customers with the end-to-end process that eliminates data conversion between steps of the process. You can reimagine your product designs, reinvent your manufacturing and rethink your business without worrying about data integrity.

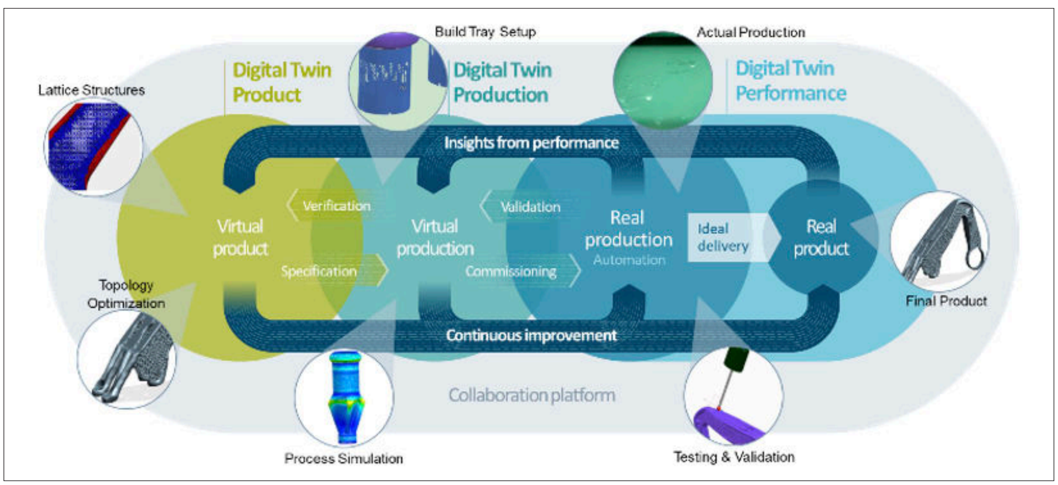

Figure 5. End-to-end software for AM.

Design for additive manufacturing

During the shift from conventional manufacturing to additive manufacturing, companies should also shift their thinking from conventional product design to design for additive manufacturing (DfAM) and for product development. By doing this a company can also facilitate the transition from prototyping and experimentation to industrial production with AM. Furthermore, DfAM can trigger a revolution in business workflows with faster innovation cycles, reduced supply chain complexity and digital inventories.

Siemens empowers users to advance their AM projects by providing state-of-the-art tools to modernize designs as well as manufacturing processes. Our software is state-of-the-art, providing a complete additive manufacturing lifecycle workflow that efficiently turns ideas into reality. The Siemens solution includes DfAM tools like the integration of multi-mechanics, enhanced simulations, design space exploration tools, lattice structures, topology optimization and implicit modeling, all of which create a powerful additive toolset.

Accelerate product development

Advancing design methods can drastically reduce energy usage and material byproducts. While these are goals for many engineers, HEEDS™ software can be used to make it happen with less engineering work. HEEDS is a design exploration and optimization software that enables engineers to determine the most efficient design. It allows users to drive product innovation and accelerate the product development process by automating analysis workflows.Completely integrated within Simcenter™ 3D software and NX™ software, using HEEDS maximizes the available computational hardware and software resources available for calculation. All of these products are part of the Siemens Xcelerator portfolio, the comprehensive and integrated portfolio of software, hardware and services. HEEDS is used to efficiently explore the design space for innovative solutions while assessing new concepts to ensure performance requirements are met. Integrating HEEDS allows you to save significant amounts of time and resources, vastly shortening a product's development cycle.

Unlike most traditional optimization tools that require expert technical skill and simplifying models, HEEDS can be used by engineers and designers to unlock innovation. HEEDS includes proprietary design space exploration functionality to enable the user to efficiently find design concepts that meet or exceed performance requirements. It automatically adapts its search strategy as it learns more about the design space to find the top solution within the chosen timeframe. HEEDS enables the user to effortlessly compare performance over a spectrum of designs that display desirable features and robustness. Instead of an entire team of engineers spending weeks to create optimized designs, HEEDS enables you to accomplish this task in hours.

