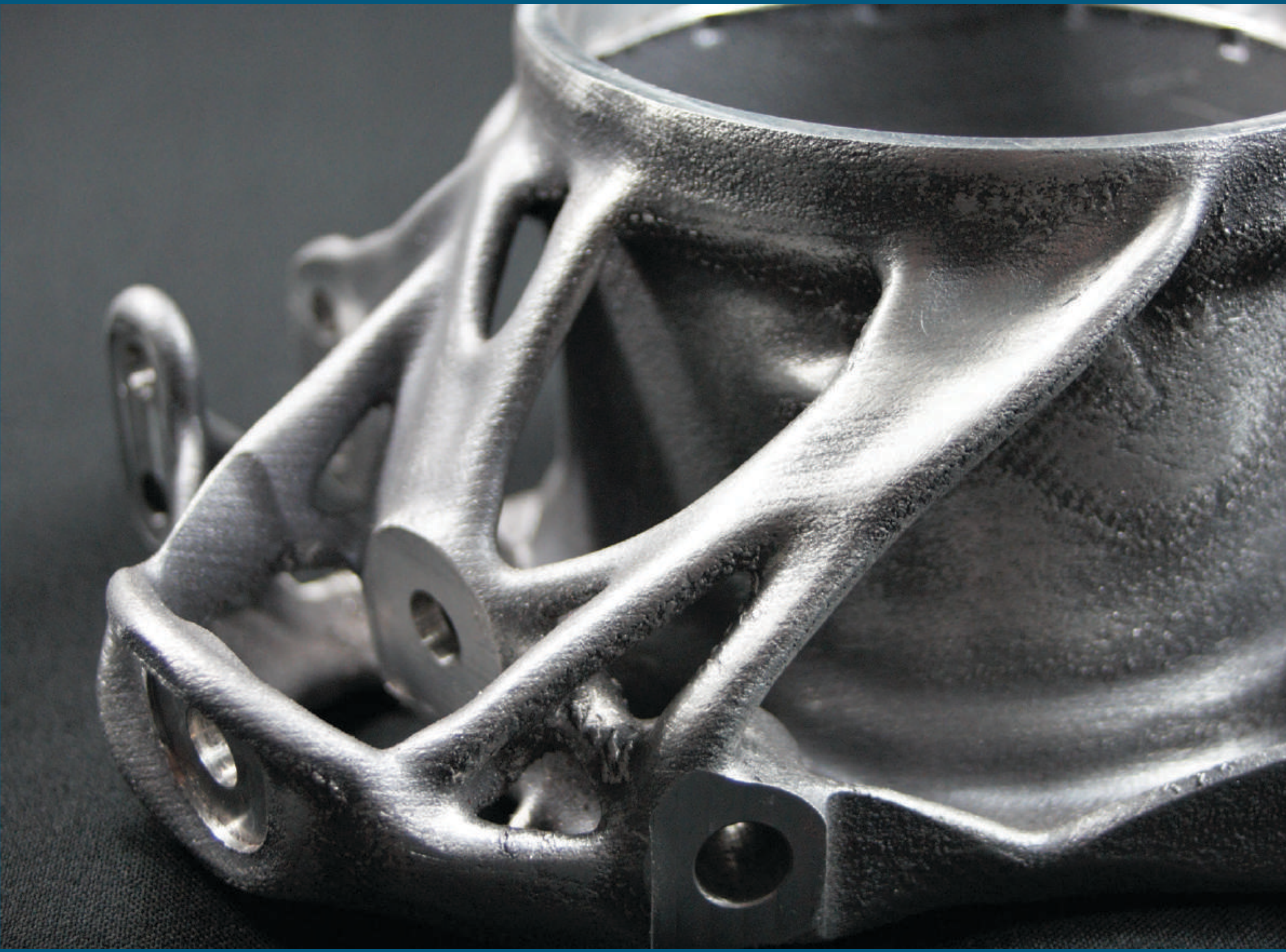
Additive Manufacturing 2020

Smarter 3D Printing
First Time Right by Design



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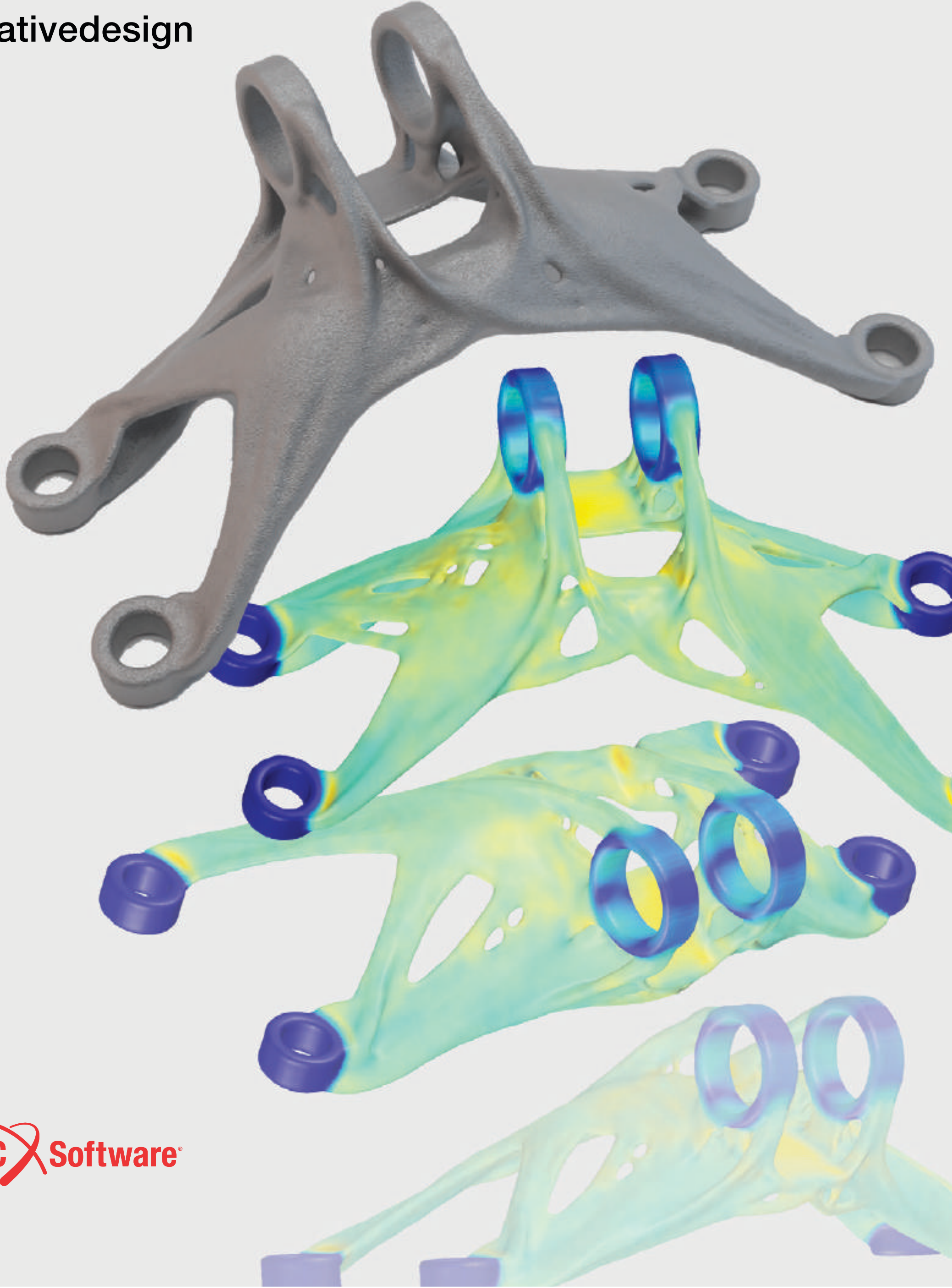
HEXAGON | MSC Software



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Foreword

For more than 30 years, dozens of Additive Manufacturing (AM) technologies have been used to realize prototyping applications. AM is now becoming increasingly widespread across industry sectors. We are starting to see additive manufacturing being used in the serial production of high-tech parts, particularly in aeronautics, space, and medical industries.

This e-book features some insightful commentary on the state of the additive manufacturing industry and some of the dominant trends. In addition, it also includes some compelling case studies that demonstrate the scope and range of applications for simulation in additive manufacturing.

Today's AM technology offers some major advantages, such as geometry design freedom that allows the creation of optimized shapes according to the targeted function. Another key benefit of using 3D printing technologies is the ability to reduce the weight, cost, and complexity of parts production without sacrificing the reliability and durability of materials. AM affords the advantage of small production runs with less material waste, significant energy cost savings, and the possibility to produce functional, high performance parts that simply can't be subtractively manufactured, cast or formed.

You can read about how engineers in Robert Bosch India are employing the Simufact Additive product from MSC Software to model the additive manufacturing (AM) metal build process and subsequent post-processing steps to help eliminate design errors before committing to AM. Similarly, there are use cases from MBFZ Toolcraft, Ampower, Safran, Samara University, and Solvay, on various facets of additive manufacturing. [each article can have separate three bullet points] on pages after foreword, or a short summary which I have already included here].

The articles in this e-book also touch upon the concept of Generative Design that helps customers engineer concepts unimaginable by the human mind and how this plays a role in enhancing the potential of additive manufacturing.

As Additive Manufacturing becomes increasingly mainstream, this e-book intends to serve as a useful compendium of useful insights on the role of simulation in additive manufacturing.

Dr. Hendrik Schafstall

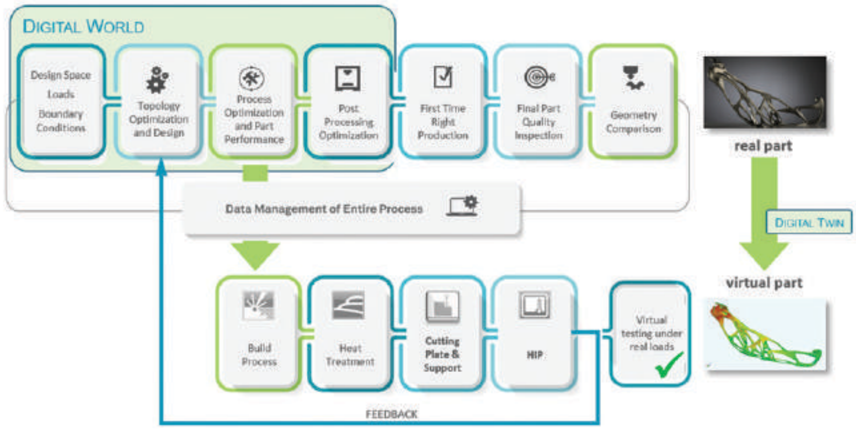
Vice President, Virtual Manufacturing & Costing, MSC Software

Bridging the Gap Between Design and Additive Manufacturing
Using Smart Generative Design

By **Hendrik Schafstall, CEO Simufact**
Raj Dua, Product Manager,
MSC Apex Generative Design

For MSC Software and Hexagon, Generative Design is an initiative to provide a tool that will help customers design concepts unimaginable by the human mind.

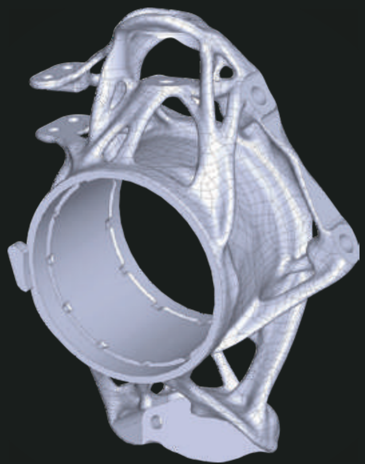
With the release of MSC Apex Generative Design, MSC Software is now offering an entire digital solution from the design to the final validated part for all materials. Connecting design solutions like MSC Apex Generative Design to virtual manufacturing simulation with Digimat AM or Simufact Additive, the design can account for the engineering and production phase challenges earlier in the product development phase. As a digital twin, the virtual manufacturing simulation is used to identify the best printing process and to optimize the orientation of the part and the build process. Furthermore, the outcome of the additive manufacturing process chain can be used for the validation of the “real” geometry, while accounting for the residual stress distribution and the local deformation under real load conditions using MSC Software’s design validation solutions such as MSC Nastran or Marc. The end-to-end process enables engineers to make sure their optimized designs are validated for manufacturability and performance.



What is Generative Design?

Simply stated, Generative Design is a process of automatically generating several design concepts that satisfy a set of user defined objectives, criteria, and constraints. Generative Design can be accomplished in many ways depending on what criteria and constraints have been defined by the user. For example, if a user defines a set of structural loads and boundary conditions that a part must withstand as criteria, an upper stress limit as a constraint, and an objective of minimizing mass, a method known as Topology Optimization (which many of our MSC Nastran users are very familiar with) can be used to generate a number of design concepts that satisfy the given criteria and constraints. However, Generative Design is more than just Topology Optimization. For instance, a user may want to know what the best way is to package a number of electronic components in a given space in order to minimize the gap between all the components. Generative Design can help answer that question. For MSC Software and Hexagon, Generative Design is an initiative to provide a tool to our design customers that will truly act as a companion and help them think of design concepts that are unimaginable by human mind.

Why Do We Need Generative Design?



The first release of MSC Apex Generative Design has been released to assist design engineers create organic topologies that can be manufactured using 3D printing, i.e. Laser Powder Bed Additive Manufacturing. Technologies such as Topology Optimization are being reinvigorated thanks to advancements in Additive Manufacturing. It is widely accepted that Additive Manufacturing has the ability to manufacture virtually any topology. As a result, the industry has seen a rise in the number of tools that allow creation of organic topologies via concepts such as Topology Optimization and Generative Design. However, if you have ever tried to 3D print any “organic” topology that resulted from the Topology Optimization algorithm, you have probably realized that AM is not very forgiving, and an unrevised Topology Optimization result often is far from feasible. Despite its unique ability to manufacture virtually any topology, AM still has many limitations today. Issues such as shrink lines, cracking, overheated zones, etc. have kept AM from replacing other manufacturing methods. These issues were not as pervasive when 3D printing was only used for prototyping. However, they become prevalent when using AM for production parts, especially primary or secondary structural parts for Aerospace or Automotive industry. Today, cost of manufacturing and time of printing are seen as two major constraints in wide adoption of AM for mass production. Therefore, there is a need to account and optimize for the total manufacturing costs and print time while designing parts for AM. With MSC Apex Generative Design, we are focusing not only on optimizing the parts for AM, but also optimizing the process for AM. We believe that it is only after we bridge the gap between design and manufacturing that we can see AM become a sustainable manufacturing method.

Bridging The Gap

MSC Apex Generative Design is being developed as a first-of-its-breed tool to bridge the gap between design and manufacturing. Our goal is to automate the process of Generative Design with user intervention only required for defining the objective, criteria, and constraints for design space exploration. MSC Apex Generative Design will then account for how the part fits within the overall assembly, how it redirects loads to other parts of the assembly as its stiffness changes, and most importantly MSC Apex Generative Design accounts for manufacturability – all automatically while generating several design candidates that all meet the user’s defined expectations. Many Generative Design tools in the market today allow users to minimize the mass subject to a stress constraint. The tool then solves a mathematical optimization problem and produces one or more design candidates. Although these candidates often are more ideas for a part and visualizations of how the forces flow through the design are. A proper Generative Design tool needs to produce directly printable designs that can be used without any need for manual rework of geometry defects. This is what MSC Apex Generative Design will deliver.

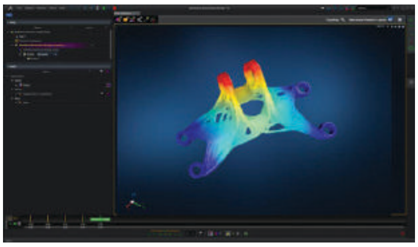


Figure 2: **Topology Optimization of a GE Engine Bracket using MSC Apex Generative Design**

Each optimization always leads to a geometrical and mechanical correct design that can be used for manufacturing. In addition to the geometric side, the user must also understand the cost and feasibility of using AM for this design candidate. With MSC Apex Generative Design, our goal is to allow users to specify manufacturing related constraints. For example, if the goal is to minimize the cost of 3D printing, then MSC Apex Generative Design will automatically check each design candidate for: (a) amount of material required for the part, (b) volume of support structure required for support and heat dissipation in the AM machine, (c) cost of removal of support structures and machining for desired surface roughness, (d) costs related to maximizing the number of parts printed at one time on a build plate, etc. These checks are performed in the background using MSC’s Simufact Additive technology for metal parts and Digimat AM technology for polymers. At the end of the optimization routine, MSC Apex Generative Design selects the candidates that meet the specified criteria and summarizes them. The design engineer can then export the selected design(s) in CAD format and perform further checks, for example, for buckling, fatigue, and nonlinear for part performance or decide for one design based on additional reasons such as of dirt problems or just aesthetic ones. The design engineer may also choose to send the part to a manufacturing engineer to perform further checks on manufacturability via Simufact Additive and/or Digimat AM. Users will be able to perform any geometry modifications needed using the geometry editing tools in MSC Apex. Eventually, MSC Apex Generative Design is able to perform these checks during the optimization process automatically as well.

Speed Is Crucial

In order to evaluate several design candidates in a time effective manner, it is necessary to have a finite element solver and an optimization engine that can take advantage of the latest computing technologies for extremely fast performance. With MSC Apex Generative Design, we have done exactly that. We have completely rewritten the FE solver and the optimization engine to scale on multiple GPUs and CPUs. The ability to explore design space in a time efficient

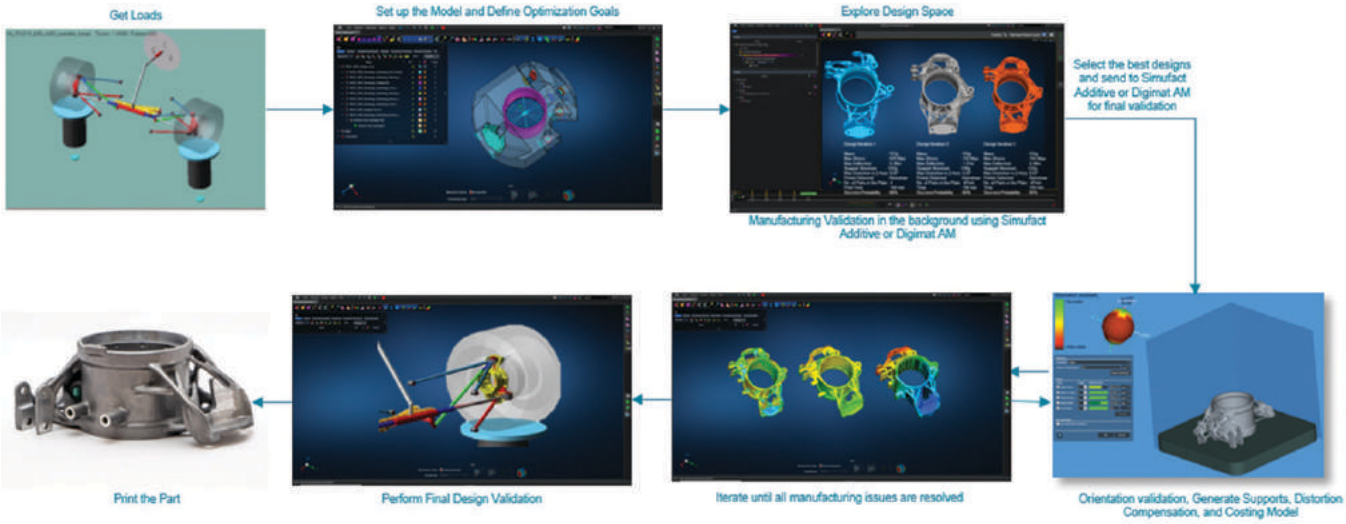


Figure 3: **Design for Additive Manufacturing using MSC Apex Generative Design**

manner ensures that the design process is not a bottleneck and thus allows our users to make decisions solely based on design criteria. Only a complete examination of the design space with a variety of results, and in a short time, leads to the best results.

Demonstrating The Potential

To bring evidence on the potential of MSC Apex Generative Design and to show its usability, a wheel carrier of a formula student team is considered to demonstrate a use case. Due to its very complex load cases and a high demand on lightweight design, it is the perfect fit for demonstration. Furthermore, there is a lot of experience in optimizing this part, as this race series officially is an engineering competition that requires to develop a new race car each year. Other MSC tools such as Adams and MSC Nastran have been used for this part in the past for optimization.

