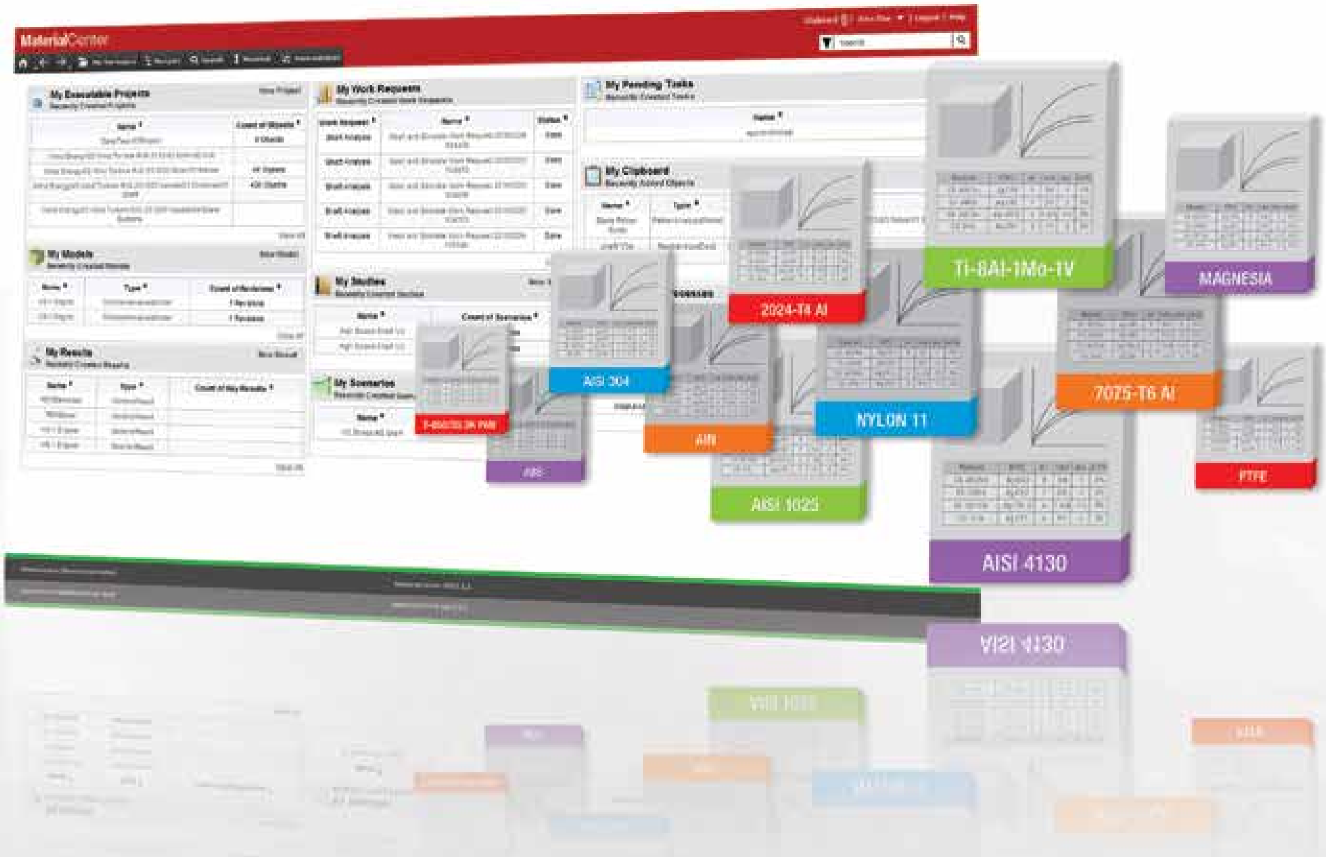
Additive Manufacturing
Analytical Framework



MSC Software

MSC Software Corporation, the worldwide leader in Engineering Lifecycle Management, would like to share some of our experiences and expertise in the area of end to end simulation process of 3D additive manufactured (AM) parts and assemblies.

MSC Software has collaborated with a number of industrial partners and developed a framework and suite of tools to address the design challenges and process optimization in AM. Its objective is to provide a clear definition of the important elements of simulation and synthesis in product creation, preferred sequence/flow, clear identification of data models/results and seamless integration of tools to control the process. The usage of all stored data also guides emerging R&D and future method development.