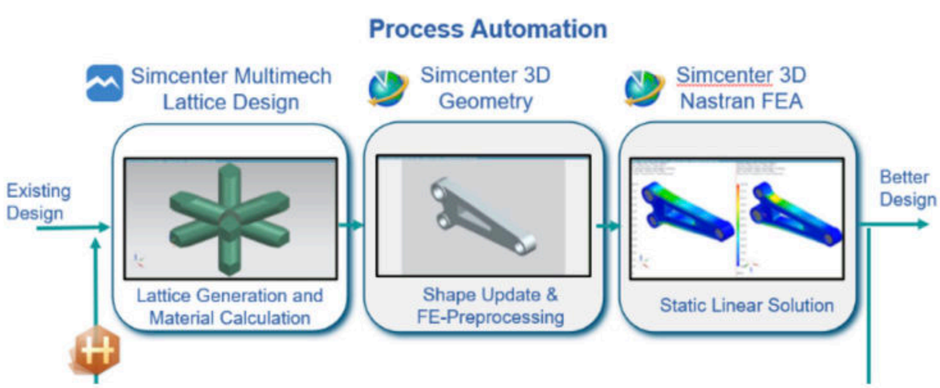

Figure 6. A visual example of HEEDS process automation.

NX lattice structures and topology optimization

With the benefits that lattice techniques add to designs, NX equips users with three command sets of lattice structures: graph-based, body lattice and triply periodic minimal surface structures. Each structure type serves a unique purpose and provides individual benefits. Lattice structures with unit cells based on triply periodic minimal surfaces (TPMS) are free of self-intersections and have topologies generated by mathematical equations. Examples of such structures include the Schoen gyroid, Schwarz diamond and Neovius. TPMS structures are often self-supporting, which makes them attractive for use with additive manufacturing.

A few examples of TPMS structures can be seen below in figure 7.

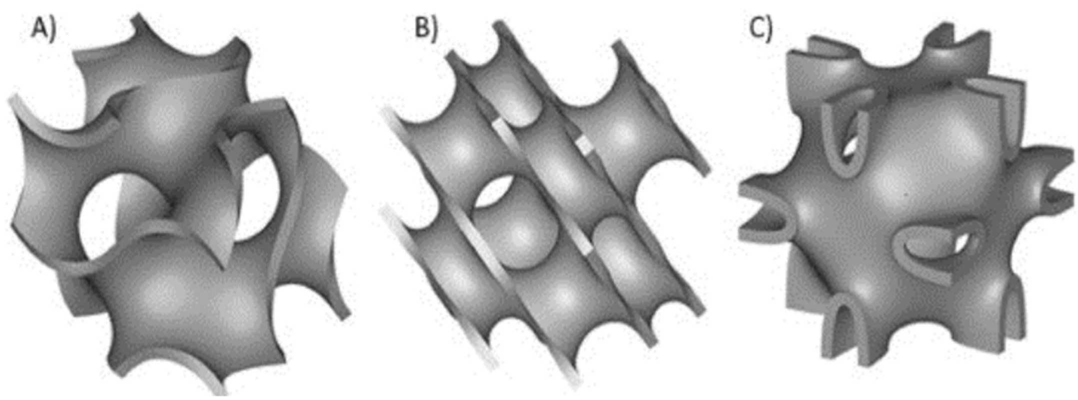

Figure 7. Triple minimal surface unit cells: (A) Schoen gyroid, (B) Schwarz diamond, (C) Neovius.

Body lattice structures allow users to create their own three-dimensional repeating pattern within a part. With endless possibilities and combinations, this option allows for design flexibility and easy customization. An example of body lattice structures can be seen below in figure 8.

Figure 8. NX equips users with body lattice applications to design for additive manufacturing.

Lattice structures can also be combined with other technologies like topology optimization, combining the best of both worlds as shown in figure 9. With both topology optimized areas and with lightweight lattice structures, a user can create an optimal part for a given set of inputs. Here we can see the final part after the analysis is complete. Not only were lattice structures applied, but the size of the structure has been varied across the part to optimize the strength versus weight ratio.

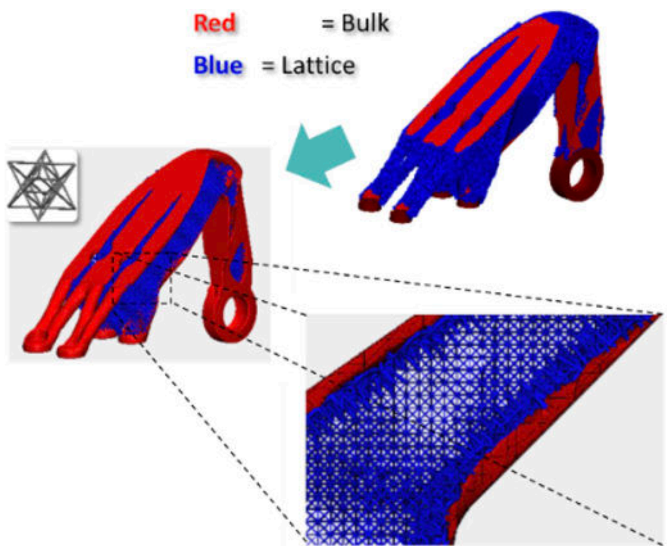

Figure 9. Implementation of lattice structures on a bracket.