As shown in Figure 3, the development process starts with retrieving the loads by a multi body simulation based on Adams Car. Hereby, the overall suspension is engineered, including all coordinates for the connection points, as well as the acting forces. This information is used to set up the optimization model and define its goals. Therefore, a “design space” as big as possible is added (shown as translucent material). In this case the overall inner space of the rim minus the installation space for wishbones and braking system is selected. Running the optimization, this material in the design space is reduced as much as possible while keeping into account the boundary conditions, constraints and optimization goal. Thus, several design candidates are produced and directly verified in the background using Simufact Additive for metals or Digimat AM for plastic products. While selecting the right candidate and iterating the manufacturing simulation, the perfect design in terms of manufacturability, weight and costs is selected. As a last step in the virtual world, this design finally gets a last validation with MSC Nastran for FE qualification and back again in Adams to ensure the correct stiffness and behavior in the overall assembly. Thus, an optimal design was found that was printed and successfully used in this year’s formula student season.

Summary and Conclusions

MSC Software’s MSC Apex Generative Design is bridging the gap between design and additive manufacturing. Additive Manufacturing has come a long way since its inception and is changing the manufacturing landscape. In order to realize the full potential and benefits of AM, users need to be able to produce designs that are specifically validated for AM. With MSC Apex Generative Design, we are developing technologies that validate manufacturability in the Generative Design process. As such, the optimization engine only produces geometry candidates that have been validated for AM.

Finally, after printing the part with your 3D printer of choice, Hexagon metrology’s state-of-the-art scanners can verify the accuracy of the simulations and compare the “as-built” part to the “as-designed” part. This allows for genuine “First Time Right” 3D printing. Time and cost are two of the major constraints in wide adoption of AM today. Typically, with MSC Software’s Generative Design solution we find that we can cut the time and cost of simulations by x10. Furthermore, most importantly, with our bridge to manufacturing, we find that we can get closer to “First Time Right” 3D printing. MSC Apex Generative Design technology is here to make the design and development for AM smarter and more sustainable.

Read an Overview in our Previous Issue for More Information on Hexagon and MSC’s End-to-End Solution: www.mscsoftware.com/Engineering-Reality-Summer-2019

Fast and Accurate

Additive Manufacturability Analysis

By **Yvan Blanchard, Coriolis Composites**
Anthony Cheruet, e-Xstream Engineering

This article focuses on the design optimization of complex 3D composites structures made by additive manufacturing processes.

There are commercial CAD-CAM software solutions for detailed offline path programming, but there is a growing need for innovative tools and methodologies for trade off studies very early in the design stage. A new innovative solution has been developed on top of the CATFIBER© software, allowing both designers and stress engineers to quickly analyze complex double-curved geometries. It also includes a variable stiffness approach with tow-steering, and structural analysis of the manufacturing defects using Digimat© software.

Design Analysis Framework Description

Today, more and more CFRP structures are manufactured by automated processes such as fiber placement robotic systems (Figure 1).

The design trade-off analysis can be done on a simplified quasi-isotropic laminate (with full plies), in order to just analyze the surface curvature impact, independently of plies shape. But thickness effects, material excess, staggering rule, part productivity rate, could not be correctly estimated.

The engineering and manufacturing requirements may quickly interfere, and a difficult compromise between feasibility, strength and cost needs to be found, especially with double-curved layup surfaces.

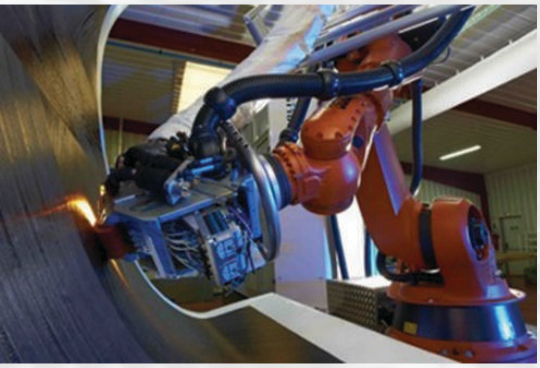


Figure 1: **Automated Fiber Placement robotic system (Coriolis Composites)**

Moreover, such analysis systems are not able to reach a good compromise between performances, level of details and results accuracy. The expected computation time is a few seconds to a few minutes so that several analysis runs can be done in parallel within a few hours only.

Designers and stress engineers need robust tools and methodologies to help them test many combinations, such as material width, maximum number of tows by course, and maximum fiber deviation angle. The solution should be able to analyze complex and representative laminates such as large aerospace panels with double curvature and hundreds of plies.

An automatic ply splicing algorithm, based on both engineering and manufacturing requirements, allows to quickly and easily generate a manufacturable design proposal. This algorithm also uses a patented rosette transfer feature, allowing steered-path propagation and then variable-stiffness modeling (Figure 2).

Ply course centerlines and splice cuts are first computed, then the ply boundary is filled with (tow) strip surfaces. This allows us to capture all the process and material specificities, such as triangle of gaps, tow overlaps, minimum course length (MCL), and minimum distance between tow cuts (Figure 3).

The design analysis system is also able to compute and output several manufacturing cost indicators, to help designers sort the manufactural design proposals (number of courses by sequence, number of tow cuts and drops, buy-to-fly ratio).

The design analysis tools were implemented on top of Coriolis Composites CATFIBER© Offline Programming solution, through a dedicated infrastructure made of scripts (Python or Visual Basic) and a Microsoft Excel© spreadsheet. This allows us to easily launch several background runs from a very light user interface.

Structural Strength Analysis

To verify the structural strength of the optimized Layup design proposal, it is important to have a quick and easy transfer of all the as-manufactured composite properties onto a structural mesh used for sizing purposes. This mapping is done using the Digimat Platform© and concerns the transfer of

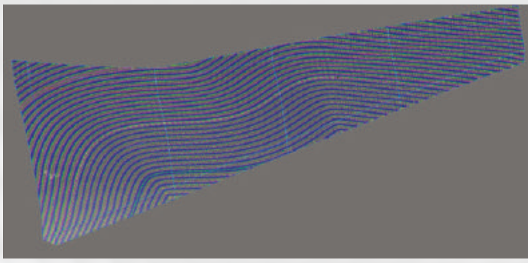


Figure 2: **Steered-paths on wing skin surface.**

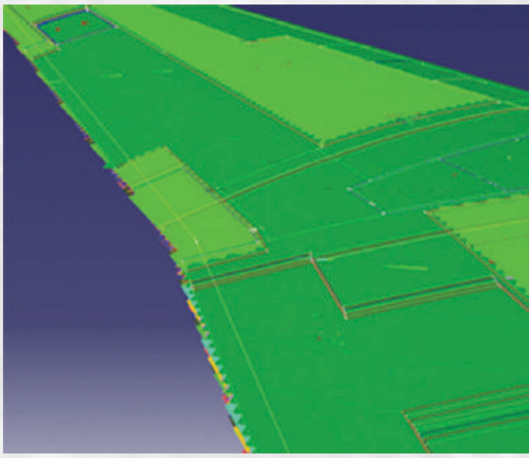


Figure 3: **Plies build-up with tape courses covering.**

the as-manufactured fiber orientation, the exact location of the gap and resin-rich area. Using Digimat, such information can be transferred automatically to the Finite Element Model used for sizing activities by Stress Engineers. In this case, Digimat can generate the composite layup command cards with the local as-manufactured fiber orientation for each ply. In addition, the effect of the gaps on the local stiffness can be handled in two ways, depending on the reconsolidation process. The first one considers that the gaps have an effect on the local thickness while the second one considers that the gaps are filled by resin and affects the local fiber volume fraction of the composite. Using a micro-mechanical model of the material, this local variation of the fiber content is computed at each Gauss point of the FE Model (Figures 4 & 5).

> **Digimat can generate the composite layup command cards with the local as-manufactured fiber orientation for each ply.**

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Fayazbakhsh, K., Arian Nik, M.,Pasini, D., Lessard, L., Defect layer method to capture effect of gaps and overlaps in variable stiffness laminates made by Automated Fiber Placement, doi: 10.4271/2012-01-0082

G. Gonzalez Lozano, A. Tiwari, C. Turner A design algorithm to model fibre paths for manufacturing of structurally optimized composite laminates. In: Composite Structures (2018), doi:10.1016/2018.07.088

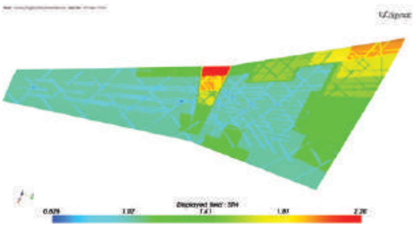


Figure 4: **Thickness map analysis (quasi-isotropic laminate) with tow gaps capture with Digimat© software.**

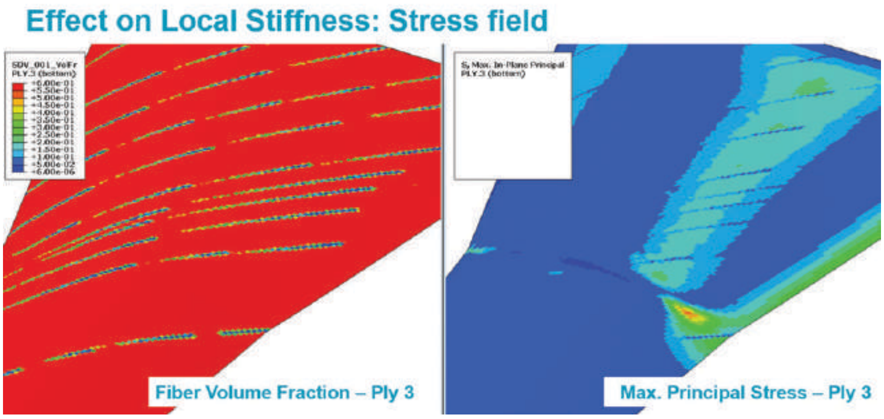
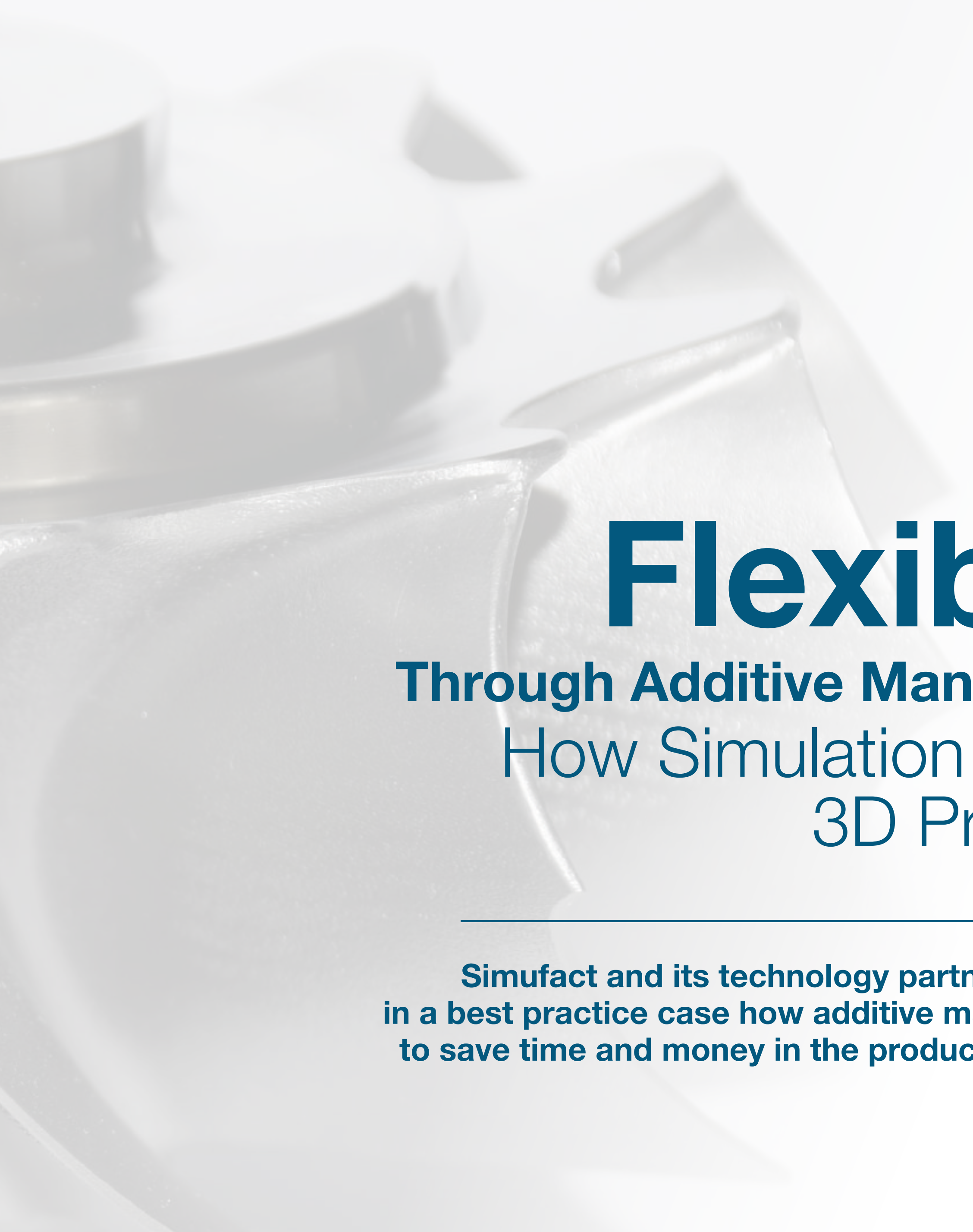


Figure 5: **Local stress field per ply and effect of gaps computed by Digimat©**

For Details About CADFiber Standalone©, or CATFiber© for CATIA Solutions: www.coriolis-composites.com

For Details About Digimat©: www.mscsoftware.com/product/digimat



Flexibility

Through Additive Manufacturing: How Simulation Supports 3D Prototyping

Simufact and its technology partner toolcraft shows in a best practice case how additive manufacturing helps to save time and money in the production of prototypes.

MBFZ toolcraft GmbH from Georgensgmünd in Middle Franconia has optimized together with its software partner Simufact Engineering from Hamburg the additive production of a turbine wheel from ABB Turbo Systems AG. Typically, these components can be found in drive units of heavy machines and vehicles, such as diesel locomotives, off-highway trucks or dump trucks. Depending on the application, manufacturers require the component to have a long service life and high wear resistance so that it can withstand mechanical and thermal loads.

From Prototype to Series / Take a View On Manufacturing and Its Challenges in Serial Manufacturing

Filigree blade geometries are typically produced by casting processes as an economical and robust production process suitable for series production. However, before a new blade geometry can be used with the required properties, many tests are required for which prototypes or small batches of blades are required. In exceptional cases - depending on the number of parts required - the turbine blades required for testing can also be produced by casting in very small series. In general, these processes are very time-consuming and cost-intensive and therefore not much more than two prototypes are available to develop the

CHALLENGE: Transfer prototyping into serial manufacturing. Using the example of a filigree blade geometry we consider the challenges of traditional manufacturing.

SOLUTION: Generate variant diversity with the help of additive manufacturing. This technique helps you save time and money. Reach the first-time-right approach through simulation.

USED PRODUCTS: Simufact Additive

USER: MBFZ toolcraft GmbH

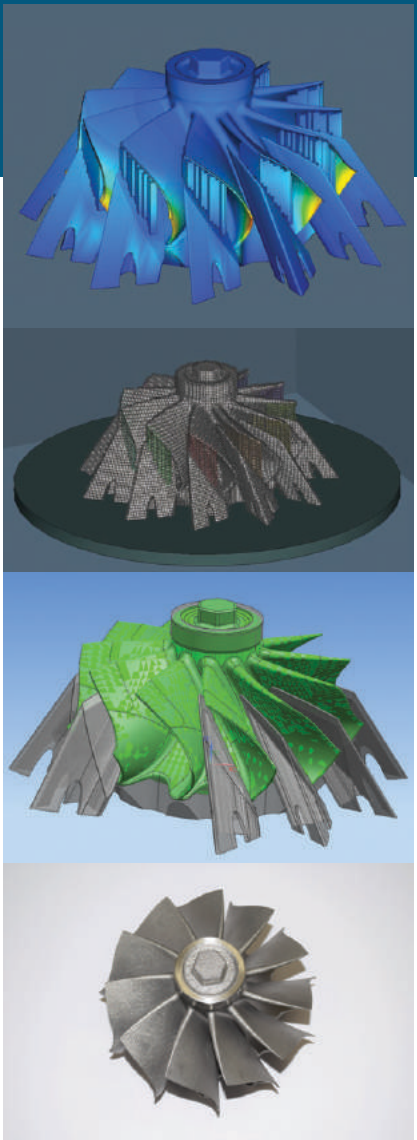


Image 1: **Simulation helps to reduce component distortion and thus to keep tight tolerances.**

final product for use in series turbines. At this point, additive manufacturing has become a key technology that saves time and money. Furthermore, the technology offers a maximum flexibility, one of the most important requirements in the field of prototyping. With the help of this innovative manufacturing process, a variety of turbine blades can be produced in a very short time, which ultimately leads to a better product. This is where MBFZ toolcraft‘s high manufacturing competence throughout the entire value-added chain in turbine blade production proves its worth. Within the framework of the cooperation between MBFZ toolcraft and ABB Turbo Systems AG, the products can be designed and implemented as 3D printing right from the start.

Simulation Provides Reliable Information on Distortion and Stresses in the Component

For MBFZ toolcraft, the greatest challenge in manufacturing prototypes is maintaining the required tolerances and dimensional accuracy. The decisive factor here is the component distortion caused by the AM process. In order to keep the distortions as low as possible, MBFZ toolcraft relies on Simufact Additive. By using the user-friendly and process-oriented simulation solution, MBFZ toolcraft makes it possible to significantly minimize distortions by means of suitable process parameters and to compensate where they cannot be avoided. In this way, MBFZ toolcraft can meet all required tolerances, thus eliminating the need for time-consuming reworking.

Problems and Challenges in the Building Process

A closer look at the building process clearly reveals the challenges and problems. Due to component geometry and thermal stress, high stresses occur during the building process. This is due to the special features of the geometry, which on the one hand has a solid core with a lot of material and volume, while on the other hand the blades are very filigree. As a result, there are large cross-sectional changes in the component, which favour the residual stresses during the manufacturing process. These in turn result in a high susceptibility to distortion.

MBFZ toolcraft solves this problem with a careful simulation-based as-is analysis in which critical areas are identified. From this, the necessary measures can then be derived to counteract the distortion problem. This includes the development of suitable support structures that generally minimize distortion and thus ensure a safe construction process. But the ideal alignment of the components to be printed on the base plate can also be very helpful in individual cases. The last step is an automated compensation of the remaining distortion based on a quantitative distortion analysis, with which the remaining distortion is determined. The results obtained in this way can be used to derive the print preparation. Thanks to the simulation, MBFZ toolcraft achieves a low-distortion component structure and can thus remain to its “ first-time-right“ approach - to fulfil all requirements on the component with the first print. The use of additive manufacturing enables MBFZ toolcraft to react flexibly and quickly to customer requests, such as design changes, and thus to significantly reduce project lead times. The virtual engineering offered by the powerful simulation solution enables significantly tighter processes in the process development of 3D printing projects. This approach can be realized through the reliable software Simufact Additive.

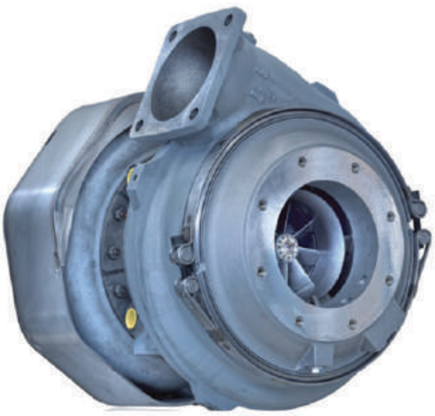


Image 2: **From design to simulation to the finished component – less distortions thanks to Simufact Additive.**

US Army Use of MaterialCenter for **Metals Additive Manufacturing Data Management**

Based on an Interview with **the United States Army Combat Capabilities Development Command Armaments Center**

The United States Army Combat Capabilities Development Command (CCDC) Armaments Center is the US Army's primary research and development arm for armament and munitions systems. It is a leading defense facility for Additive Manufacturing (AM) of Metals and is located in New Jersey. Armaments Center has been investigating AM for a number of years now with programs aimed at exploiting the novel capabilities of additive manufacturing. The facility has a number of AM systems at their disposal including a laser powder bed fusion EOS M290 machine that prints in Steel (4340/4140/17-4), Inconel, and Cobalt Chrome; and an E-Beam system, an ARCAM A2X machine that prints in Titanium, Inconel, and Cobalt Chrome. In addition, there is access to a wide range of support and testing equipment for powder synthesis (Plasma Reactors, High Energy Mills), post processing (HIP, Heat Treatment, Surface Finishing), machining in a full machine shop (EDM, CNC, etc.), testing (Tensile, Charpy Impact, Hardness), and part characterization (Scanning Electron Microscopy, Particle Size Analysis, X-Ray Fluorescence & Diffraction, Oxygen/Nitrogen Analysis).