The paper is primarily intended for two type of readers:

ENGINEERING AND CAE MANAGERS who are involved in managing various phases of design and analytical activities through the application of advanced CAE tools and technologies.

CAE / DESIGN / MANUFACTURING PROCESS ENGINEERS who are involved in the day to day product lifecycle activities (design/development/CAE/prototype build and test) and interested to improve the end quality of parts/assemblies via application of advanced simulation techniques.

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EXECUTIVE SUMMARY

Traditional manufacturing methods have historically focused on the conversion of raw materials in various forms into a finished product through subtractive processes. These techniques use well-established design/fabrication methods, tools and equipment (e.g. foundry, lathe, CNC, etc.), production activities and steps.

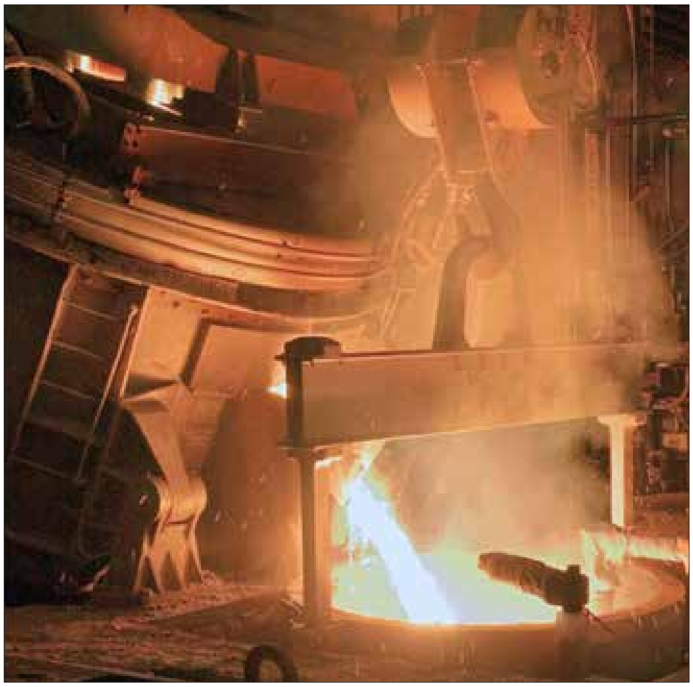


Figure 1: Traditional Manufacturing

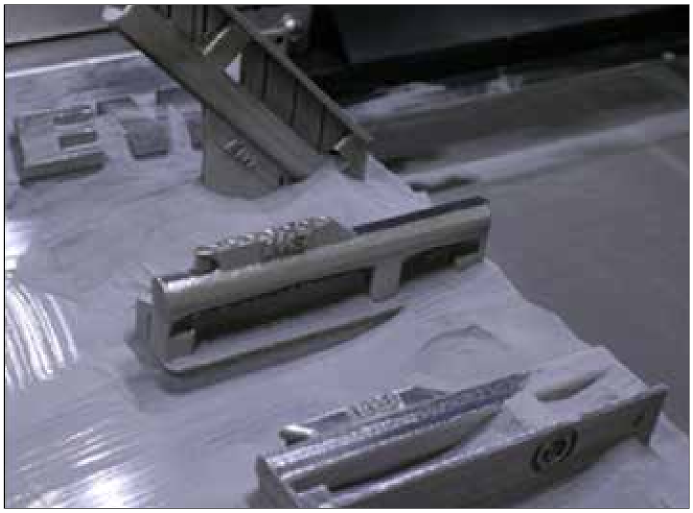
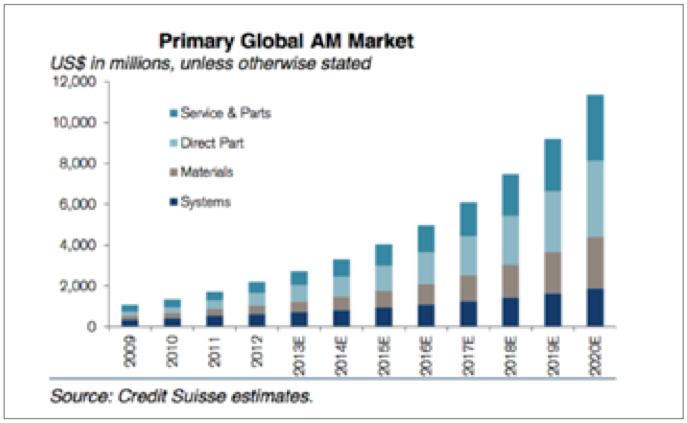