Integrating Simcenter Multimech for additive manufacturing

Another investment made in industrializing additive manufacturing is the integration of Simcenter Multimech(TM) platform or multi-mechanics with NX. With Simcenter Multimech, engineers can predict how, when and why advanced materials may fail at the microstructural level. Simcenter Multimech is a fully integrated solution that allows for multiscale material modeling and simulation. It extends the flexibility and robustness of finite element analysis (FEA) down to the microstructural level, strongly coupling the macro and micro mechanical response. Integrating materials engineering into part design supports the acceleration of the product development lifecycle by predicting failure in innovative materials or shapes, such as lattice structures.

Using Simcenter Multimech aids engineers in simulation and predicting advanced material performance by combining three unique capabilities. The first is the automatic microstructure generation and optimization. This allows designers to automatically generate the geometry and meshing of microstructural models. The only inputs required are basic design variables. Users can also quickly and easily apply various loading scenarios to gain insight into how the material will perform in various conditions.

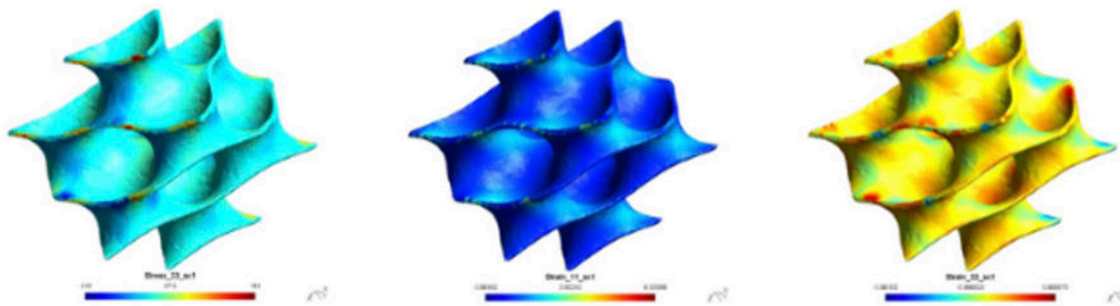

Figure 10. Simcenter Multimech shows the stress and strains on a triply periodic minimal surface diamond structure.

The second capability of Simcenter Multimech is to understand manufacturing variability and imperfections. It accounts for manufacturing variability and imperfections to maximize product reliability by allowing you to import process-induced variation data and automatically convert it to microscale, including volume fraction and fiber orientation tensors. The third capability of Simcenter Multimech is to perform multiscale material modeling. This software enables you to zoom into the material microstructure to identify the root cause of failure and see what damage mechanisms affect structural performance. From this, companies can optimize material microstructure for the most cost-efficient performance.

Scale additive manufacturing production

One software product can support multiple AM technologies. In figure 11, we see four primary 3D printing technologies that are prevalent in industry today.

Figure 11. Four prevalent AM technologies.

On the left are two technologies for making metal parts by using an energy source to fuse metal powder and build up the workpiece layer-by-layer. The top left is a multi-axis approach, while the bottom left is fixed-axis planar. On the right are two technologies for making plastic parts. The top right uses a material extruder to deposit material, while the bottom right uses fusing agents and energy to bond different types of powder. NX is the only software that offers connections to all four technologies in one system.

Depending on the additive manufacturing technology deployed, there are algorithms that allow automatic nesting of multiple parts in the build chamber. Moreover, you can pattern the placement of parts to optimize space utilization. In addition to that, support structures can be generated automatically or according to your individual preferences. Important here again is the integration into the entire product design environment. If changes happen in the released design of a part, these changes will propagate automatically to the build tray. The user can freely regenerate the build strategy with the new design, updating the supports or the hatching strategy for the build job. This is an important element of an industrial process chain.