Armaments Center is interested in using AM equipment to prototype, develop, and fabricate metal parts via a layer by layer powder bed laser sintering process. AM has the potential to provide a wide range of design flexibility over traditional manufacturing methods allowing for rapid prototyping, part weight reduction, novel part design, reduced time to product, and overall manufacturing flexibility. The benefits of AM include a reduced logistics footprint and time-to-field for replacement parts, manufacturing options to reduce single point failures, and creation of novel and improved part designs for reduced weight while meeting or exceeding performance requirements. In turn AM results in a manufacturing process for providing parts on rapid response, and on-demand basis.

Armaments Center has identified six practical areas of interest for additive manufacturing technologies in the US Army (see Figure 1):

1. Novel Materials: Novel powder synthesis for Non-COTS materials,
2. Rapid Prototyping: Multiple build iterations on the same build plate for design optimization. Small runs for prototype testing,
3. Replacement Parts: Investigating component replacements which match properties but can be delivered in an accelerated timeframe,
4. Novel Designs: Investigating novel weapons systems components with designs difficult or impossible with traditional machining,
5. Rapid Fielding: Investigating Additive Technologies to overcome the challenges of bringing metals additive to the field, and
6. Process Monitoring: Working to develop custom In-Situ Monitoring Hardware which can be retrofit on existing equipment.

For AM benefits to be fully realized, processes must be developed and qualified for part acceptance for use in armament systems meaning design and manufacturing process data required to support repeatable additive manufacturing production must be defined. Several examples of additively manufactured armaments produced are shown in Figure 2.

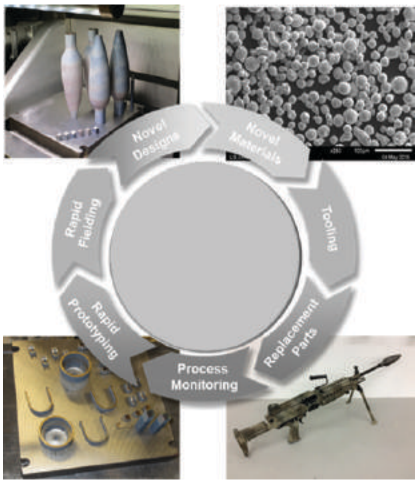


Figure 1: **Additive Manufacturing Areas of Interest to the US Army**

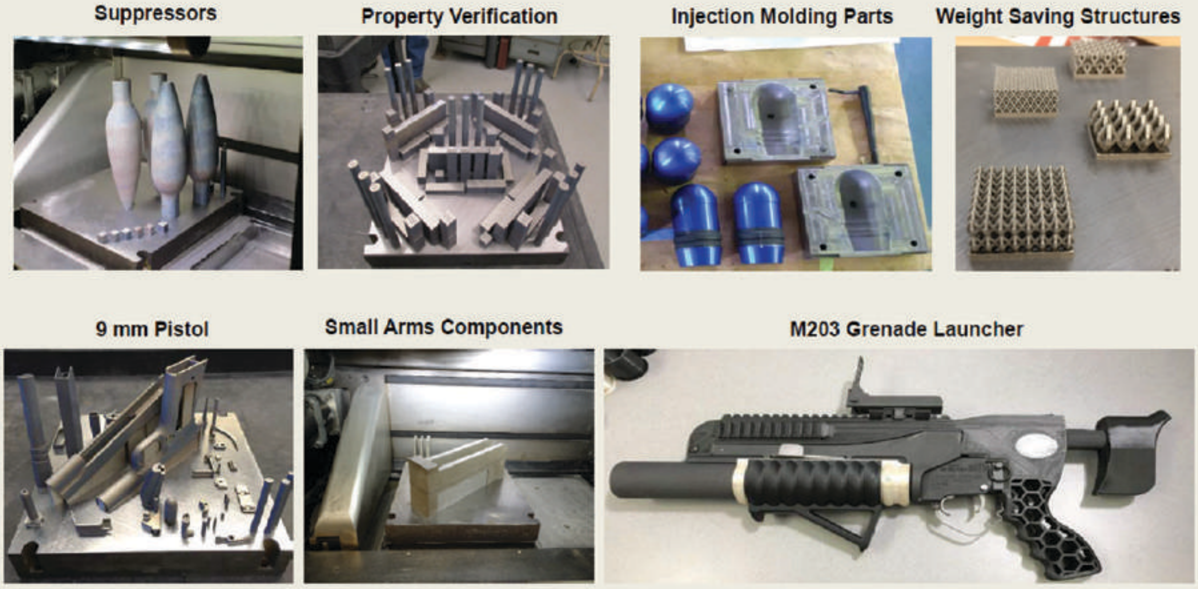


Figure 2: **Metals AM Build Examples for the US Army at CCDC Armaments Center**

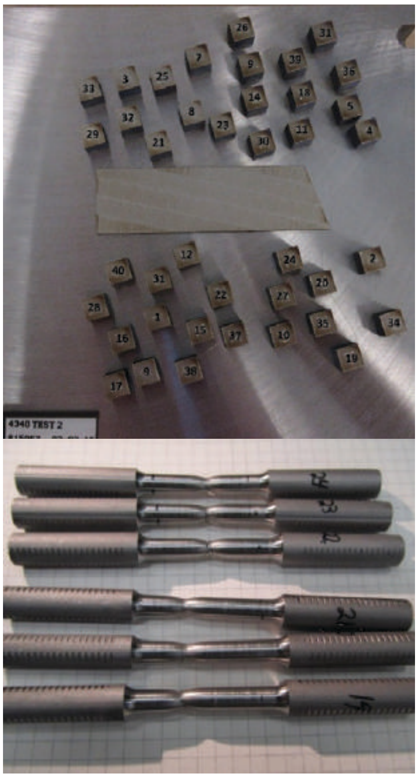


Figure 4: **Selection of some of our 325 AM Benchmark samples and parts**

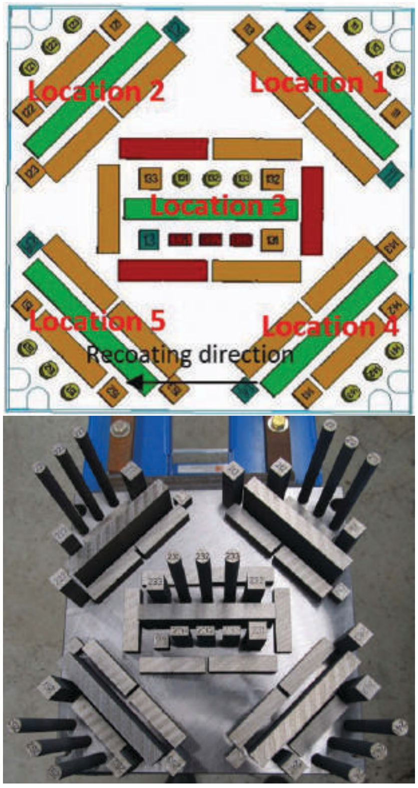


Figure 5: **Benchmark Steel 3d Printing Test showing Locations of Parts of the Base Plate**

What is the L-PBF Quality Strategy?

CCDC Armaments Center at Picatinny, NJ, have focused on additive manufacturing process development for AM materials and parameters along with the development of Quality Assurance provisions and requirements to develop manufacturing guidelines for robust and reliable new build L-PBF components. To do this, test components for new build demonstration and testing were selected. The team wanted to establish a process for qualification and certification of AM components, then transition the process on to internal government facilities and the AM industry with a manufacturing guide. In addition, the US Army wanted to share knowledge of the additive manufacturing process and create a knowledge base of AM products aligning to their roadmap.

What are the Challenges to the Use of Additive Manufacturing in the Military?

First and foremost, part acceptance for US DoD (Department of Defense) applications relies on a process for qualification and certification. However, the relationship between AM materials properties, processing parameters, and component performance are extremely complex, and complicated further by unique part geometries. There is also an extremely large pool of materials and AM equipment to choose from, raw materials must be readily available and trusted to manufacturer or internal specifications, processing condition windows must be defined to ensure part quality, In-Situ Monitoring technology must be utilized and improved upon, and a recognition that technology advancement might introduce previously unforeseen manufacturing variables.

It is fair to say that AM standards are still in development. There is a clear need for continuing collaboration between academia, industry, government agencies, and others to push standards adoption. Moreover, with respect to design for AM there is a need to educate and inform part designers of new principles and the constraints for AM. Today, widespread adoption of the AM process is limited due to a combination of these many challenges. Finally, with respect to utilization of Digital Product Data in AM, a system for controlled electronic data management and sharing must be implemented - software types used and digital file control must be set prior to manufacturing initiation.

CCDC Armaments Center Additive Manufacturing Benchmark Demonstration

A CCDC Armaments Center goal is to qualify powder bed fusion AM technologies as a viable alternative manufacturing process to fabricate armament systems components. To do this, multiple areas in the total manufacturing process need developmental efforts addressed to them to be able to produce an accepted additively manufactured component. An additive manufacturing benchmark testing method was devised using 4340 Steel Powder due to its chemistry, particle size, and flow characteristics. AM processing parameters were developed focusing on energy density ranges, and a DoE (Design of Experiment) was established that looked at the following parameters over 325 samples that were fabricated (see Figure 4):

1. Laser Power
2. Scan Speed
3. Hatch Distance
4. Energy Density Range

The resultant AM parts were evaluated based on microstructure, density, porosity, and hardness. Their mechanical properties were compared to wrought steel after stress relief, quench and temper heat treatment.

For each mechanical test specimen, four identical consecutive builds were printed to assess process reliability. The team focused on variations in location and orientation within and across builds, while collecting tensile, hardness, density, and toughness data. The team normalized samples with heat treatments per the AMS 2759 standard.

Sample Description	Modulus (Mpsi)	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)	Standard Deviation of % Elongation (%)
Typ. Wrought Prop.	29	220	270	11	N/A
Build 1	29	222	285	10.5	0.7
Build 2	29	223	280	9.0	1.6
Build 3	29	223	282	11.5	0.7
Build 4	29	221	279	9.9	1.2
Location 1	29	222	281	10.7	1.3
Location 2	29	221	280	9.2	2.1
Location 3	29	223	282	10.6	0.8
Location 4	29	223	283	10.2	1.4
Location 5	29	223	281	10.3	1.0
Overall Z	29	222	281	10.2	1.4
Overall X-Y	29	223	283	11.6	1.0

Figure 6: **Benchmark AM Printing Sample Mechanical Property Results for the different print locations in Figure 5**

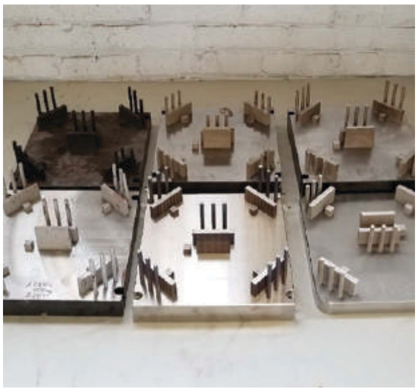


Figure 7: **Six AM Printer Machine results for the same set of parts being printed the same way**

AM Benchmark Results and Lessons Learned

The tests indicated that parts printed in the XY direction had 12% higher elongation values than parts built in the Z direction. Ultimate Tensile Strength (UTS), Density, and Hardness values matched wrought steel properties. The parts printed at Location 2 (top left of Figure 5) had the lowest mechanical properties (~9% less) of all builds. Build locations 2 and 4 had Z oriented tensile data with the lowest values (see table in Figure 6). This was because gas flow worsened when the machine's filters were nearly full. In addition, many AM process conditions needed to be taken into account such as powder coverage, build plate material/condition, recirculating gas filtration, gas flow rates, part orientation, and part location on the underlying build plate and these parameters must be controlled for consistent AM part mechanical properties. Hence, a manufacturing plan with defined operating windows is needed to ensure parts are consistently made to specification.

The Effect on the AM Benchmark Tests on Using Different Machine Types

To check for the effect of different additive machines, six AM commercial machines were chosen to print the same parts in a "round robin" demonstration of variability (see Figure 7):

- Equipment chosen included an EOSM290, ProX320, SLM, and the EOSM280
- 4340 steel powder was procured from a single lot to minimize variance
- A manufacturing guide was written and disseminated to all participants outlining all major aspects of the manufacturing process
- The aim of this round robin test was to observe variance in material properties as a function of orientation and plate location across equivalent and different equipment types, with the same or equivalent process parameters.

AM Engineering Simulation Digital Data Storage Challenges

In particular, given the sensitive nature of military parts, data security is critical in AM – how is digital data adequately protected in additive manufacturing? How is data sharing implemented especially if different network security protocols exist, where cloud-based solutions are not widely adopted? Moreover, in terms of data classification where data aggregation could raise the classification, there is a need for a controlled system. Invariably, different formats occur across a wide variety of OEM machines for metals AM with no standardized software or file format.

In terms of data organization, a unified file structure does not in general exist. With AM, large amounts of data generation will occur. Complex data sets can be generated from even a single build. Hence, data storage solutions are needed where process monitoring solutions require large file storage spaces and bandwidth. In effect, AM processing pedigrees are required. There is a need for historical records of print builds to exist for data tracking and analysis to relate back to field performance without duplicating efforts, allowing teams to learn from mistakes or successes. To do all this raises big questions over IT infrastructure issues. If there is no uniform software and network system across different branches and centers, then it will be difficult for approvals and data sharing to happen with additively manufactured parts.

MSC's MaterialCenter as the AM Data Management Solution at CCDC Armaments Center

To overcome digital data challenges of additive manufacturing, a software solution is necessary for traceability, storage, and analysis of simulation material data. Armaments Center used MSC Software's MaterialCenter (Figure 8) and developed an additive manufacturing schema to enable the storage of all printer machine parameters along with corresponding material properties. It utilizes M/S Excel integration in order to map and import custom templates. The data collected is:

- Machine Information
- Part Data (CAD/STL/MAGICS Files)

- Starting powder properties
- Machine Build Parameters
- Build Layout and Orientation
- Laser Parameters
- Post Processing
- Metallographic Analysis
- Mechanical Testing Data

The data stored using MSC Software's MaterialCenter involves a flexible schema for different applications, an automated method for input of material process information, data analysis to compare and contrast properties and understand how to optimize them, and finally allowing traceability of test data.

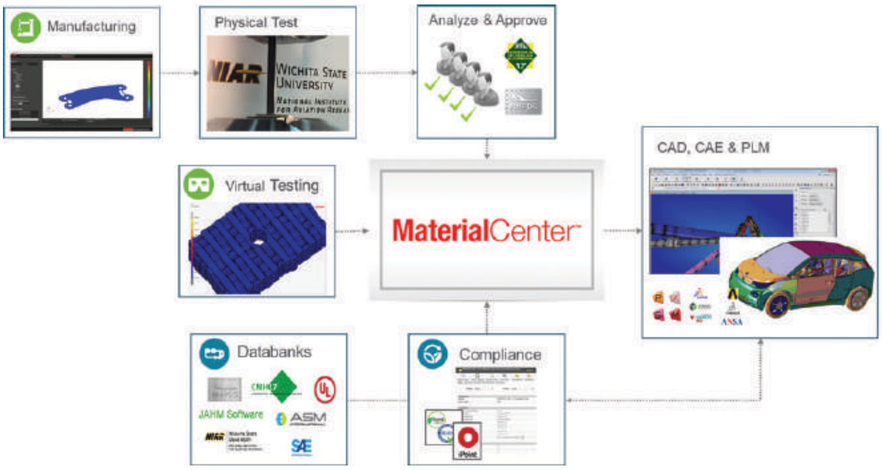


Figure 8: **MSC MaterialCenter in the center of the entire AM Material Lifecycle workflow**

Capturing the Entire AM Material Lifecycle

Figure 8 shows the data tracking process for additive manufacturing and Figure 9 depicts the two parts of the AM process:

1. "Left of Test" where manufacturing inputs that are used to create a part or specimen are captured. This side of the test leverages MaterialCenter's Work Request, Pedigree and Process features. MSC Software's MaterialCenter tracks the test specimen from raw material through the complete specimen build process (Figure 10). The team tracked the materials & the environment, Batch/Specimen numbers and the Part Inspection.
2. "Right of Test" where Material products are tracked from *test to export.*

Finally, PTC Windchill was chosen as the ePDM system for this application and the overall central data system for AM at CCDC Armaments Center - this is shown schematically in Figure 11 where the integration between Windchill and MaterialCenter for additive manufacturing is shown pictorially. The benefits of this system are that it is always up-to-date for version control tracking; it leads to less duplication of efforts and therefore reduced costs; it is a common file system for traceability, file security, historical storage, etc; it provides for a better collaborative environment in order to coordinate efforts; it allows for quicker fabrication of hard to replace parts with standardized file systems and organization; it yields common data models for standardization and validation; it is a single source of data for linkage between systems; and it provides true lifecycle configuration management for additive manufacturing. In short, for us to make Additive Manufacturing as "available" as traditional manufacturing techniques, materials and process data, it must be linked to part data using this enterprise ePDM approach.

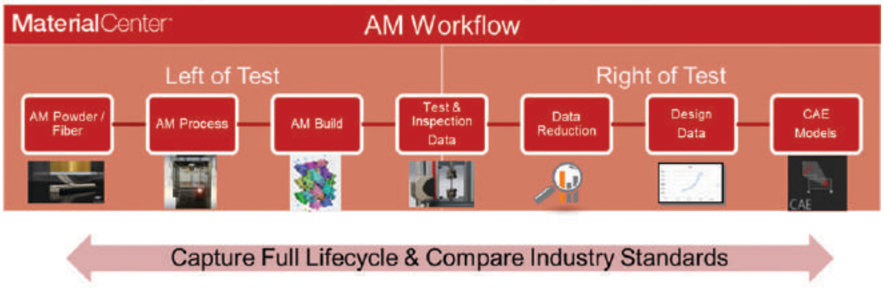


Figure 9: **Data management applied to additive manufacturing process**

This additive manufacturing ePDM workflow helps to deal with the management of data issue and can become a US Army Standardized Tool for Lifecycle support when printing a component. It provides confidence through validation to the end user of part performance. Everything is in the chain from raw material, files, machines, and post treatment and it is validated to perform as designed. In terms of Data Capture, automated processes to feed into the data management system were enabled. In terms of On-Demand Manufacturing, the team has qualified and authorized personnel with access to the data. In terms of Predictive Modeling, knowing how a part will perform before printing is invaluable. In terms of Cooperation & Data Sharing, it will lead to the saving of money and time by building on the most up-to-date work. And, lastly, in terms of Data Analysis, the team can optimize process parameters via statistical modeling and understand the relationship between key AM process parameters.

Future Focus of Additive Manufacturing in the US Army

The US Army CCDC Armaments Center is aiming at integrating material data management with other enterprise software, eg. PLM, and collaboration with other services such as the US Air Force, US Navy, etc. Ultimately, this approach can be expanded to other manufacturing processes and the capture of legacy manufacturing data with the creation and storage of new data libraries. It is also looking at new materials systems (functionally graded materials, novel alloys, hybrid materials), the fielding of AM parts and AM systems for on-demand Battlefield manufacturing, a wide range of qualification & certification of materials, processes and parts via additive manufacturing, and advanced fabrication integration with sensors and electronics.