Figure 2: Additive Manufacturing

Additive Manufacturing (AM) is a monumental shift from traditional manufacturing methods. Widely known as 3D printing, AM is a modern manufacturing technique that produces layer by layer of a three dimensional (3D) object from a Computer Aided Design (CAD) model. Fig. 1 and Fig. 2 present both types of manufacturing processes.



Source: Credit Suisse estimates.

Figure 3(a): Primary Global Additive Manufacturing Market

The global AM market is comprised of 3D printers, materials and service providers. Applications are targeted towards rapid prototyping and rapid manufacturing. The entire market excluding materials is expected to reach $11.4B by the year 2020 at an annual growth rate of 21.0% from 2016 through 2020. Fig. 3 (a) and 3 (b) illustrate the global AM market and major industries.

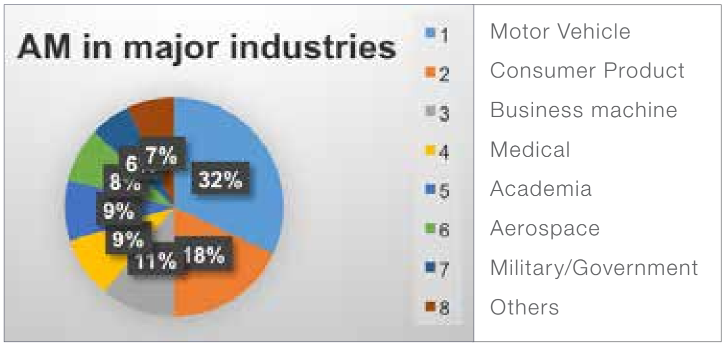


Figure 3(b): Industries that use AM Technology

Standards set by ASTM International F42 committee play an important role in the adoption of AM technologies. The standards established by ASTM are geared towards materials, processes, technology, design, data formats and test methods. These have proved to be inadequate in the production of quality AM parts.

AM technology poses a number of challenges from design to production phases. Parts manufacturers and leading AM researchers have identified the following as the some of the key indicators behind poor product design and after market performance of AM products:

1. Lack of analytical (simulation) processes to guide the “what if” scenarios;
2. Inaccurate study of manufacturing variability that affects material properties;
3. Wide variation in machine/process control parameters that affect the quality of AM parts.

MSC Software has collaborated with a number of industrial partners and developed a framework and suite of tools to address the design challenges and process optimization. MSC’s objective is to enable product designers and engineers to fully benefit from the potential that AM will offer in the future.

ADDITIVE MANUFACTURING PROCESS

Parts manufacturers experimented and commercialized Rapid Prototyping (RP) techniques in 1980s and 1990s to a high level of perfection. Those techniques were used to fabricate a scale model of a physical part or assembly using 3D Computer Aided Design. This eventually gave rise to Rapid Tooling (RT) - the production of tooling directly from an RP process.

Late 20th century advances in manufacturing created the demand for a new class of processes called "Additive Manufacturing." Kenneth Sabo, Concurrent Technologies Corporation, presented the benefits and challenges of AM processes at SHIPTECH 2016 Conference on March 3rd, 2016 in Charleston, South Carolina. Table 1 presents the summary of AM process benefits and challenges.

Benefits	**Challenges**
1. Low Quantity Requirement	1. Qualify machine/process materials
2. No tooling, No Setup	2. Consistency across all machine/builds
3. Geometrically Complex Design	3. Cost effective logistics solution
4. Custom Fitted Parts	4. Innovate process control
5. Better Strength than Wrought / Cast	5. Lower ductility than Wrought/cast
6. Excellent for Prototypes	6. Must control in process distortion

Table 1: AM Process Benefits/Challenges

Common applications of Additive Manufacturing may be found in the following products. Fig. 4 exhibits a sample part produced via AM.