Powder bed fusion

NX supports advanced powder bed methods for additive manufacturing as well. This 2.5-axis printing method involves spreading a thin layer of metal powder over a previously applied layer and selectively fusing some of this powder to the workpiece with a laser or electron beam. Parts are built up in one direction by layers. The very fine powder and laser fusion can produce small details and a good surface finish compared with other methods. NX AM software supports robust capabilities for support structure creation, build tray setup and build processors to drive a wide range of powder bed 3D printers.

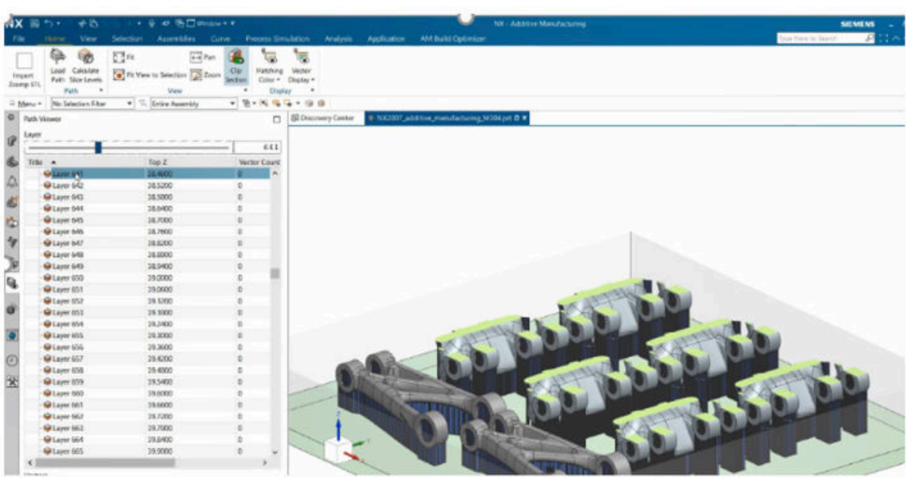

Figure 12.NX AM build preparation.

NX AM is directly integrated with EOS EOSPRINT2, Renishaw QuantAM and Cura. If you have a printer that uses one of these software packages, you can use the unique capabilities of these printers to print parts in the build tray. NX is also integrated with the Materialise Build Processor framework, providing to the access the machines supported with Materialise Build Process (for the detailed list, please reach out to Siemens sales). This delivers an integrated and associatively linked additive manufacturing process from design to advanced 3D printing on a wide range of machines.

Multi Jet Fusion

NX has been certified by HP for use with their MJF 3200 and 4200 series industrial printers. This certification means you never have to leave the NX environment to print parts using Multi Jet Fusion. The entire process from design to print can be performed with NX and it is the only CAD/CAE/computer-aided manufacturing (CAM) Materialise Build Processor system certified by HP.

Printing to other HP printer systems (300 series, 500 series, 5200 series) is also possible by utilizing NX for design and prep and transitioning to the HP provided software for finial printing.

Hybrid additive and multi-axis

NX AM also has best-in-class support for hybrid additive and multi-axis printing. This includes directed energy deposition (DED), electron beam AM (E-Beam), arc welding deposition and material extrusion-robotic printing (FDM/FFF).

The Siemens AM software solution includes the ability to quickly define 2D and 3D toolpaths for multi-axis deposition. This includes the ability to decompose a designed part into constituent areas, each with its own deposition pattern. This allows customers to utilize the strengths of multi-axis printing to their advantage when working with models appropriate for printing with that technology. When paired with the integrated CAM solution in NX, these multi-axis AM tools can also be used to seamlessly drive hybrid systems that provide both additive and subtractive capabilities in a single machine.

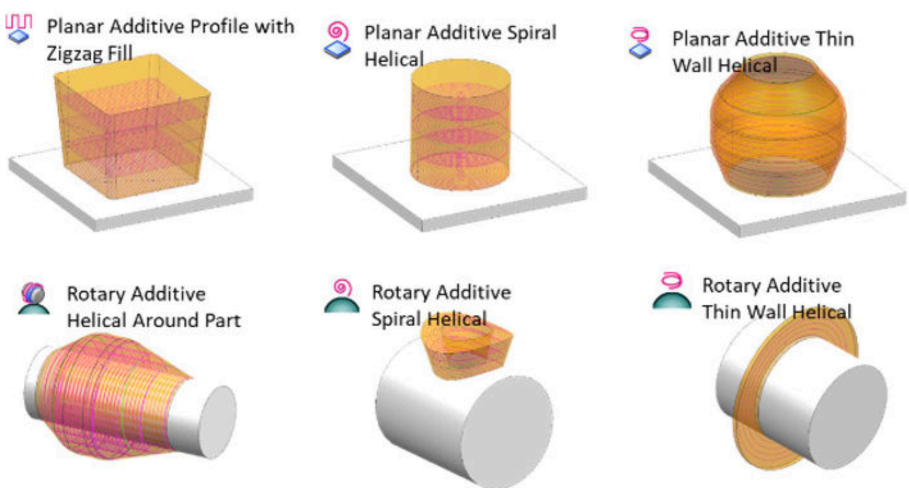

Figure 13. Tool path for multi-axis deposition.