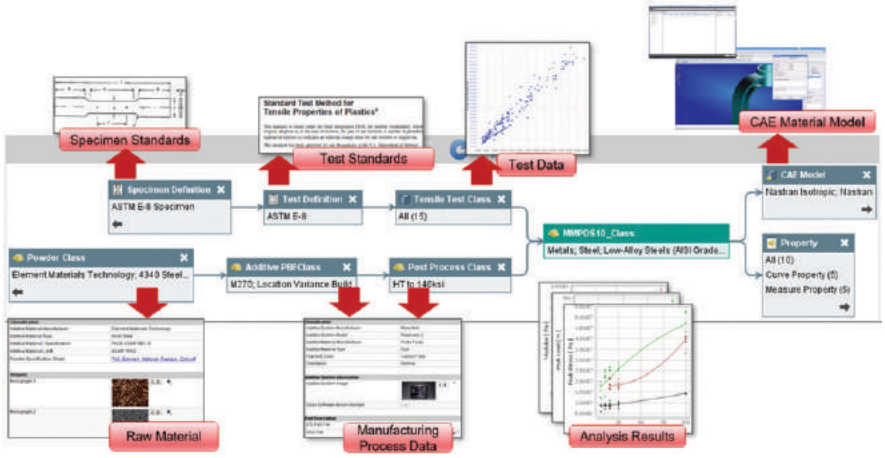


Figure 10: **Overall Flowchart of Additive Manufacturing Data**

Reference

"Army Efforts in Metals Additive Manufacturing & Data Management", R. Carpenter, SME Smart Manufacturing Series – Additive Manufacturing, 07 June 2018

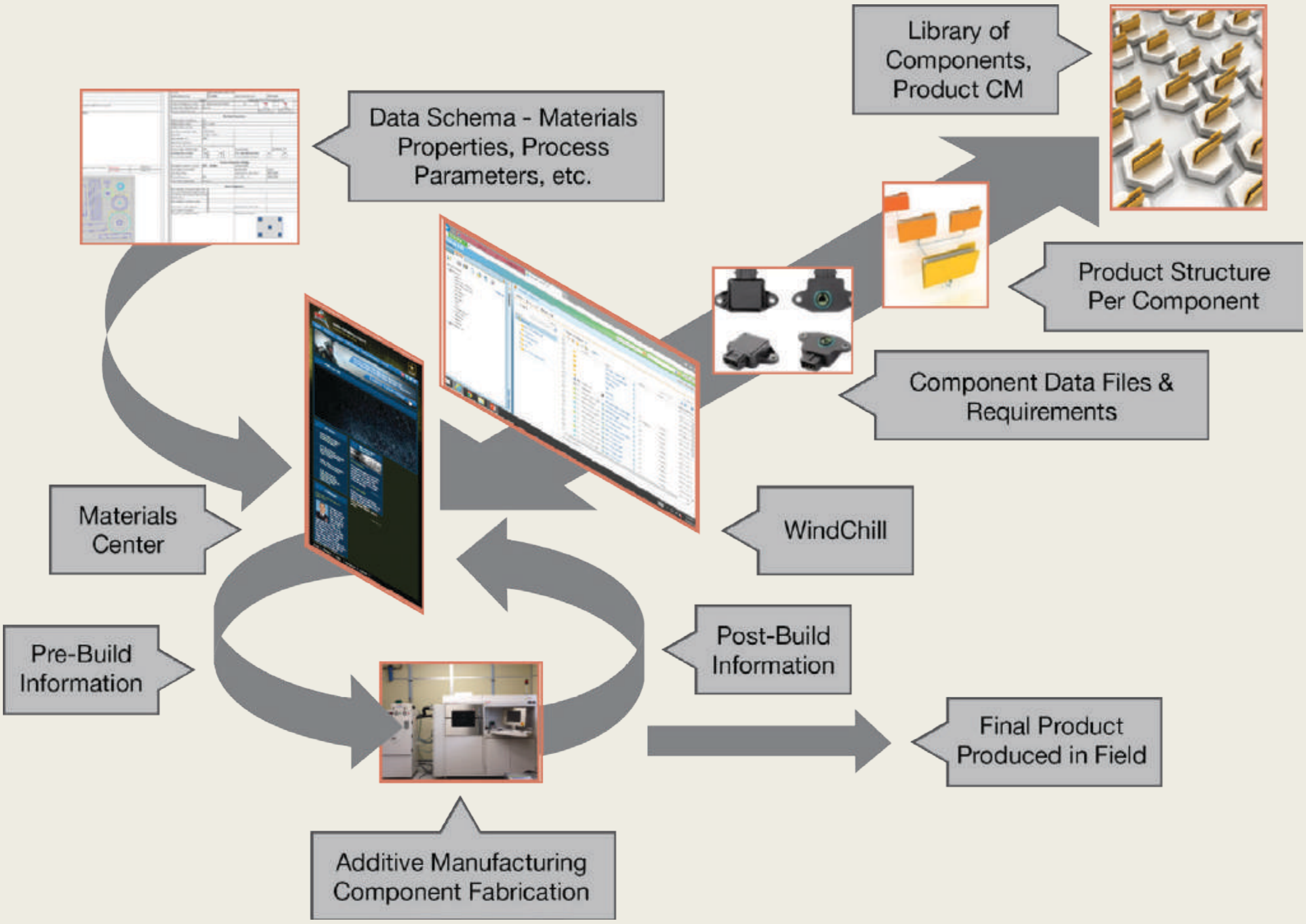
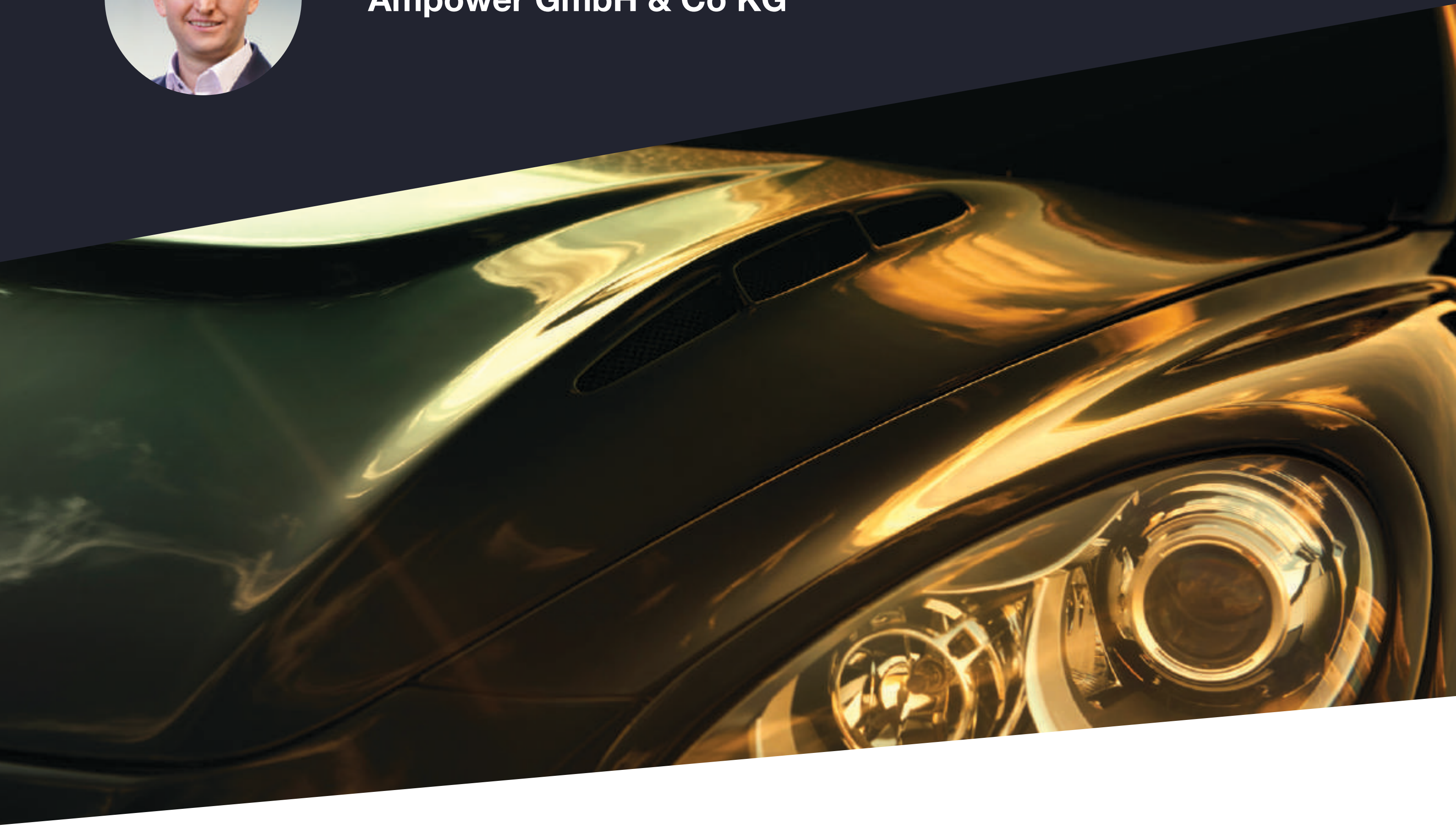


Figure 11: **PTC Windchill and MSC MaterialCenter integration ePDM system for Additive Manufacturing Data**

Use of Simulation in Additive Manufacturing
Process Chain of Thin-walled Automotive Parts

By **Dr. Maximilian Munsch, Ampower GmbH & Co KG**



For more than 30 years, dozens of Additive Manufacturing (AM) technologies have been used for realizing prototyping applications. Over the past few years, AM was increasingly adopted for serial applications throughout industry, such as medical or aviation. The process of powder bed fusion with laser beam (PBF-L) of metals has the largest impact. It offers the highest degree of freedom of design and flexibility as well as excellent material properties.

Identifying automotive PBF-L applications becomes challenging when taking the industry's high demands regarding cost, quality and time into account. Because of the cost per volume of AM parts, currently only high priced, low volume vehicles or racing sports cars are targeted for application screening. In automotive production for mass markets, cost per part dominates the final decision on whether they will be manufactured additively or

Figure 1 Additive Manufacturing process chain

conventionally such as forging or casting. Manufacturers of high performance sports cars with limited quantitities up to approximately 5,000 units per year will be early adopters of AM. Ampower expects the largest potential in automotive applications to be in the power and drive train as well as the suspension system.

To analyze the status quo, Ampower conducted a study on Additive Manufacturing of a high-end automotive application - a tail pipe blend from a Porsche GT2 RS sports car and analyzed the complete AM process chain. Tail pipe blends are the visible part of the engine exhaustsystem. Optical requirements are high since the component reflects the engine's performance to the customer's eye. Conventionally, those blends are manufactured from stainless steel or titanium alloys. Two metal sheets formed by deep drawing are joined by a welding seam. Requirements for the mechanical properties are driven by vibration and corrosion which put high stress on the welding seam. Additionally, tail pipes are subject to major design iterations. This leads to remanufacturing of deep drawing tools at extremely high cost and typical lead times of over 12 months.

AM rarely make sense without exploiting the potential of redesign. A redesign has to consider not only specific parts but also all surrounding components, functions and assembly steps. For the present application, realized redesign advantages are short time to market due to tool-free manufacturing, increase of quality due to homogenous material properties, reduction of number of parts – and thus less assembly steps – and potential for customized design.

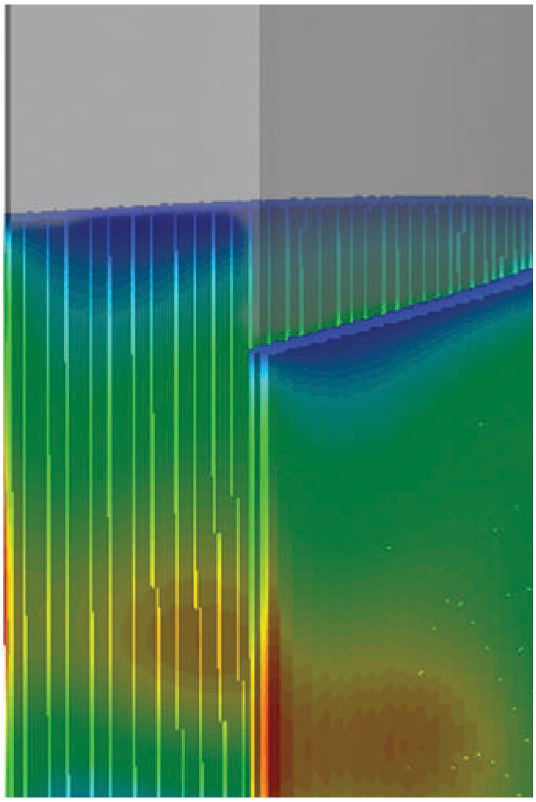


Figure 2 Re-designed, printed and post-processed tail pipe blend of sports car Porsche GT2 RS

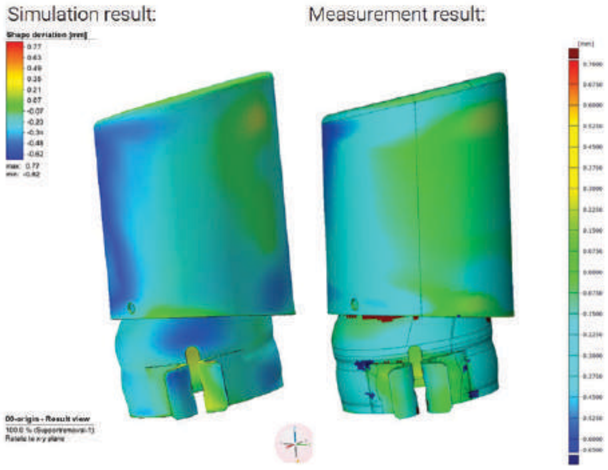


Figure 3 Results of simulation with Simufact Additive and computer tomography measurement of printed part

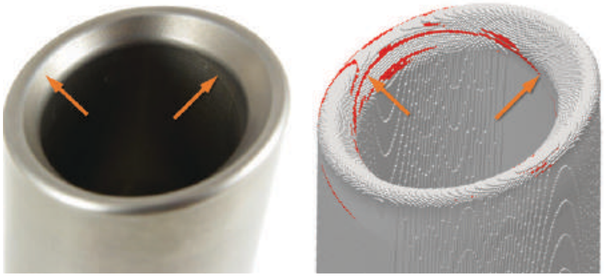


Figure 4 Detection of shrink lines with the new function inside Simufact Additive

The AM process chain used for production of the tail pipe blend is displayed in Figure 1. The final part manufactured with PBF-L using titanium alloy Ti-Al6-4V is shown in Figure 2 .

For complex free-form surfaces, optical 3D scanning, e. g. with Hexagon metrology devices, and computer tomography (CT) imaging are well suited methods to accurately measure the resulting geometry. In this study, the results of CT imaging were used to assess the feasibility of simulation tools that allow prediction and compensation of stress-induced deformations. The overall accuracy is mostly affected by distortion and part shrinkage from residual stress formed during the PBF-L process, where material cools at rates of several thousand Kelvin per second.

The simulation of the PBF-L process was conducted with Simufact Additive using the inherent strain model. The voxel size for discretizing the CAD data was set to 2 mm – the range of the wall thickness of the part. The simulation yielded a stress distribution and a prediction of the shape deformation. The comparison of the results of the simulation and the CT measurement are displayed in Figure 3. The conducted simulation shows a good match of absolute range of distortion, and the deviation is represented quite well.

Further analysis was done in collaboration with Simufact headquarters in Hamburg employing a brandnew function to detect specific part defects - so-called ‘shrink lines’. Such shrink lines are formed in layers where manufactured areas grow together, shrink during solidification and leave visible marks on the surface. These defects were visible at the upper region on the tail pipe blend after production as displayed in Figure 4. The part defects were correctly predicted by the simulation software and will allow for future compensation.

In conclusion, the study revelaed the feasibility for use of PBF-L process of thin-walled automotive parts. However, the relative high cost of the process will limit the use to high end applications with low volume. Simufact Additive predicted the deformation and shrinkage correctly and will allow improved process chains by enabling first time right production.

About Ampower:

Ampower is the leading consultancy in the field of industrial Additive Manufacturing. Ampower advises their clients on strategic decisions by developing and analyzing market scenarios as well as compiling technology studies. On operational level, Ampower supports the introduction of Additive Manufacturing through targeted training program as well as identification and development of components suitable for production. Further services include the setup of quality management and support in qualification of internal and external machine capacity. The company is based in Hamburg, Germany. More about Ampower at am-power.de.

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Simufact Additive: Collaborative Simultaneous Engineering Tool **for Additive Manufacturing**

By **Clara Moriconi, Head of Safran Additive Manufacturing's Methods, Tools and Application Team, France**

Additive manufacturing is a process that has been used for some years in Safran's production centers. Safran Additive Manufacturing - a technology platform attached to Safran Tech, Safran's dedicated research center - is aiming to support the widespread use of the additive manufacturing technology within the Group: first by recommending tools and standards while evaluating and validating the solutions through use cases, then by accompanying the companies of the Group in the deployment and use of these tools.

Additive manufacturing of metal components is becoming more and more widespread in all sectors of industry. A major advantage of this technology is the geometry design freedom that allows the creation of optimized shapes according to the targeted function. It now starts to be used for the serial production of high-tech parts, particularly in the aeronautics and space industry. Another key benefit of using 3D printing technologies is the ability to reduce the weight, cost and complexity of parts production without sacrificing the reliability and durability of materials.

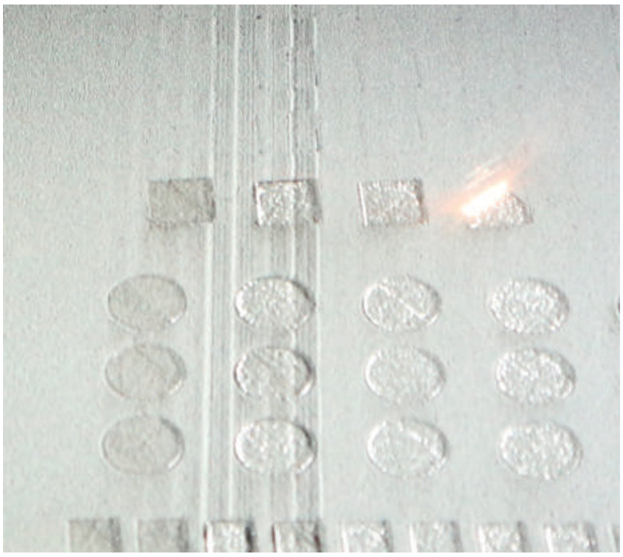

Figure 1: Example of the effect of a 3D printer scraper / workpiece collision on the powder bed

The Additive Manufacturing Challenge

Although some applications are already in production, many are still at the proof-of-concept stage. Thus, in order to expand the use of additive manufacturing and make the most of this technology, it is essential to accelerate the capability to model additive manufacturing processes in detail - and more broadly, to improve the understanding of the technology by the relevant employees within our Group.

The Methods, Tools and Application team of Safran Additive Manufacturing is operating in this context. The objective of the team is to evaluate and qualify additive manufacturing process simulation solutions, and then facilitate their deployment within the various Safran operating units.

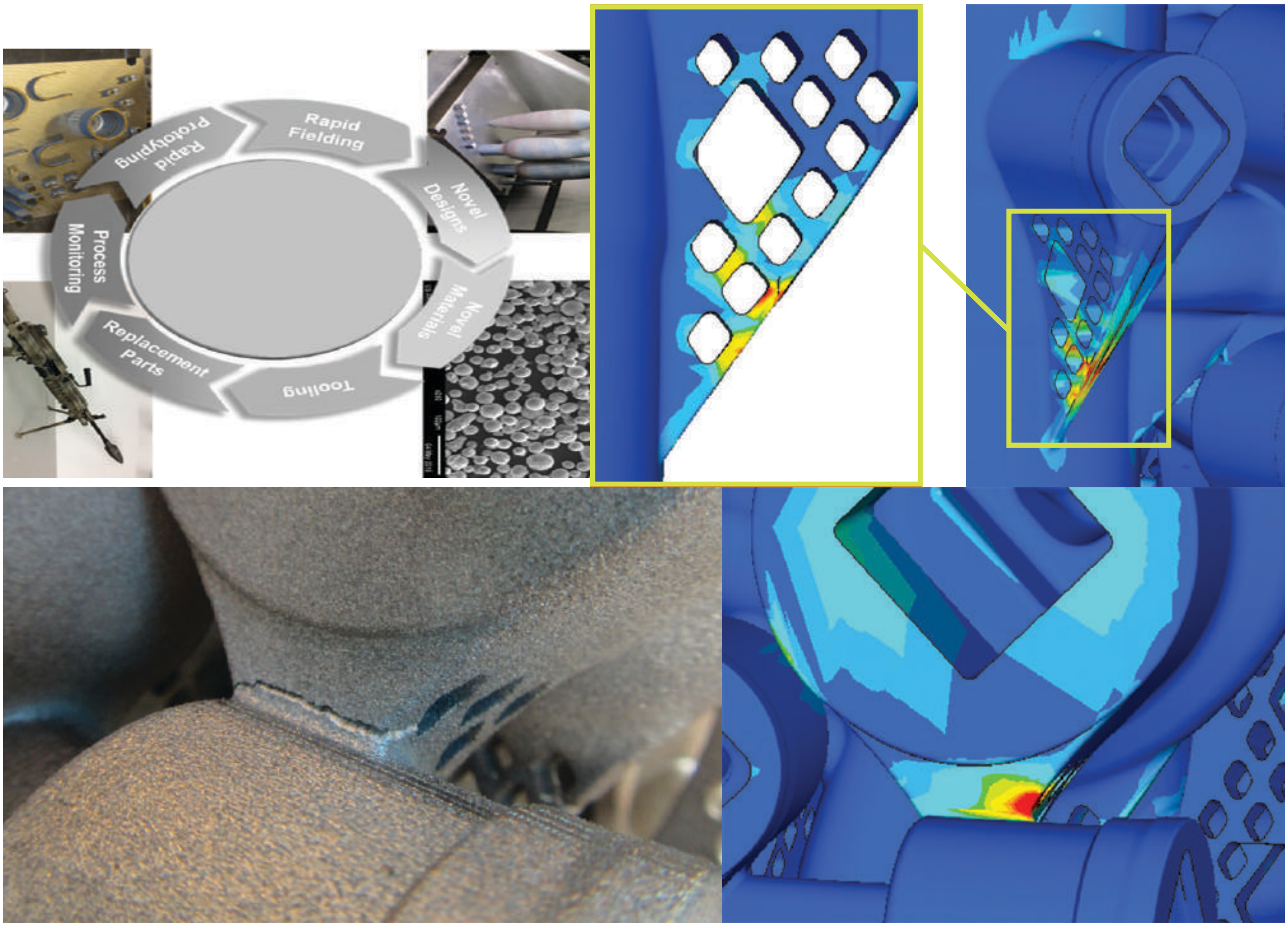

Figure 2: Example of macro-cracks on LBM parts that appeared during the manufacturing process due to part distortion and Simufact Additive stress predictions of the parts (Red is high, blue is low)

Simulation of the Additive Manufacturing Process

One of the manufacturing processes in which Safran Additive Manufacturing is more specifically interested in, is the Laser Beam Melting (LBM) process. The simulation of this process aims at identifying issues associated with part distortion during the manufacturing process, as well as the potential risks of failure of the part and its supporting structure.