- Medical implants
- Mold/die manufacturing
- Weight reduction through topology optimization
- Brackets/tools/fixtures
- Patterns
- Custom fit assemblies
- Small production runs

Figure 4: Fuel Nozzle of GE Leap Engine

COMPARISON OF ADDITIVE AND SUBTRACTIVE MANUFACTURING

Dr. Swee Mak, Director, Future Manufacturing Flagship, CSIRO, presented Fig. 4 on June 4th, 2014 at the Hunter Research Foundation meeting. He concluded that "in comparison with the traditional subtractive manufacturing method in which a block of finished material is machined down to make a product, additive manufacturing methods are fast, use less energy, and generate less waste material."

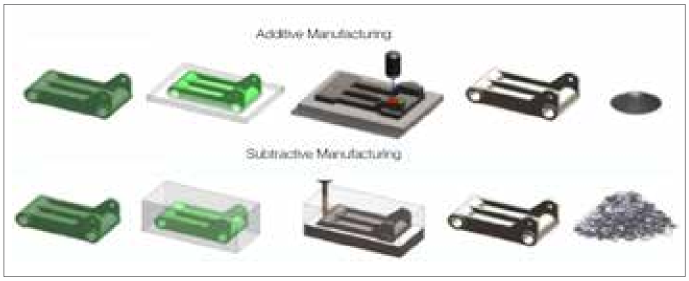


Figure 4: Comparison of Additive and Subtractive Manufacturing

In Additive Manufacturing, new levels of geometric complexities can be created, delivering the opportunity to achieve functional designs that are impossible or very costly using conventional manufacturing methods. Applied in the production of metal or plastic parts, AM offers the ability to create novel, lightweight designs potentially with fewer parts.

CONSIDERATION/MAJOR CHALLENGES IN AM

Additive Manufacturing has made significant strides over the past 25 years. However, technical challenges related to materials, equipment, machine/process variation and application continue to be major consideration factors in producing quality parts.

Mr. Kenneth Sabo, Director, Concurrent Technologies Corporation (CTC), summarized CTC research and presented in the ShipTech 2016 Conference. Fig. 5 illustrates the challenges in AM design to production stages.

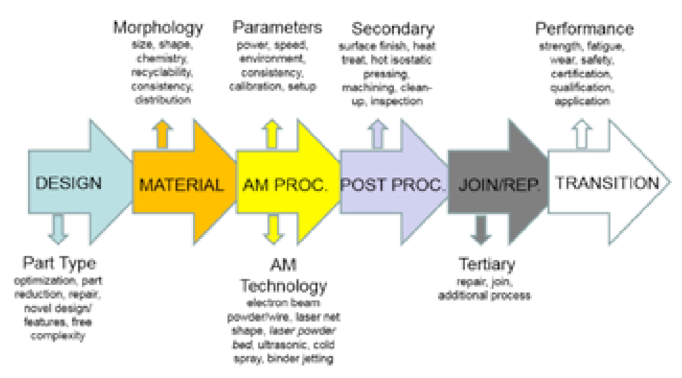


Figure 5: Challenges in AM Design to Production Stages

Design to production includes challenges in material characterization, machine qualification and process variation.

- Materials characterization: Currently, AM parts producers do not have a central repository of materials property data. The industry cannot fully transition to offer complete manufacturing solutions unless/until material properties data for available materials are recorded/stored. AM material capabilities for part selection (e.g. material properties as a function of build orientation, tensile strength, yield strength, environmental considerations, fracture toughness) need to researched/recorded and made available for all manufacturers. If the material properties of AM parts are not available, engineers/designers will not consider AM as a method of manufacturing.

- Process variation: Existing methods are inadequate to address the process repeatability and uniformity. Sometimes as high as 85% scrap rate is recorded for powders. Innovative methods need to be developed to improve early defect detection. Better process controls will lead to reduced machine downtime – currently a major issue for many machines and processes.
- Machine qualification: Machine to machine as well as part to part repeatability is noted to be high. Part placement consideration (part placement, location and build angles based on machine capabilities) need to be fine-tuned. Material strength relative to build axis/orientation needs to be estimated via statistical analysis. A series of “what if “studies is required to understand the high level of variance.