First-time-right printing with build simulation

Print process simulation allows operators to examine how material will be laid down in the additive manufacturing process. This gives the operator insight into the AM process, including early identification of possible printing errors.

AM build simulation considers the material properties, machine technology and material deposition path to calculate things such as residual heat buildup and material deformation. These results can then be fed back into the design process to adjust the design accordingly. The associativity inherent in the NX AM solution set means this feedback can be easily integrated, unlike with other tools.

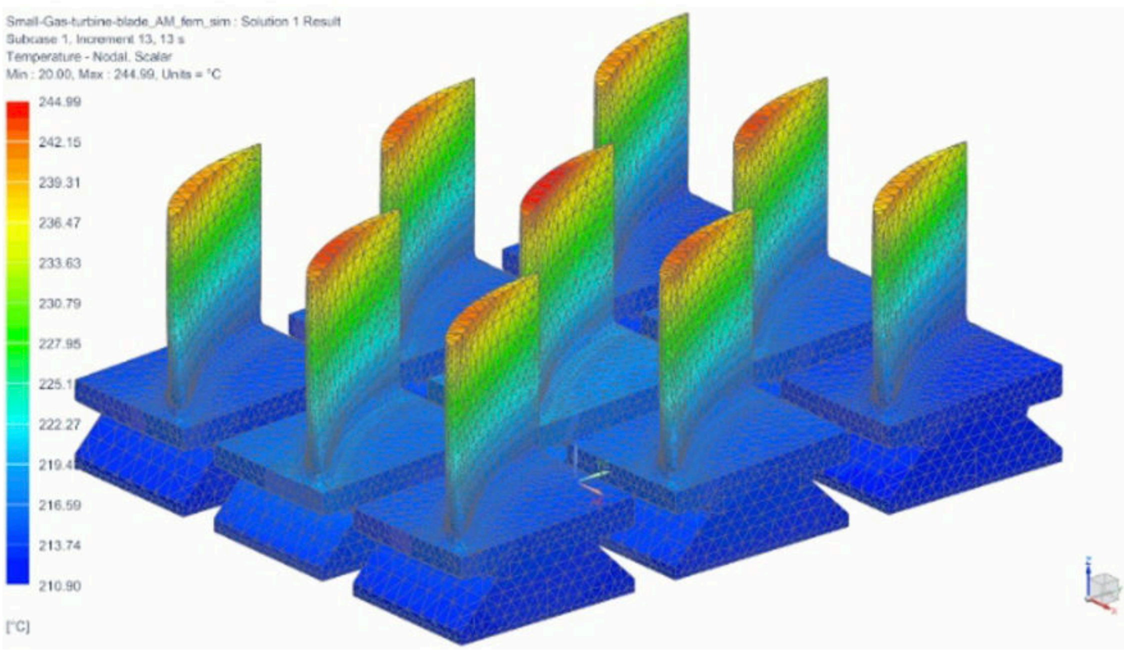

Figure 14. Print process simulation for turbine blade.

Postprocessing and inspection

Three dimensional (3D) printing is often followed by additional manufacturing steps to clean up precise mating surfaces or remove supports. Having AM, CAM and coordinate measuring machines (CMMs) integrated in the same system eases the finish machining inspection programming necessary for these post-print processes.

Leveraging NX CAM software tools allows the operator to define post-print processing steps like final machining or finishing. Utilizing the precise tool paths generated by NX CAM means that parts are finished to the highest quality standards. Operators can also employ the integrated CMM tools to define inspection steps and to validate final product geometry. The result of using these integrated post-print solutions is impeccable quality, fewer production errors and large savings in time and money.