Safran called on MSC Software, which offers a solution that uniquely covers the entire manufacturing process, from the initial melting step of the part to the completion of a final HIP treatment (Hot Isostatic Pressing), including all post-processing operations such as a stress-relaxation heat treatment, baseplate cutting and supports removal. This solution is Simufact Additive.

Safran Additive Manufacturing uses the software iteratively as part of our feasibility studies for the following two applications:

- For production support: to virtually develop and validate the process, in order to reduce physical iterations on the machine;
- Further upstream, in the product design phase: to check the manufacturability of parts and to take into account the specific constraints linked to the process during the product design phase.

Simufact Additive allows for the identification of potential issues due to deformation of parts during the manufacturing phase and post-treatment operations, risk of collision with the recoater, as well as the possible risks of failure of the part itself or the supporting structure attached to the part. Figures 1 and 2 illustrate two types of failures that can happen in additive manufacturing: 3d printer scraper / workpiece collision in the powder bed during the manufacturing process, and large scale crack formation during the 3d printing process due to inherent stresses in the part during the manufacturing process

The Benefits of Simufact Additive to Safran

The use of Simufact Additive has enabled us to save considerable time in production preparation thanks to the predictive nature of the software, which limits development by manufacturing iterations by using virtual development upstream, but also during the part design phase, by enabling us to anticipate the effects and limitations of the process at the product design level.

One of the added values of the Simufact Additive solution is that it allows us to bring together two activities: engineering and production. On the one hand, people from engineering who design parts with a strong focus on part performance in service, and, on the other hand, the methods office who master the industrial processes and their associated constraints. Simufact Additive is a solution well adapted to simultaneous engineering that facilitates dialogue between the different business activities involved in the same project. In addition, the software is easy to use, with an intuitive, business-oriented interface that allows for quick and easy appropriation/ownership.

Conclusions

Safran Additive Manufacturing has taken full advantage of the added value of the *Simufact Additive* solution in order to secure the integration of the additive manufacturing processes into its “product-process” development processes, both upstream during product design and downstream for the production launch.

Safran Additive Manufacturing is now focusing on extending the use of the Simufact Additive solution to different types of parts and different grades of material, in order to improve the design process for additive manufacturing as a whole. MSC Software supports Safran Additive Manufacturing and the Group in achieving this objective through this solution that integrates into the global additive manufacturing value chain, ensuring a quality and open digital continuity.

Try Simufact free for 30 days! Learn how: www.mscsoftware.com/simufact

Optimize the Product Part, Not Just the Geometry **- A Real World End2End Additive Manufacturing Solution**

By **Dr. Hendrik Schafstall, Vice President,**
Virtual Manufacturing & Costing, MSC Software

With the continuing rapid adoption and development of additive manufacturing techniques and technologies in multiple industries led by aerospace, defense, medical and automotive, many benefits can be obtained in companies. This includes the huge potential for lightweighting, small production runs with less material waste, significant energy cost savings, and the possibility to produce functional, high performance parts that simply can't be subtractively manufactured, cast or formed. One of the challenges is a full automation and to minimize the physical try-outs. This can only be achieved with a full digital transformation and a fully connected workflow.

With the acquisition of MSC Software in 2017, and its manufacturing oriented and material focused business units of Simufact and e-Xstream in particular; Hexagon's Manufacturing Intelligence Division now has in its portfolio a unique combination of tools including cutting edge CAD/CAM production software plus existing market leading metrology solutions. The smart factory solution Xalt from Hexagon is offering the needed framework for the connecting of all data (from real and virtual sources) to enable a fully connected workflow and transparency of the process.

Figure 1: End2End Workflow for Virtual Simulation, Printing and Scanning in Additive Manufacturing

Figure 2: Concept of a folding bicycle with 3d printed Metal and Polymer parts

These technologies within Hexagon allows the development of a compelling solution for the challenges of the additive manufacturing industry where unit costs can be high and errors can be costly. It is important to not just optimize the 3D CAD geometry during 3D printing, but also, to optimize the end product part. There is a need for real world solutions that are fast, accurate and robust than alternative PLM and CAD-based methods. In effect, with this combination of technologies I believe it is now possible to plan, optimize, validate and replicate high quality additively manufactured metal or polymer parts in a straightforward way so that they are 'First Time Right' printed. Let us unwrap that statement a bit by way of first outlining a typical End2End Additive Manufacturing workflow (see Figure 1). And secondly, using an example for a new innovative lightweight folding bicycle concept (see Figure 2). We choose two typical parts from the bike, to demonstrate the principles for the available solutions for metals and polymer. The first is a handlebar upper fork as a 3D printed metallic part and the second one a bike saddle as a polymer part.

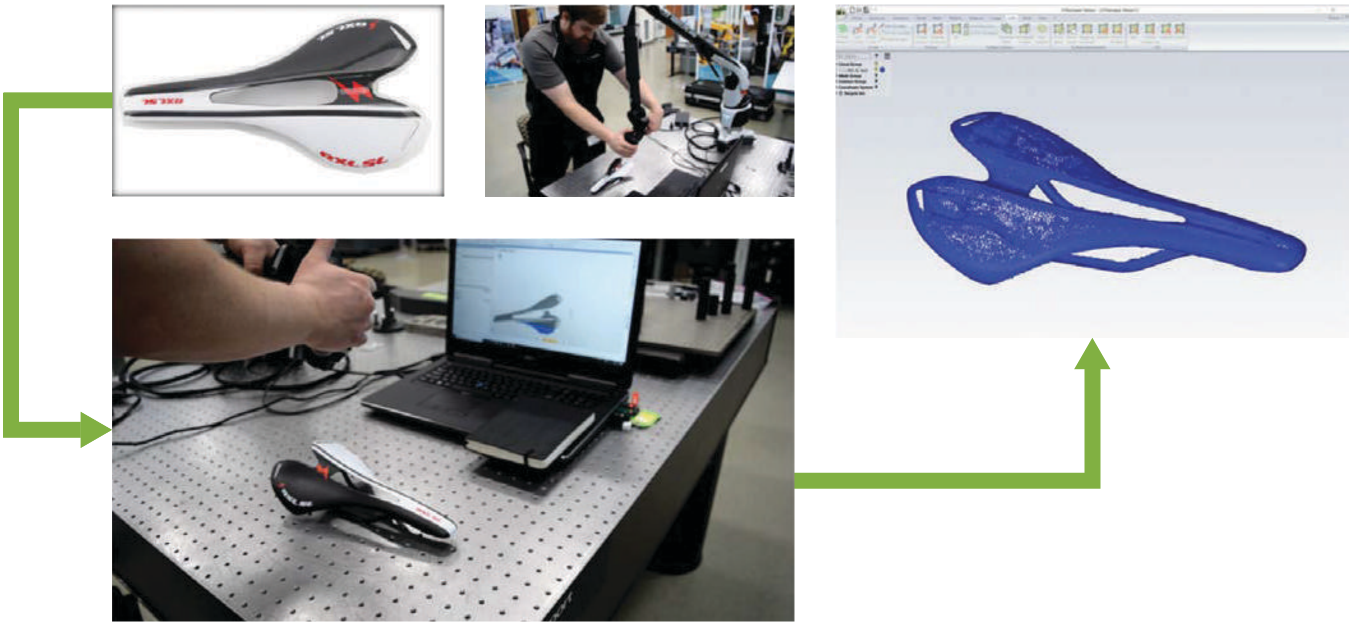

Figure 3: Process of Reverse Engineering the Arena Seat Saddle using a 3D Scanner

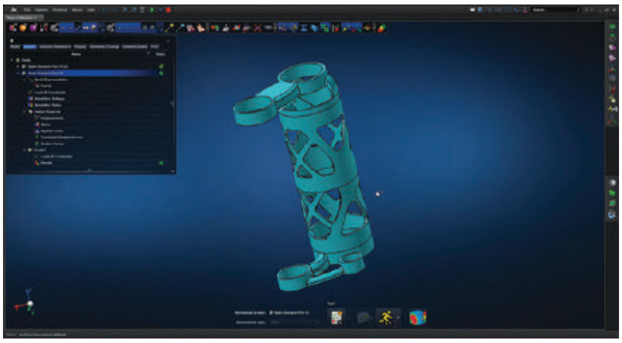

Figure 4: MSC Apex topology optimization of the folding bike fork geometry

The wheel in figure 1 shows the overall workflow and data flow. You can start in any of the segments depending on the requirements and parts you want to produce. The geometry for the part, which we want to print, can come from different sources. As an example for a 'reverse engineered' part, we used the bike saddle. The geometry was created out of a 3D scanned point cloud, see Figure 1: 5 o'clock (Figure 3), where we used a Hexagon Absolute Arm 7-Axis machine.

For the handlebar upper fork, we carried out a topology optimization of the part, Figure 1: 7 to 8 o'clock, in a suitable CAD-centric tool like MSC Apex (Figure 4 shows the fork part). Used in early design, MSC Apex allows users to obtain geometries that will withstand the loads on the component and minimize its weight (by as much as 70%). Topology optimization therefore can be used to redesign existing components and account for manufacturing constraints early on. After this optimization step, the user needs to be able to evaluate the strength and stress of the optimized design by predicting its distorted geometry on full loading to see if it fits within allowable tolerances.

Once a suitable geometry has been designed, like all computer-aided engineer simulation predictions, the build process need to be qualified, critical areas to be identified and at the end the whole

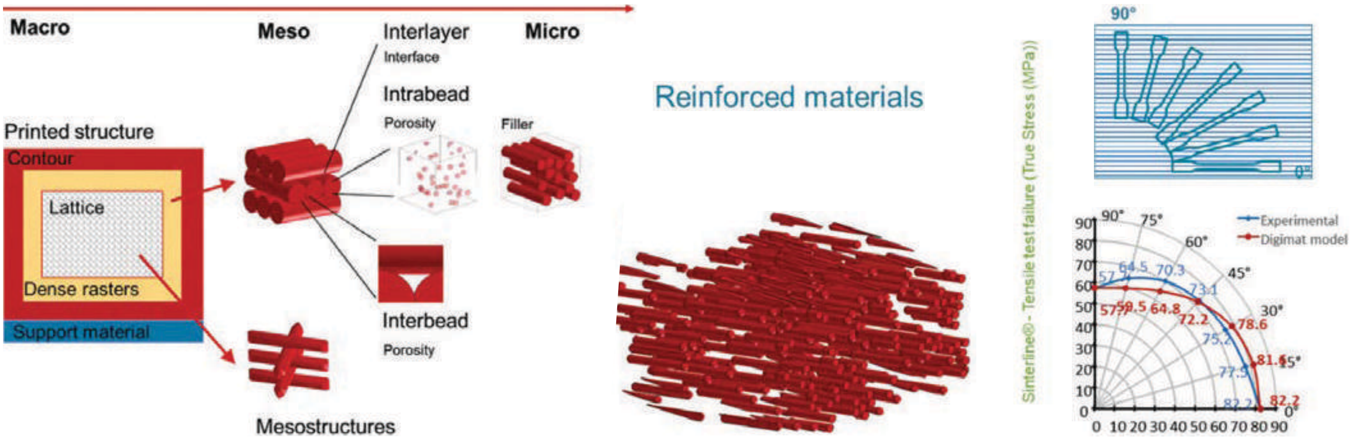

Figure 5: Schematic representation of polymeric materials in MaterialsCenter

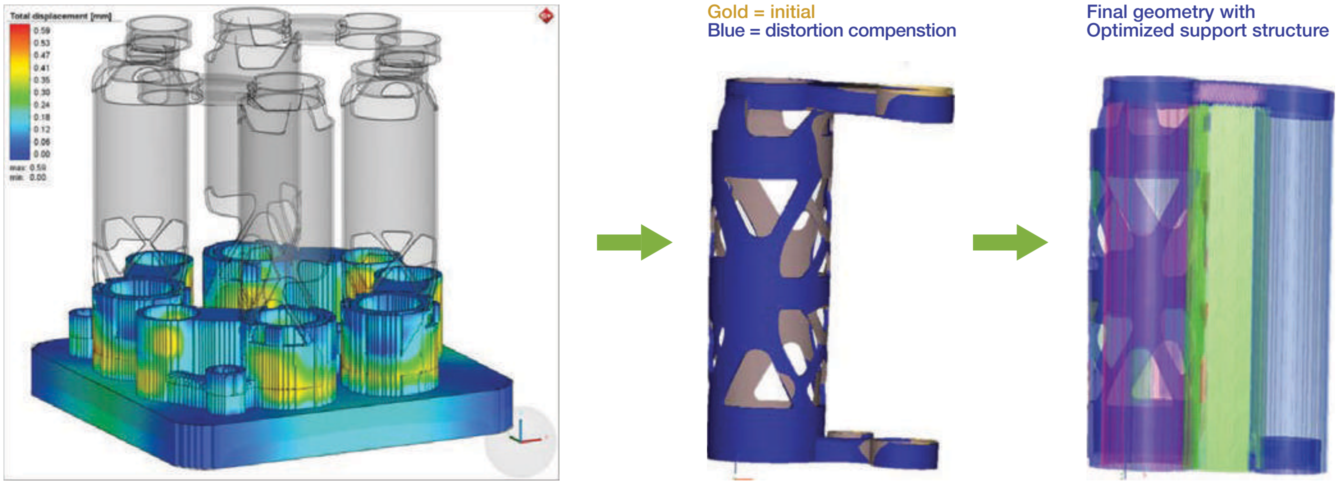

Figure 6: Comparison of simulated and optimized 3D printed metal Fork part in Simufact Additive

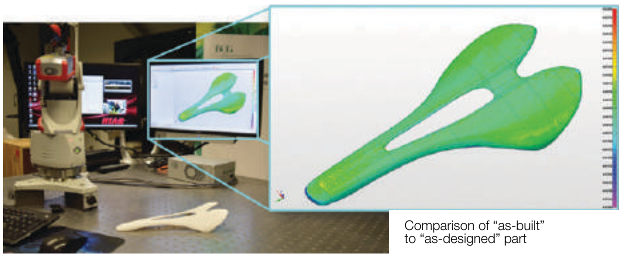

Figure 7: Comparison of the final 'as-built' 3D printed polymer seat part to the 'as-designed' part in Digimat Additive

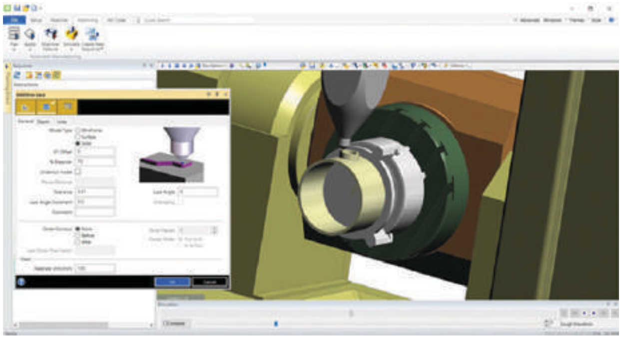

Figure 9: Hexagon EdgeCAM's knowledge of machine control in Additive DED machines

process chain needs to optimized, so that we will get the right shape with the required part performance. The final part performance is the outcome of the used process and print parameter. The data can be taken for all materials from an open and flexible material data management tool like MaterialCenter from MSC Software (Figure 5). This solution was adjusted dedicated to AM, to be able to handle all experimental data, to calculate the needed parameter out of it for the material models for the simulation and finally, also to control all material properties during the production process. The final material properties need to be documented and stored for sensitive parts in AM. MaterialCenter is the perfect solution to be used besides the production and for the virtual manufacturing simulation as a digital twin.

But let us go back to the manufacturing simulation (Figure 1: 11 o'clock). MSC Software offers best in class technologies with Simufact for metals (Figure 6) and Digimat for polymers (Figure 7). The simulation will predict the distortion and behavior of the parts (fork and saddle) during the whole process chain and will detect critical areas or possible problems. This enables the user to optimize the whole process steps and minimize the risk for manufacturing problems. The whole process will become more transparent and the process can be made more robust to ensure that all errors are eliminated before the designs are committed to in the printers.

In the shown folding bike scenario, we worked with a Hexagon partner organization, NIAR, at Wichita State University in America to use their 3D printers to additively manufacture both the fork and the saddle (Figure 8). This part of the process is represented by the segment in Figure 1 at 1 o'clock where you go through the 3D printing process based on the optimized designs from the CAE software predictions at Figure 1: 11 o'clock. We want to thank NIAR for their collaboration in this project.

30% of the costs are incurred directly through the post-processing step for machining of the printed part. The used orientation of the part during the process and therefore the needed support structures etc. are directly influencing the effort for the machining stage. So there is a need also to take this manufacturing step into account to be able to optimize the whole process chain with all the main influencing steps. It also has an impact on the predefined design and can be used to minimize the total costs. That is why MSC is developing an

Figure 8: NIAR facilities for 3D printing and the machines used in the bike saddle and fork printing

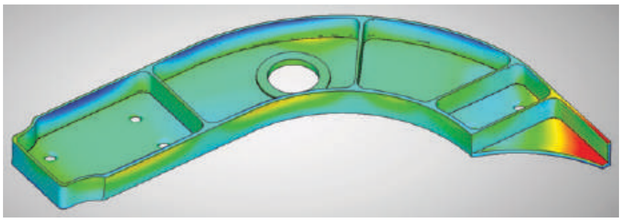

Figure 10: Distortion of a DED additive manufactured part after the machining process

Figure 11: Final inspection of the 3D printed polymer seat part Hexagon Absolute Arm

End2End solution with a closed feedback loop. It further allows supporting better hybrid machines in the future.

Hexagon MI has dedicated production software tools for machining operation, which are simulating the toolpath and machine behavior that will be connected with the manufacturing simulation to predict and optimize the tool path and machining and printing strategy. This can be used also for direct energy deposition processes (DED) based on blown powder or wire-feed for large structures or repaired parts (figure 9). Figure 10 shows the final distortion of an Airframe after a DED process and machining simulation. This solution from Simufact is still under development and should demonstrate the ongoing activities from MSC in the field of Additive manufacturing processes and how we take advantage out of being part of Hexagon for the most benefit for the customer, to connect production software and manufacturing simulation.

Finally, we validate all simulation results with the real measured data (Figure 1: 4 o'clock), by using a Hexagon Absolute arm to scan the 3d printed plastic seat by acquiring a point cloud using the physical dimensions of the 'as-built' part to inspect the final part for quality assurance. The simulation results were proofed and it was found to be very close to what was required in the specification, as indeed was the metal handlebar fork we had NIAR print. The simulation results stand for quality and the use of the software tools for productivity.

Summary and Conclusions

Hexagon's virtual predictive design & engineering simulation software from MSC Software, production simulation software, and 3D metrology measurement workflow for additive manufacturing captures the entire process chain (Figure 1) through a printed part's final 'as-built' performance. Virtual printing stress analysis simulation (either by Simufact for metals or Digimat for polymers) allows users to optimize the 3D print process via these innovative simulation tools, thus saving time and material cost. We have illustrated this by way of two components from an innovative folding bike design.

Good 3D CAD geometry topology optimization (under development via MSC Apex, our modern CAE preprocessing tool) allows for fast identification of the part geometry design parameters in order to minimize material cost and printer time. It will be directly linked to the manufacturing simulation and will take the manufacturing constrains into account. This enables the designer to optimize a good printable part with the right part performance for the loads.

The data management of all important material data, from test through simulation up to the production and process parameter, requires a good data management solution. MSC has developed a solution dedicated for AM based on MaterialCenter. Support of good material properties ensures the most accurate simulations predictions for either metals or polymers. Finally, after printing the part with your 3D printer of choice, Hexagon metrology's state-of-the-art scanners can verify the accuracy of the simulations and compare the 'as-built' part to the 'as-designed' part. This allows for genuine 'First Time Right' 3D printing. Typically, with this workflow, we find that we can get useful engineering simulation results for additive manufacturing in minutes and hours versus hours and days for alternatives.

The virtual and real world with all different sources can be connected via Xalt and linked to PLM systems. With Hexagon technology the users will be able to make the design and development smarter and at the end have a smart virtual and real factory.

MSC Software and Hexagon's Unique Additive Manufacturing Solutions: www.mscsoftware.com/additive

Development of an Additive Manufacturing Quality System for Gas Turbine Engine Part Production

By **A.I Khaimovich, V.V. Kokareva, V.G. Smelov, A.V. Agapovichev, A.V. Sotov**
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Introduction

Selective laser melting (SLM) is a powder bed fusion additive manufacturing (AM) process which occurs at a high metal melting temperature. High local temperature gradients and brief cooling effects can cause residual stresses and part deformation during 3d printing, the consequences of which can be additional surface treatment and reduced productivity for the process. To understand how to control the formation of AM residual stresses and part form deformation, a reliable method to investigate influences between technological parameters and quality behaviours is required. There are basic physical mechanisms of the selective laser melting process that can lead to part distortion and cracking: high temperature gradients, high viscosity and surface tension of the molten powder zone, un-melted powder and oxidized particles.

The following variables of the SLM process can be established as the most important:

1. Powder, composition, size distribution, shape, and thickness of the melting layer;
2. Laser, power, spot size, beam spatial distribution, scanning velocity and protective gas atmosphere; and
3. Strategy of additive manufacturing

The main target of our research was to find and control the optimum SLM process parameters to minimize printed part roughness, its residual stresses and part deformations. An SLM quality system for gas turbine engine parts production should be based on an interaction model of the technological factors affecting the quality of the final fabricated parts.

There are three main methods for predicting the temperature distribution and residual stress during the SLM process:

1. Simulation methods,
2. Experimental work, and
3. Combined simulation and experimental approach

Since it is difficult to predict part distortion in micro detail due to enormous computational resources being required, a SLM process for a practical part can be divided into three scales; micro scale, meso scale and macro scale. With this type of approach, the temperature history and residual stress fields during the SLM process can be predicted. Thermal information has to be transferred through micro scale laser scanning, meso scale layer hatching, and macro scale additive part build-up.

Description of our SLM Model

The laboratory of additive technology at Samara National Research University developed a model of influences on the SLM process parameters of quality by way of an Ishikawa diagram. The quality of the final additive manufactured part can be decided by powder properties, process parameters, SLM

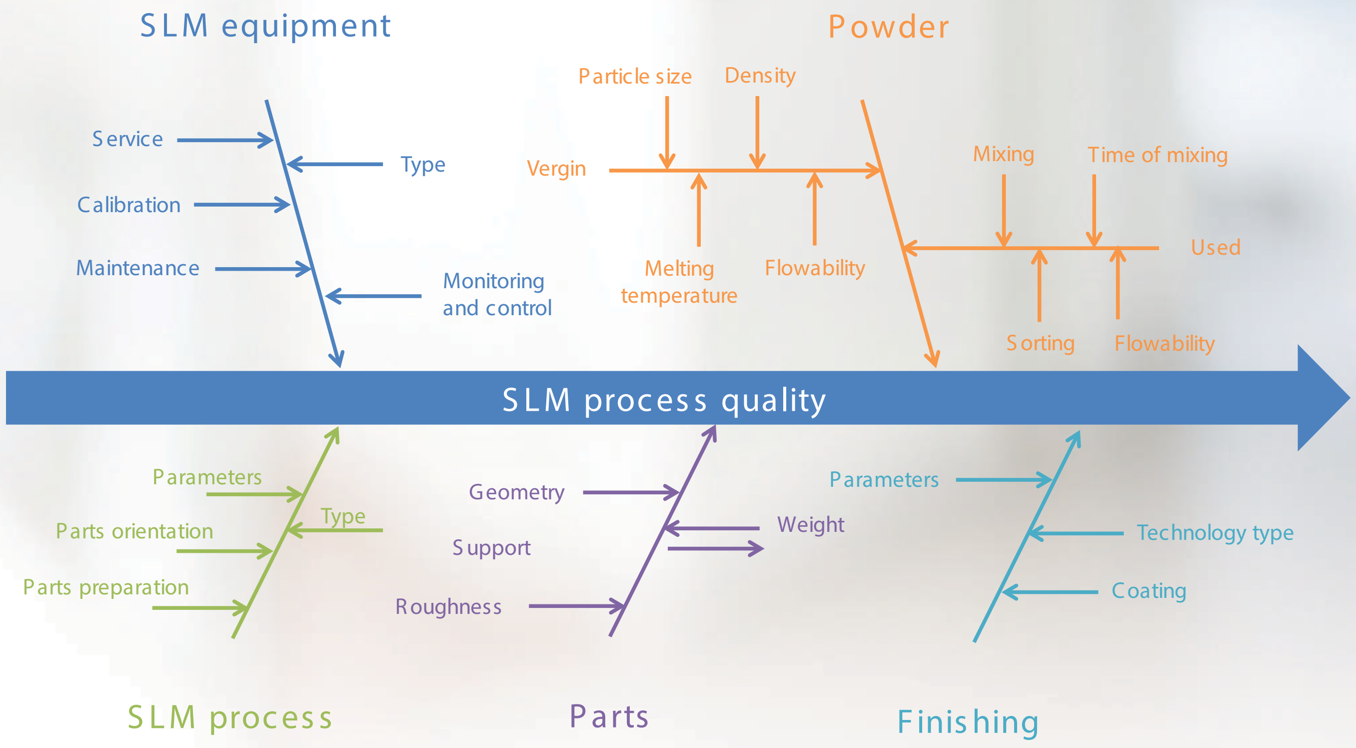


Figure 1. Ishikawa diagram of a SLM process' quality

equipment characteristics, finishing and detail behaviours as shown in Figure 1.

SLM equipment characteristics are determined by the type of 3d printer, the monitoring system, kind of technologies used, and its frequency of service and maintenance. In order to ensure technological accuracy, it is recommended to calibrate the production system and to build in every month test samples as the benchmark for complex shapes. Then it is necessary to check weight (density), dimensions, tolerances, and surface roughness under different part orientations. Quality maintenance requires keeping the equipment's daybook rigorously where all actions are recorded: powder changing, cleaning, stopping, optic system controlling, and parts replacement. Powder analysis includes understanding of the particle size distribution and particle shape using scanning electron microscope. Furthermore, it is necessary to evaluate powder 'flowability' and its apparent density. A SLM quality system should therefore include registration of the qualitative and quantitative parameters of powders especially the proportion of mixed powders. In addition, the main material quality parameter is the rate of sieved and reused powder in a subsequent process powder.

It is clear that an additive part quality is therefore dependent on SLM process parameters which should be controlled and managed. In order to determine the optimal AM built parameters with the aspired objectives and technical requirements, there is a need to consider many factors, such as cost, time, part quality, batch quantity all together. For simplifying this task, we developed a database of SLM technological parameters for domestic powders: aluminium, titanium, heat resistant steel, stainless steel. We produced this database in the PDM system, Teamcenter Manufacturing. The input technological parameters were all the influences on part quality: scan speed and laser power, the powder layer thickness, the hatching distance, the hatching angle.

Development of the SLM Quality System

In our study (reference 1), an effort to better understand the factors influencing part quality resulted in us developing an evaluation method. Technological parameters were divided into two types: those controlled by the operator of the additive machine (inputs) and those defined by the final part's functional use (limiting conditions).

The input SLM parameters were:

1. Gas atmosphere concentration (percentage of oxygen);
2. Powder layer thickness; and
3. Set of 3d printer process conditions: scan speed, laser power, hatching.

The limiting SLM conditions were:

1. Powder behaviours,
2. Geometry accuracy, and
3. Powder grain size.

The input parameters influenced the SLM process by the way of the layer thickness increasing effort on the bed fusion while the density of melting material is decreasing. Another example of the input parameters' influence is if we increase the oxygen concentration in the building camera a melting material becomes more crack-sensitive. We therefore proposed to use a SLM

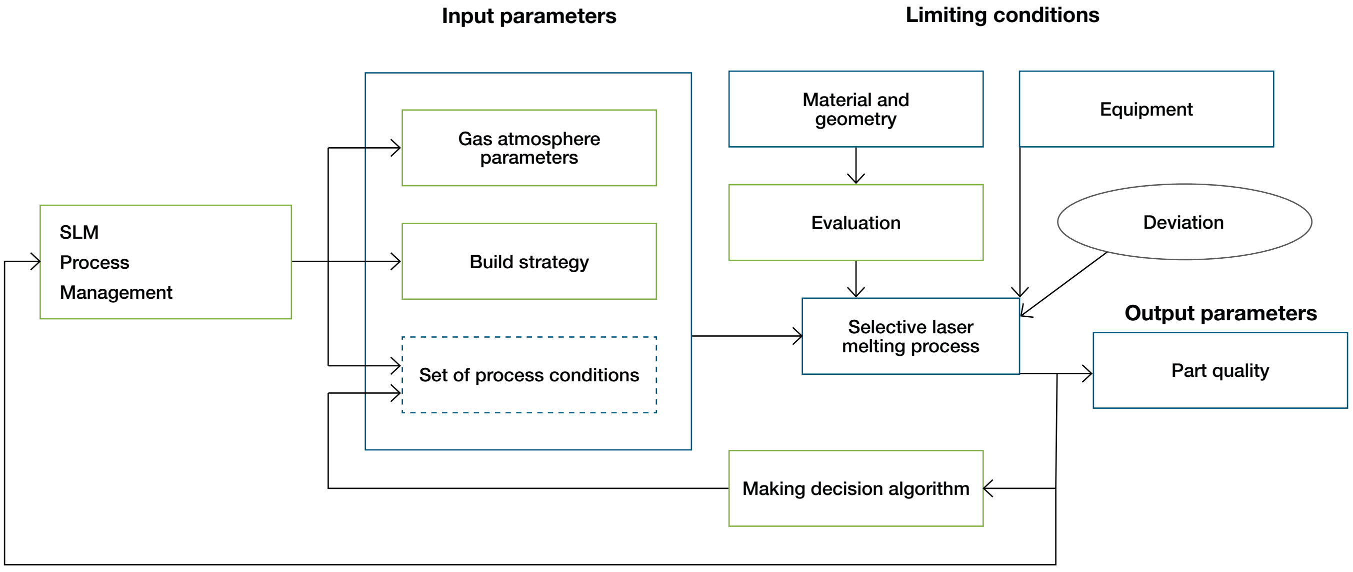


Figure 2. Schematic of the SLM quality system

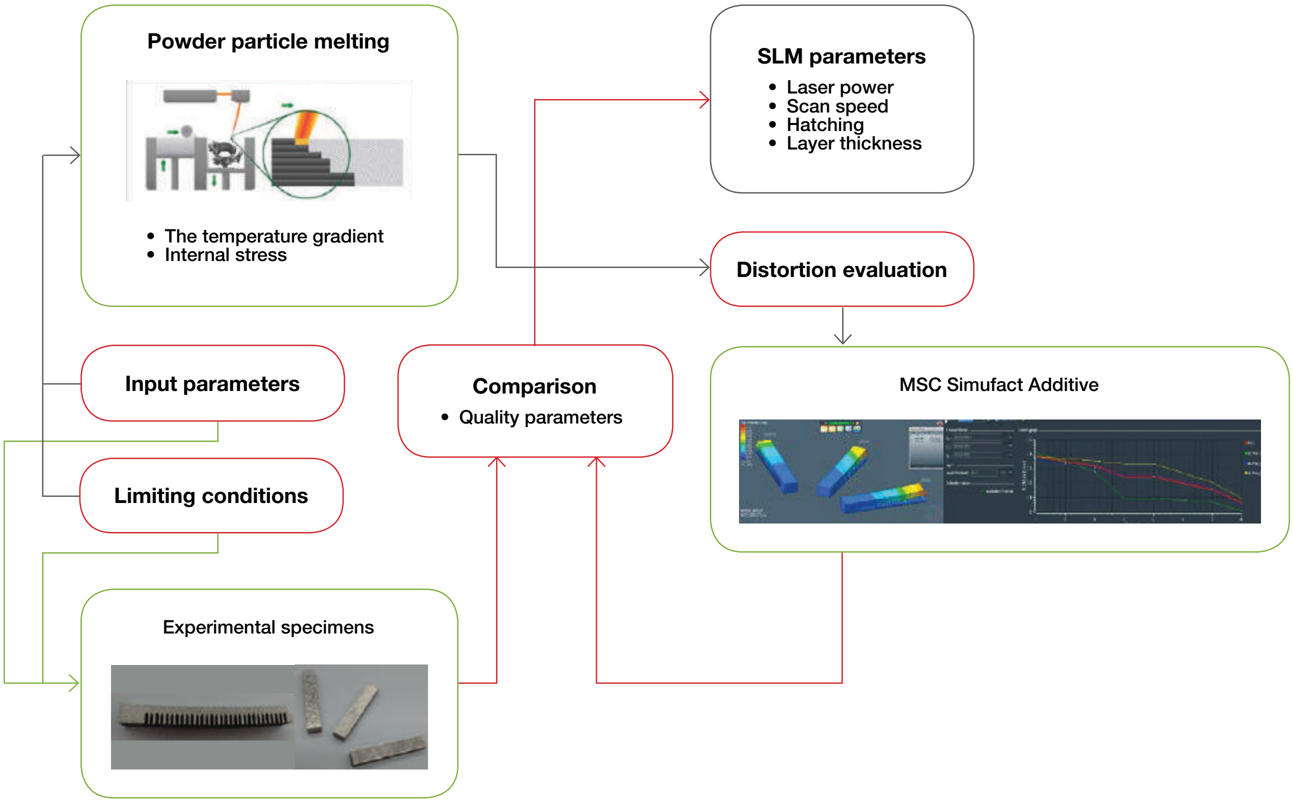


Figure 3. Our proposed SLM quality system

quality system which is based on managing and controlling of input parameters taking into account the limiting conditions. The main blocks of the proposed SLM quality system are shown in figure 2. In order to select the appropriate set of technological parameters, the system uses a making-decision algorithm, and selection of input parameters depends on the link between part requirements (accuracy, geometry, surface) and building regimes for corresponding material and mechanical behaviors. The main idea of this quality system is that decision and denoting of SLM parameters are based on experience, and our statistical database is included in the making-decision algorithm. After each part is manufactured 'successfully', its database record's input parameters with certain limiting conditions are recorded as meaning that all quality requirements are satisfied.

The making-decision algorithm should include not only the statistical database, but a method of quality prediction. The prediction of accuracy and surface behaviors found in the physical process during SLM: temperature gradients and distortions, internal stresses and deformations. For this approach we needed the ability to both monitor the SLM process and to manage this process. Such a system is the key step to achieving digital manufacturing transformation according to the well-known Industry 4.0 concept.

Figure 3 illustrates the developed additive manufacturing quality system we devised for SLM. It should be noted that we needed an engineering simulation model of the SLM process for better understanding of the link between input and output parameters under different limiting conditions. We achieved this by employing the predictive simulation tool, Simufact Additive, from MSC Software.

Simulation techniques have been widely used to predict residual stresses and part distortions in the SLM processes. But they are only suitable for analyzing the thermal-mechanical model to predict residual stresses and distortions of a sintered specimen. For an original SLM part, it is difficult to predict part distortion due to requiring millions of micro-scale laser scans which will increase the computational hardware requirement prohibitively. However, Simufact Additive allowed us to compare numerical and experimental results and to develop a multi scale approach to achieve acceptable accuracy of part distortion and internal stress. As already mentioned, if we divide a SLM process for a practical part into three scales such as micro scale, meso scale and macro scale; with this approach, the temperature history and residual stress fields during the SLM process can be predicted. Thermal information can be transferred through micro scale laser scanning, meso scale layer hatching, and macro scale part build-up. The aim of our research was to develop a perspective quality system for the SLM process based on a making-decision algorithm and predicting the part quality by SLM process simulation in consideration of the temperature distribution and internal stress

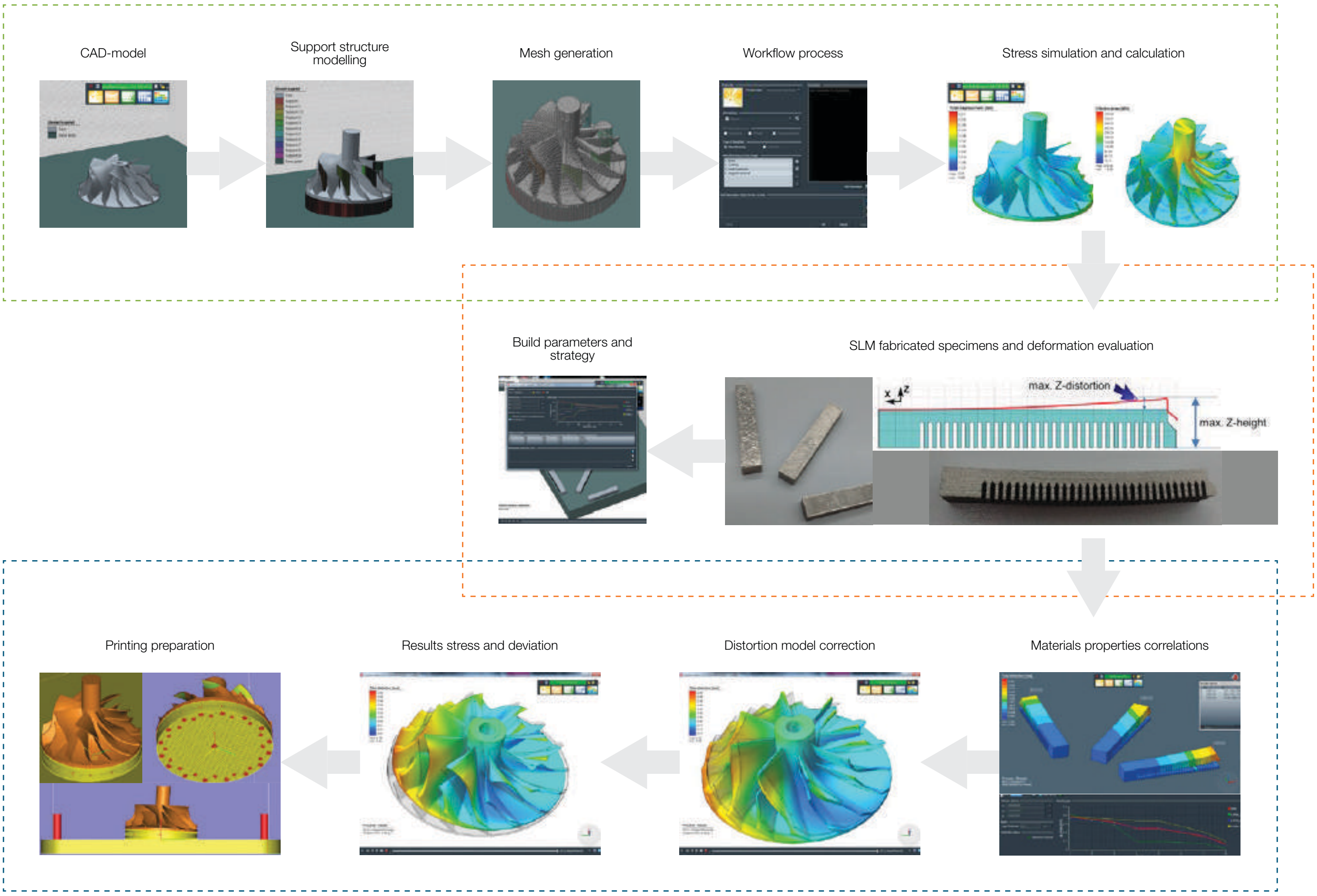


Figure 4. SLM distortion prediction by Simufact Additive for a Gas Turbine printed part

in the workpiece. For developing the SLM quality system, a conceptual model was established. We chose to simulate the entire metal SLM process of a gas turbine engine part including Simufact Additive predictions: build, baseplate cutting and support removal process (see figure.4). Simufact Additive allowed us to predict the distortion and residual stresses in the turbine blade part and guided the quality system in how to pre-compensate to ensure a quality part was printed the first time right. Process control variables were selected in Simufact Additive to optimize this SLM process to reduce printing time and material waste successfully.