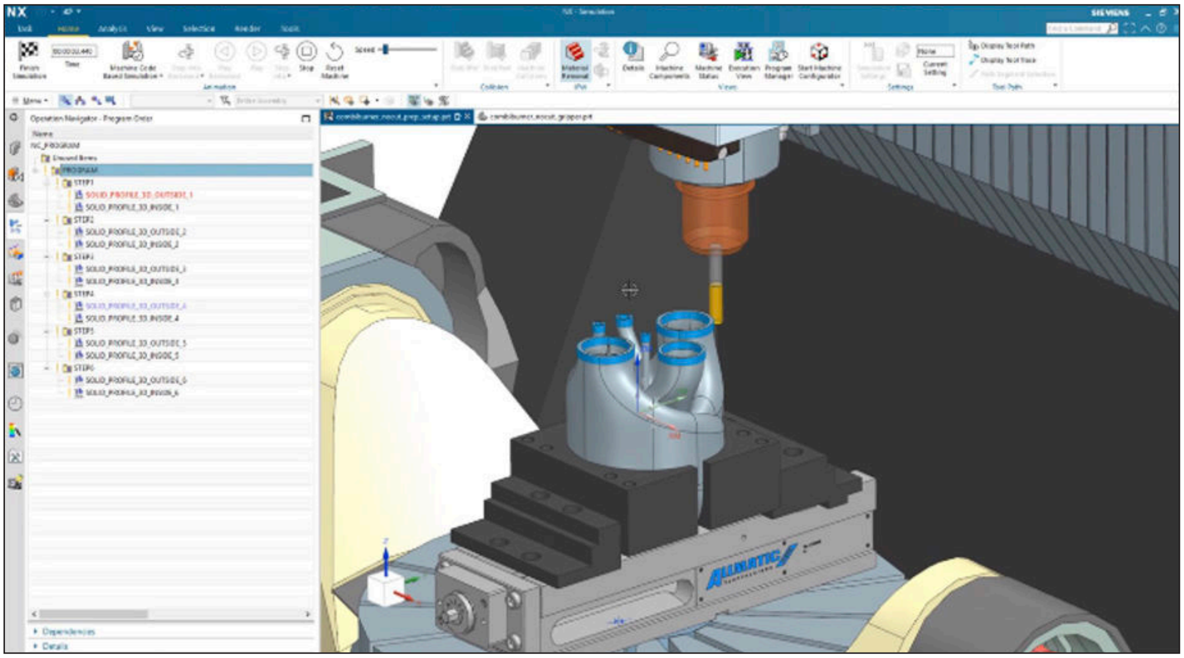

Figure 15 - Generate CAM programs for AM post-print processing.

Monitor and track print production processes

The value of of machining in manufacturing operations management (MOM) and other production work is often well understood. What is less understood is how this technology can be key to achieving overall production goals with AM as well. MOM allows the operators of a modern factory to account for operations performed on the produced good prior to, during and after any additive manufacturing steps.

Processes like machine setup, material mix and delivery, substrate separation, heat treatments and finishing and inspection are all processes that can be managed by a MOM solution. These solutions help organizations to appropriately allocate resources on their manufacturing floor and to monitor production progress.

With proper MOM systems in place, shop floor operators receive guidance about what to do and when in the appropriate sequence with detailed instructions. Operators must confirm they have performed all compulsory activities before they can proceed to the next step. The correct 3D printer is identified for a given AM process according to constraints defined at product and process engineering steps as well as run-time availability of resources. Product serial numbers associated with the work order are passed to the system responsible for embedding them into the print job file for downstream tracking. Collateral processes of powder batch management and substrate management are also handled, both to ensure that production proceeds correctly and to provide full genealogy and traceability of produced items. Traceability is extended to many more pieces of information, including data from all involved production machines, activity timestamps, operator identifiers, etc.

Additive manufacturing can only be effectively industrialized when it is tightly controlled by proper MOM systems.

Conclusion

As AM technologically evolves, there will be an increasing number of additive manufacturing applications going into production in the aerospace and defense sector. The key to industrializing the additive manufacturing process is to manage every step. Siemens has recognized this evolution and is on the forefront of sustainable innovation, developing a full additive manufacturing software workflow from design-to-print and beyond that can turn these new aerospace and defense applications into reality.

Siemens provides solutions for additive manufacturing by using a smart, model-driven process. Our fully integrated system for additive manufacturing, including NX, Simcenter and Teamcenter™ software, also part of Siemens Xcelerator, can enable you to support your entire 3D print process using one software solution set. This allows your organization to easily design parts, manage change, print parts and optimize your print operation using associative part models and full product lifecycle management (PLM) integration.

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