Summary and Conclusions

We developed a model of all the influences of additively manufactured SLM process parameters for a gas turbine part based on quality and influencing parameters as described by an Ishikawa diagram. The SLM quality system includes technical-organizational methods of managing and controlling the SLM process. For getting the required part quality influence factors correct, factors must be considered such as limiting conditions (material properties, equipment specifications), and input parameters (building conditions and process parameters). However, during the SLM process, the localized increased compression and tension caused by large temperature gradients and fast cooling of the 3d printing process can lead to significant internal stresses in the workpiece and consequent shape deformation. Simufact Additive was a major predictive simulation tool to avoid this and for the success of our proposed SLM quality process.

Reference

1. “Development of SLM quality system for gas turbines engines parts production”, V V Kokareva, V G Smelov, A V Agapovichev, A V Sotov, and V S Sufiiarov, ISPCIET’2018, IOP Conf. Series: Materials Science and Engineering, 441 (2018) 012024

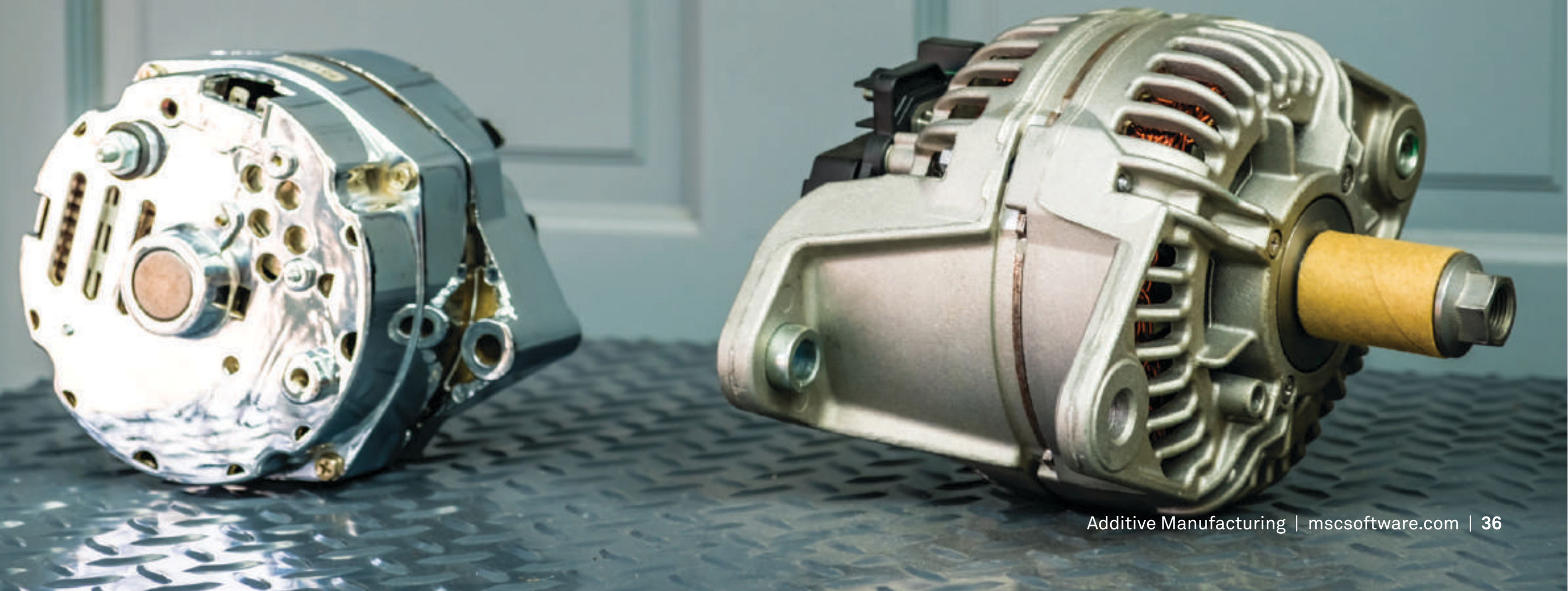
Robert Bosch India Use Simufact Additive to Digitally **Lightweight a Fixture Tool and Save 70% in Mass**

By **Radhakrishnaiah Bathina, Technical Specialist Electric Drives, Bosch India**

Robert Bosch Engineering and Business Solutions Private Limited is a 100% owned subsidiary of Robert Bosch GmbH, one of the world's leading automotive Tier 1 suppliers of technology and services with 400,000 employees and $100Bn annual revenues. Bosch in India offers end-to-end Engineering, IT and Business Solutions and employs over 19,000 associates. It has the largest software development center outside of Bosch Germany and is a Technology Powerhouse with a global footprint and presence in the US, Europe and the Asia Pacific region.

In making the rotor parts of motors, Bosch employs an IRIS fixture tool (figure 1). Each year typically 200 units of this IRIS tool needs to be produced for assembling various types of motors. Until recently, the IRIS tool used to be manufactured by a conventional casting process as two parts. To save tooling costs and time, the idea was put forward to produce the fixture tool by additive manufacturing in a single part with the goal of removing as much weight as possible without compromising the part's mechanical strength.

Bosch engineers decided to employ the Simufact Additive product from MSC Software to model the additive manufacturing (AM) metal build process and subsequent post-processing steps to help eliminate design errors before expensive AM was committed to. Simufact Additive is very powerful at predicting the magnitude and distribution of residual stresses in an additive manufacturing situation taking into account variables such as process type, build rate, build sequence, amount of constraints, etc. Highly localized heating and cooling during the AM process typically produces non-uniform thermal expansion and contraction in the part, which results in a complicated distribution of residual



stresses in the heat affected zones and unexpected distortion across the entire structure. Moreover, these residual stresses may promote fractures and fatigue in the AM part, and induce unpredictable buckling during the service of the printed part. Hence, it is vital to predict the behavior of the AM process and to optimize the design/manufacturing parameters before committing to 3D printing. Simufact Additive is able to predict the influence of several components in the AM build space, determine the best build orientation by performing sensitivity studies, reduce the number of physical iterations and yield high design productivity benefits because it leads to a reduction of total time for AM.

A first Simufact Additive prediction (Case 1) for the part being considered for replacement without precompensation of the part (Figure 2) identified severe manufacturing issues due to high local temperatures in the 3D printed part, final part distortions with tolerances exceeding 3.5 mm, and final part effective stresses exceeding 1,260 MPa if this part was additively manufactured.

Using Topology Optimization methods, Bosch engineers iterated to a Simufact Additive prediction (Case 2) where they were able to integrate the formerly two-part fixture into just one part and to result in a reduction of the component's overall weight by 70% (figure 3). In Case 2, Simufact Additive delivered a shape deviation in distortion reduction of 70% to 1.067 mm after 1 pre-compensation run by ensuring a more uniform metal particle melting temperature of 1399°C throughout the simulation process in order to avoid thermal-stress issues. Effective metal maximum

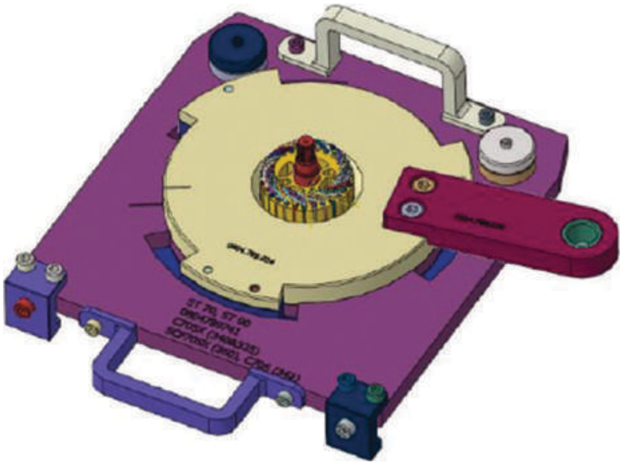


Figure 1: Traditionally manufactured cast metal IRIS tool (cream and maroon parts) inside its assembly

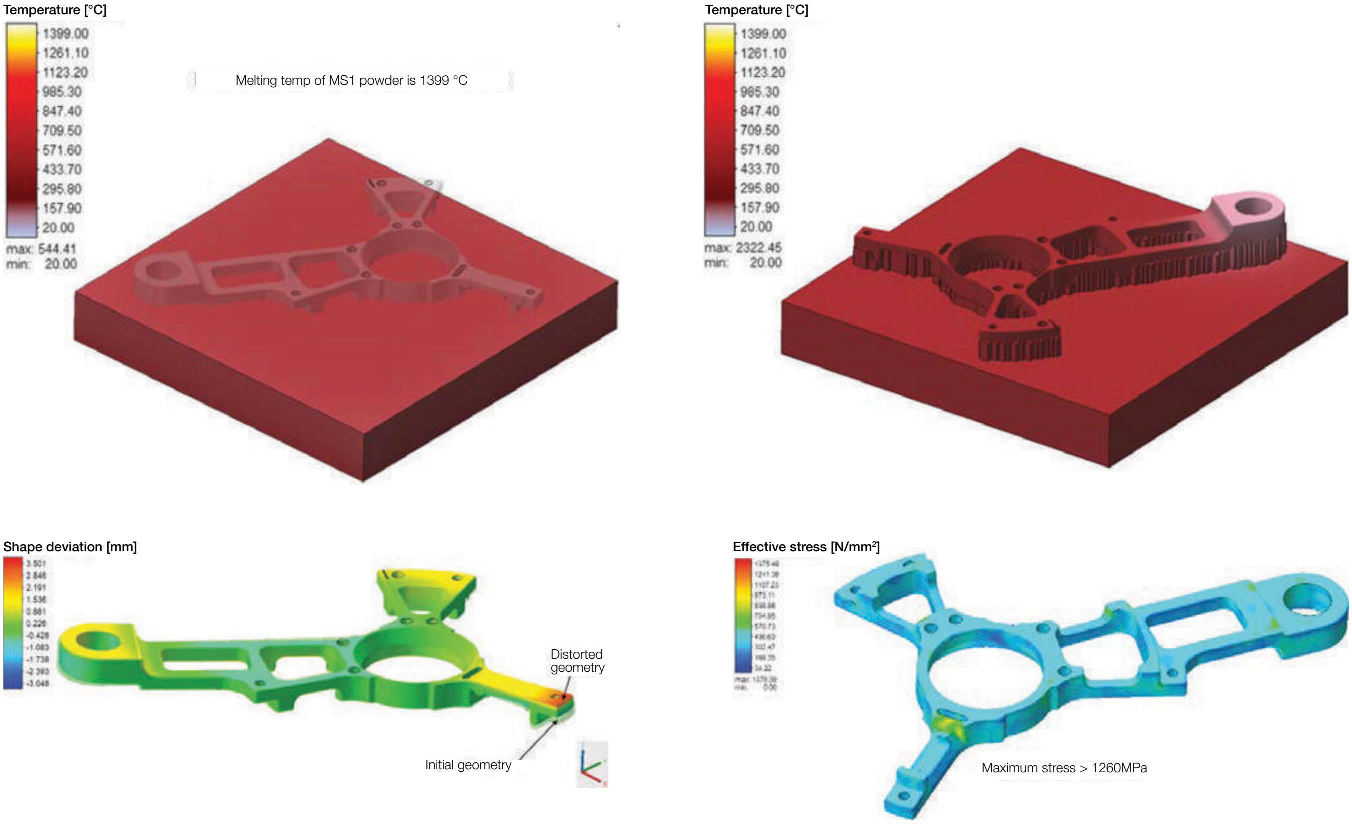


Figure 2: Additively Manufactured IRIS Fixture Tool prediction that has not been topology optimized showing non-uniform melting temperatures of 1399°C, part distortions of up to 3.5 mm and final part effective stresses exceeding 1,260 MPa (Case 1)

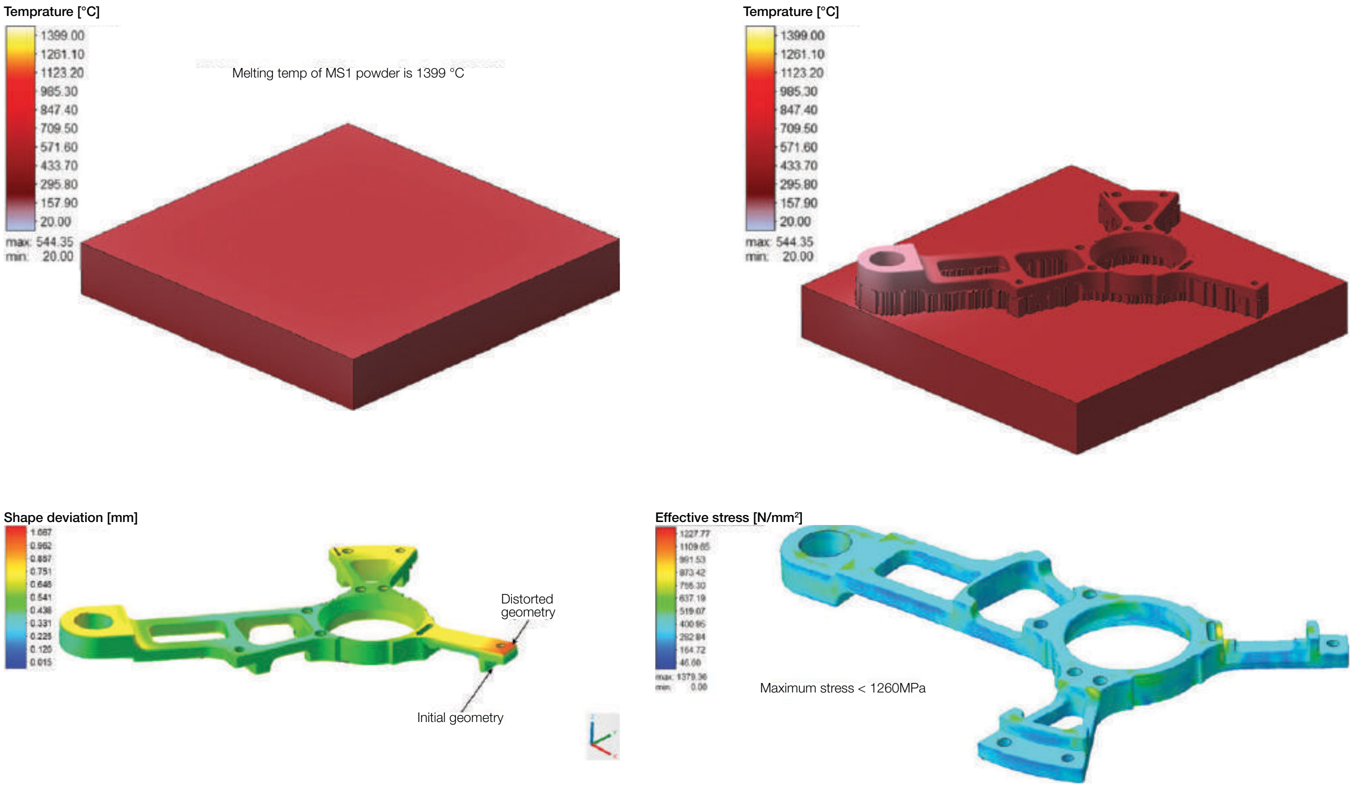


Figure 3: Additively Manufactured IRIS Fixture Tool prediction that was been topology optimized showing constant melting temperatures of 1399°C, part distortions of up to 1.07 mm and final part effective stresses less than 1,260 MPa (Case 2)

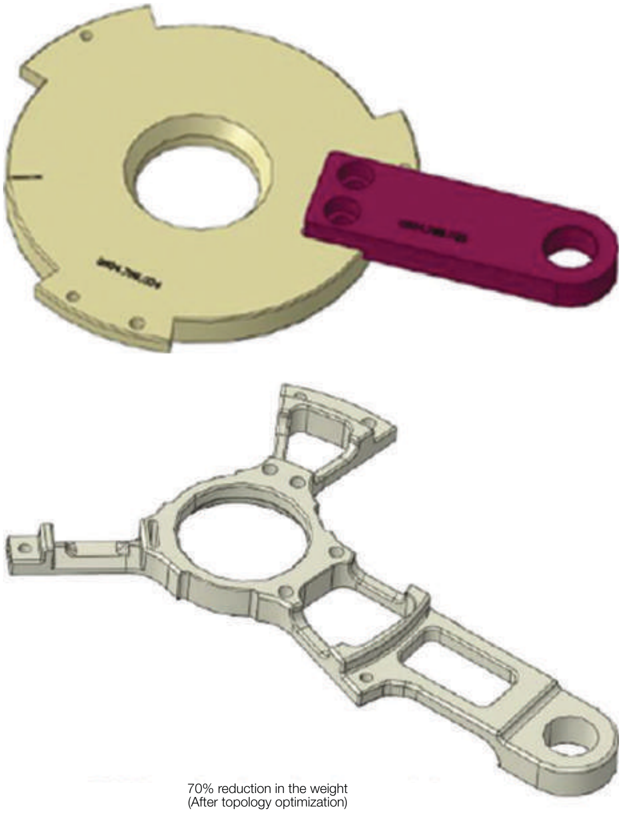


Figure 4: IRIS Fixture Tool from a traditional cast part (top) and fully topology optimized AM part (bottom)

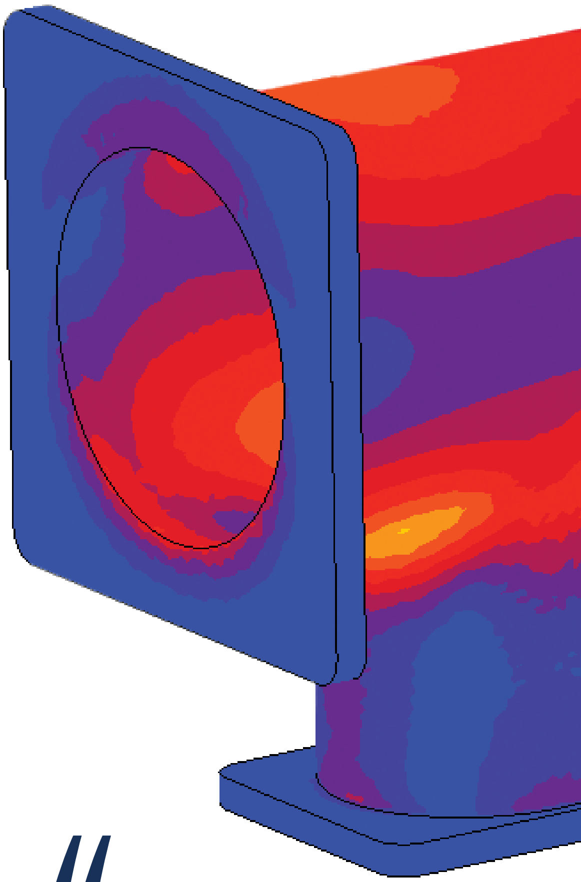
stresses in the AM part were kept below the yield strength limit of 1260 MPa. For the optimization of this AM build process, they used the Simufact Additive pre-compensation method which aimed at a part geometry within acceptable distortion tolerances. In addition, Simufact Additive optimization methods for the build process (e.g. support structure optimization) and post-processing (e.g. cutting strategies, support removal strategies) were also used to improve this manufacturing process.

By applying topology optimization methods to Simufact Additive predictions, Bosch engineers were able in this study to re-design the IRIS tool parts with the objective of developing a lighter single part with adequate stiffness, lower material usage and thus AM power consumption, and ultimately yielding a process cost saving (as well as a mass reduction) – see Figure 3.

Summary

Bosch India used Simufact Additive to replace costly low-volume tool production (casting) by tool-less additive manufacturing for a motor IRIS fixture tool. By re-design and topology optimization, Bosch engineers managed to integrate the functionality of what was once two cast parts into a single AM metallic part with similar mechanical characteristics while at the same time reducing the part's weight by 70%. AM process simulation with Simufact Additive therefore helped Bosch engineers to overcome additive manufacturing issues (distortion, residual stresses) and to establish a new manufacturing process "first time right".

Sinterline® Prototyping by Solvay



Ultimate strength prediction of a plenum under pressure produced by selective laser sintering

Sylvain Mathieu
Software Dev. Engineer, e-Xstream

Dominique Giannotta
Project Director, Solvay EP

Solvay, a global leader in advanced polyamide solutions, is the principal material sponsor for the Polimotor project. It aims to open the way for a technological breakthrough in the automotive sector by replacing up to 10 metal parts by plastic materials in the engine Polimotor 2 engine.

Among the manufactured plastic parts, the Polimotor 2 engine will feature a 3D printed plenum chamber produced through selective laser sintering (SLS) by using a Sinterline® Technyl® polyamide 6 (PA6) powder grade reinforced with a 40 percent loading of glass beads.

The target is to demonstrate that the plenum plastic part (manufactured with this technology and material) can perform with the same reliability as its injection-molded counterpart.

Challenge

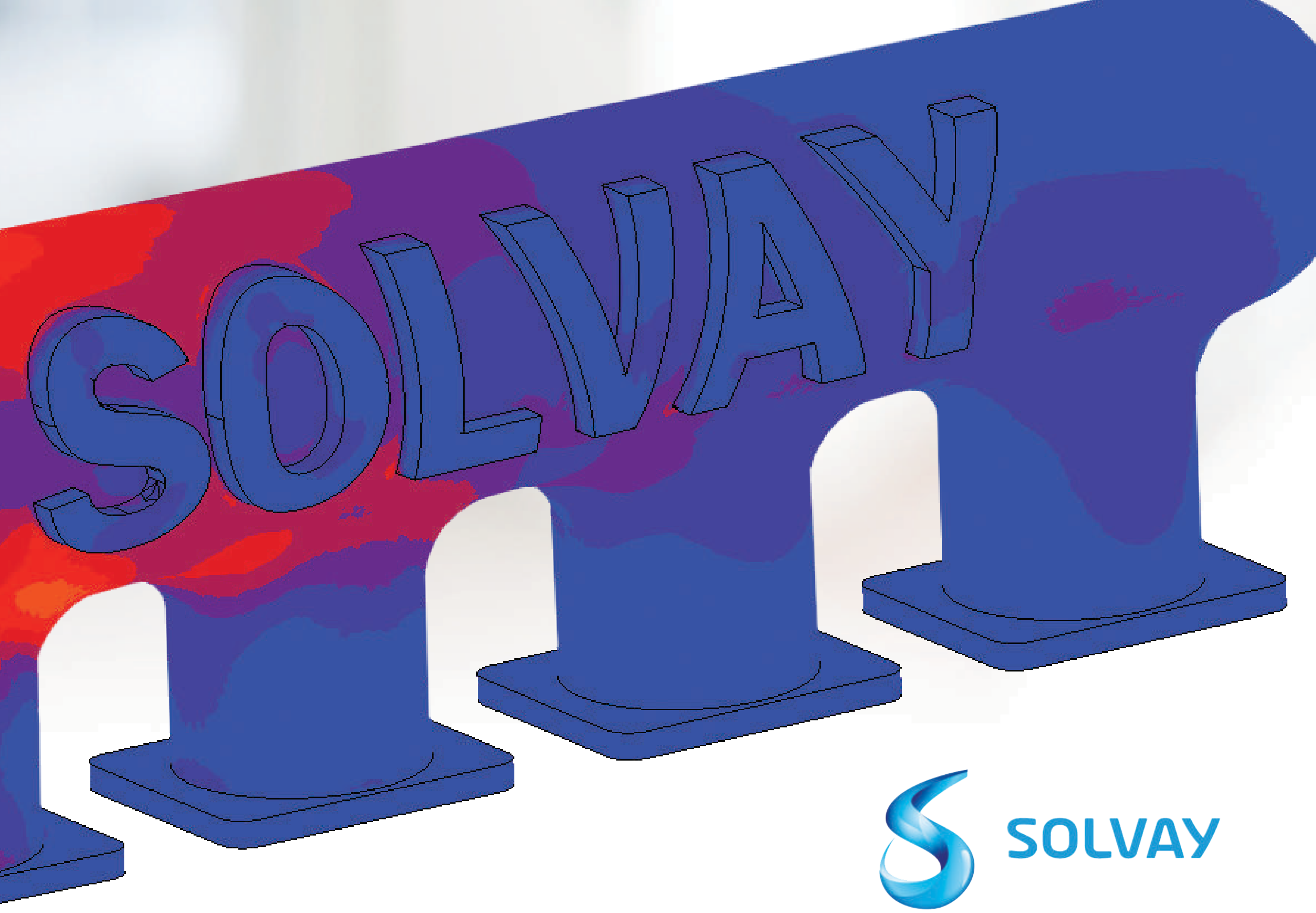
Due to the fact that parts are built of layer superposition without the need of support materials, laser sintering can quickly produce components that integrate complex internal features and functions. However, the direction in which the part is built greatly affects the printed part strength. Although the printed material behavior is not affected by the building direction, its ultimate strength is reduced in the stacking direction. This issue is inherent to additive manufacturing processes, as successively deposited layers are not perfectly bound together.

The impact of the produced part orientation in the build chamber of SLS devices, and AM processes in general, must not be neglected and this new parameter influence must be evaluated.

In the image below, the plenum has been printed in a peculiar direction due to the limited space available in a building chamber: this will be taken into account while predicting the ultimate pressure load it can sustain.

> "The designed plenum should sustain the working load conditions and may be redesigned by topology optimization in order to lighten the structure while taking advantage of the 3D printing technology.

Polimotor 2 Plenum printed with Sinterline®



Solution

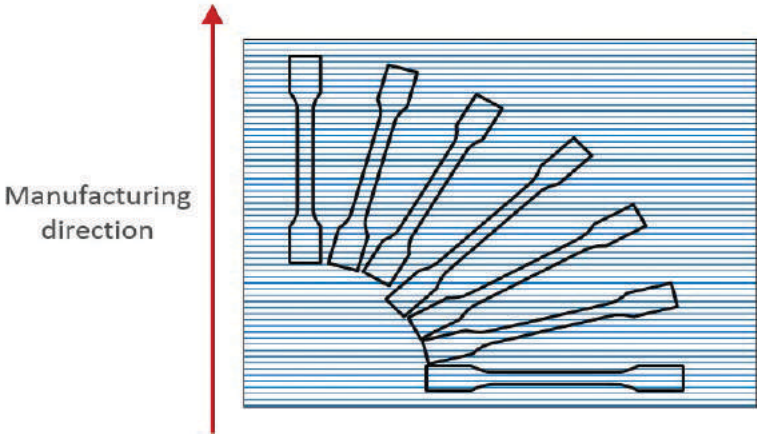
- Create and calibrate the material behavior using the appropriate constitutive law. The glass beads are modelled using an elastic law while the pressure-dependent Drucker-Prager model is well suited to catch the matrix behavior.
- Fully characterize the failure surface using the appropriate failure criterion. The failure surface shape, specific to 3D printed material, can be well fitted with a generalized version of the Tsai-Wu transversely isotropic failure criterion.
- Perform a coupled MSC/Digimat AM calculation to establish the ultimate pressure load the part is able to withstand.

Results/Benefits

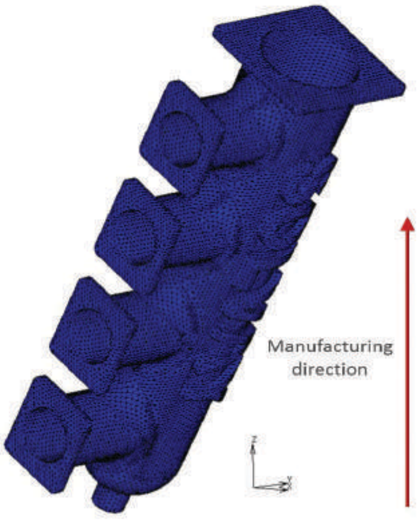
- Precise description of the material behavior and failure surface
- Study sensitivity of the part strength to its orientation in the build chamber
- Avoid producing parts that do not meet the strength requirements by taking into account the specificity of 3D printing processes

Results Validation

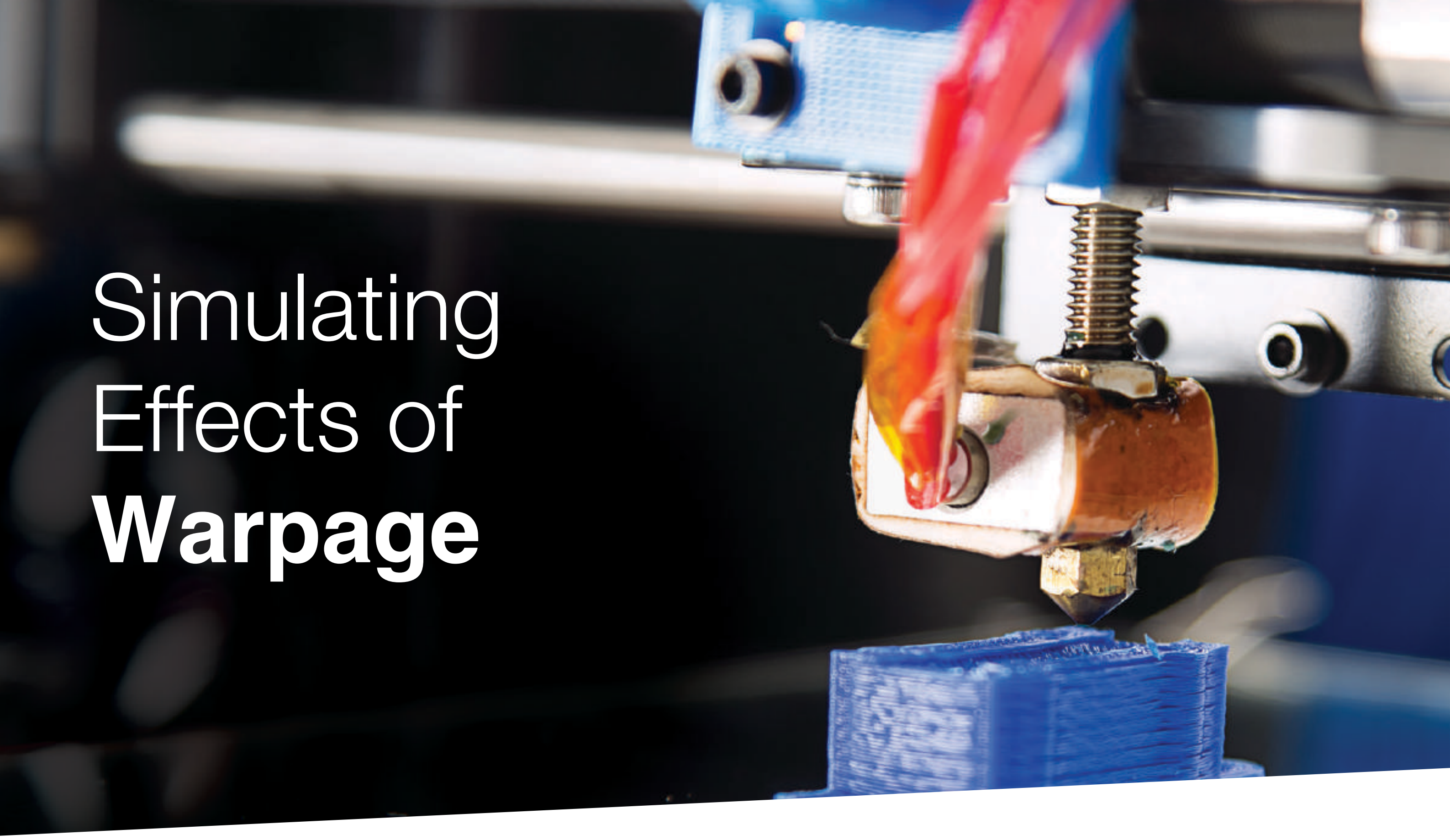
The maximum pressure load sustainable has been numerically predicted to 9.1 bars, whereas 3 bars has been experimentally applied without failure in the same environmental conditions. The designed plenum should sustain the working load conditions and may be redesigned by topology optimization in order to lighten the structure while taking advantage of the 3D printing technology. ◆



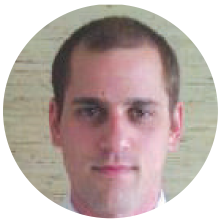
Manufacturing direction vs. various tensile samples



Manufacturing direction of the plenum



Simulating Effects of **Warpage**



Bender Kutub
Senior Additive Manufacturing
Research Engineer, Stratasys

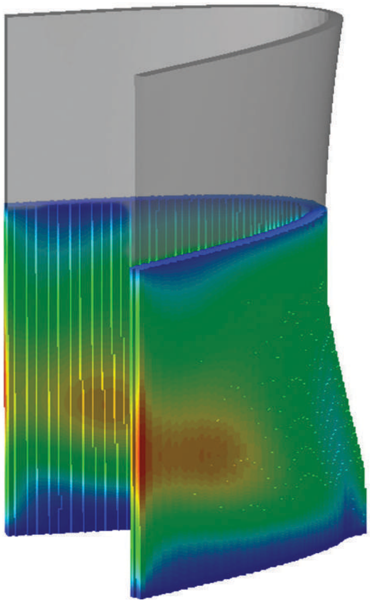
Olivier Lietaer
Business Development Engineer,
e-Xstream

For more than 25 years, Stratasys has been a defining force and dominant player in additive manufacturing – notably inventing the Fused Deposition Modeling (FDM) Technology. The company's solutions provide customers with unmatched design freedom and manufacturing flexibility – reducing time-to-market and lowering development and manufacturing costs. FDM® (fused deposition modeling) is becoming the technology of choice for rapid production of high-temperature (> 177 ° C), low-volume, composite lay-up and repair tools, as well as for moderate-temperature (<163 °C) production sacrificial tooling. Relative to traditional tooling materials and methods, FDM offers significant advantages in terms of lead time, tool cost and simplification of tool design, fabrication and use, while enabling increased functionality and geometric complexity.

Challenge

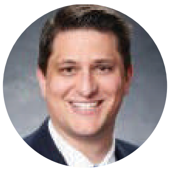
To unlock the full value additive manufacturing has to offer, simulation tools are needed to predict and mitigate part warpage as well as realize the impact of design decisions on the manufacturing process before the part is printed. Several challenges face the development of this process simulation:

- The complex thermomechanical loadings that occur during the layer-by-layer deposition of the material and the successive cooling of the part
- Additive manufacturing is a true multi-scale challenge: the position of bead deposition creates specific microstructures based on the printing toolpath pattern, which drives the macroscopic mechanical behavior – typically inducing anisotropy.
- The thermal history of the material deposition generates differential shrinkage between adjacent beads or layers that affects the end tolerances of the part.

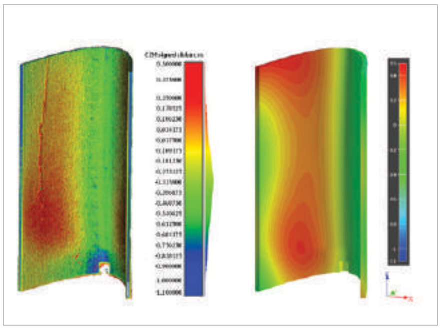


Virtual printing of the composite tooling in Digimat-AM

> For engineers to unlock the design freedom that additive manufacturing offers, they need tools for accurate and effective analysis. Working with e-Xstream, we're enabling 3D printing to become a high performance production technology.



Scott Sevcik,
Head of Aerospace, Defense & Automotive, Stratasys



Comparison between measured warpage on a physically printed part (RMS signed distance, left) and Digimat-AM warpage prediction (X displacements, right)

Solution

Stratasys is working with e-Xstream to create FDM process simulation via a multiscale approach as a function of process setup and material choice:

- Solve a fully coupled thermomechanical problem of the deposition process to identify the warpage behavior of the printed material accounting for thermal exchanges inside the printer build (conduction, convection and radiation)
- Load the toolpath issued from the manufacturing processing software and extract information about the deposition sequence
- Model via micromechanics the heterogeneous material microstructure as a function of the toolpath (e.g., porosity volume fraction and orientation)
- Predict the resulting warpage induced by the printing process
- Iterate the design and optimize the manufacturing process parameters to minimize the warpage.

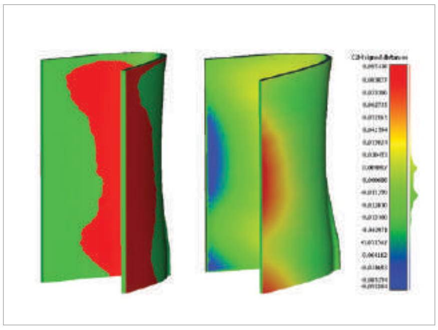
Results/Benefits

Working with Digimat AM, Stratasys Engineers were able to:

Print it right the first time
Iterate designs and parameters through simulation rather than wasting time and materials with iterating through printing

Save time & material
Anticipate printing issue with simulation (e.g., evaluate the impact of the printing direction and location on results)

Minimize warpage in only two steps!
Thanks to a predeformed geometry



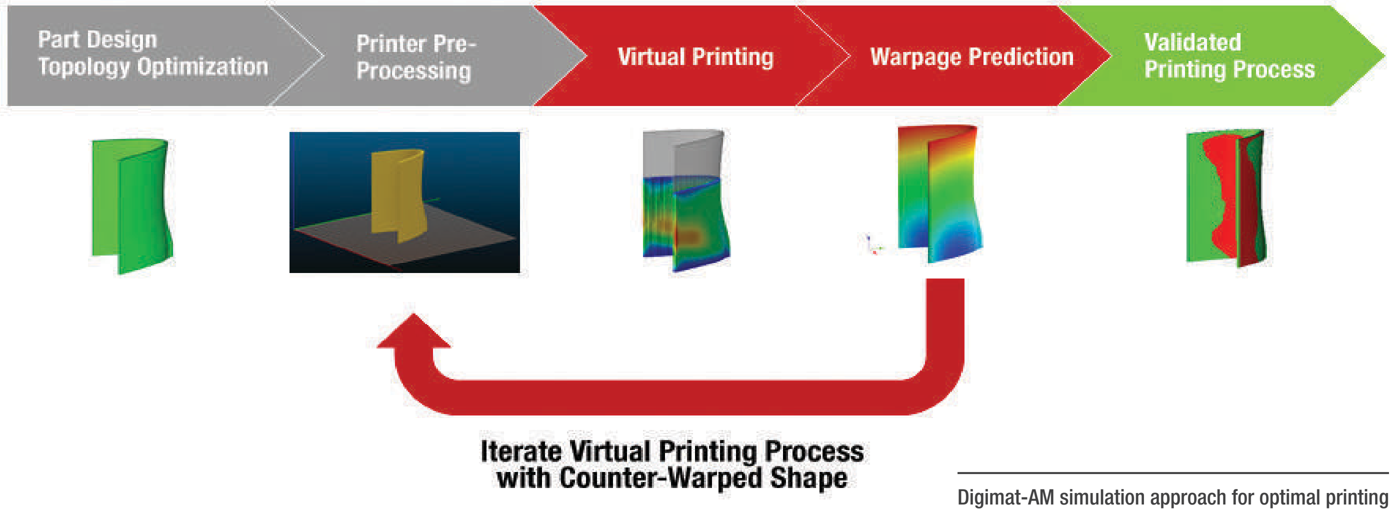
Warpage prediction after geometry compensation in Digimat-AM. Left: Superposition of the as-printed (red) and as-design

Optimize the manufacturing process
Quickly explore at virtually zero marginal cost the sensitivity of process parameters on the process quality and part fidelity

Work with an efficient and user-friendly GUI
Designed to follow the printing workflow and accessible for non FEA experts

Results/Correlation to Test Data

The warpage prediction has been compared to 3D-scan measurement of a physically printed composite tool. Given the different modeling assumptions, the comparison shows a good general correlation with similar deformation pattern and amplitude. The warpage compensation procedure decreases significantly the maximum deviation between the reference geometry and the as-printed part (0.5 mm to less than 0.1 mm). ◆



Digimat-AM simulation approach for optimal printing

Image Source: Materialise

Dr. Hendrik Schafstall

Vice President, Virtual Manufacturing & Costing, MSC Software

Dr. Hendrik Schaftall is Vice President, Virtual Manufacturing & Costing, MSC Software. Together with his partner Michael Wohlmuth, Hendrik Schafstall founded FEMUTEC engineering in 1995 – today´s Simufact Engineering GmbH.

Prior to the company founding, he was employed as a research associate at the Helmut-Schmidt-University of Hamburg, obtaining his doctorate researching friction models in cold massive forming. He was a mechanical engineering student at the Leibniz University of Hannover and received a diploma as a graduate engineer.

Dr. Roger Assaker

Chief Customer Engagement Officer, MSC Software

Dr. Roger Assaker is the Chief Customer Engagement Officer, MSC Software. He is also the Co-Founder & CEO of e-Xstream engineering, a high-tech company 100% focused on advanced material modelling. Roger holds a PhD and MS in Aerospace Engineering with a strong focus on nonlinear computational mechanics where he totals more than 20 years of experience. Roger complemented his engineering education with an MBA in International Business and several advanced technology, business and entrepreneurship courses from prestigious universities such as MIT. In parallel to growing e-Xstream to be the world leader in advanced composite modelling, Roger is the Vice Chairman of NAFEMS Composite Working Group and active member of other technical material associations such as SPE and SAMPE.

Volker Mensing

Global Director of Business Solutions Marketing, MSC Software

Volker Mensing is the Global Director of Business Solutions Marketing at MSC Software. He is responsible for driving cross-product global marketing campaigns for MSC & Hexagon, such as Additive Manufacturing, Autonomous Driving, etc. With a background in journalism and public relations specialising in manufacturing technology and Information Technology, he has built a 20-year marketing career in the software and IT sector.

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