Most of the mid/large sized US manufacturers deal with the above challenges on a day to day basis. Some of the concerns expressed by them are as follows:

1. Is Additive Manufacturing producing lightweight, cost-effective quality products?
2. Does Additive Manufacturing make sense?
3. What should I recommend to logistics/suppliers?
4. What is the sensitivity matrix of key variables?
5. Why is the surface finish too rough or too fine?
6. Why is powder scrap rate so high?

WORKFLOW FROM DESIGN TO PRODUCTION IN ADDITIVE MANUFACTURING

Additive Manufacturing is the process of producing a 3D object from Computer Aided Design (CAD). In an additive process, an object is created by laying down successive layers of material until the entire object is created. Steps 1 through 8 present the workflow as an object moves from design to production. Fig. 6 exhibits the typical AM workflow.

Step 1: Computer Aided Design (CAD)

Additive Manufacturing workflow begins with CAD. Designers sketch, position, assign material, color and glossy/matte finish of a given AM part. The CAD model is examined for errors around holes, faces normal, and self-intersections and if required, reconstructed with higher accuracy.

Step 2: Generation of Stereo Lithography (STL) File

The design, model translation and position of the 3D object in the tray is saved and stored as one STL file.

Step 3: Input into Catalyst Software

Once completed, the STL format file is processed by a Catalyst software that converts the content into a series of thin layers (3D slices) and produces a G-code file containing build information tailored to a specific type of 3D printer.

Step 4: Print in Dimensional Printer

The G-code file is loaded into the 3D printer. The 3D client-specific software instructs the printer to initiate 3D printing process. It reads in the data, lays down or adds successive layers of liquid, powder, sheet metal and other in a layer upon layer fashion to fabricate a 3D object. Printer resolution describes the layer thickness and X-Y resolution in dots per inch (dpi) or micrometers (um). Typical layer thickness and X-Y resolution is around 250 DPI, although some machines can print as thin as 1600 DPI.

Step 5 through 8: Take Sample Out, Measure & Test

Production of a given 3D part may take a few hours depending on the type of machine and complexity of geometry. After the part is produced, it is measured, tensile tested and checked for surface roughness. All data is recorded in the schema and a sensitivity study and statistical analysis is run, which guides the design/build process for the next batch.

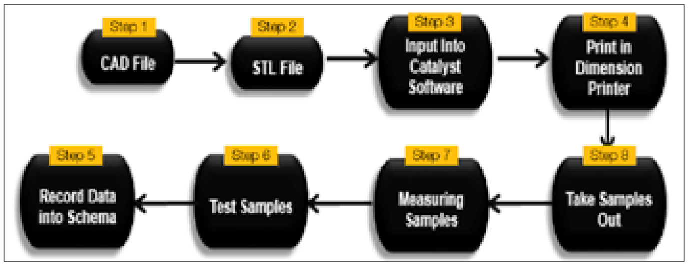


Figure 6: Workflow of Standard Additive Manufacturing

There are a number of commercial 3D printer manufacturers. A typical 3D printer is shown in Fig. 7. A typical build tray and print head is presented in Fig. 8.

Figure 7: MarkerBot Replicator 2 AM Machine

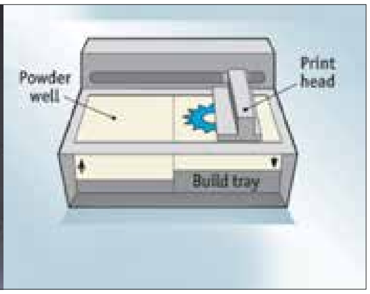


Figure 8: Typical AM Build Tray & Printhead

APPLICATION OF MSC SOFTWARE: AM END TO END SIMULATION FRAMEWORK

MSC Software’s collaboration with the industry over the past decade innovated an end to end analytical framework that involves advanced multi-scale, math-based multiphysics tools. The framework takes into account functional/manufacturing constraints, cost functions and virtual simulation of a 3D AM part that is geared towards high quality producibility.

Dr. Alonso Peralta, Principal Investigator, Honeywell and in charge of DARPA Open Manufacturing Program, reported the following in 2016:

> “...Residual stress and deformation are a function of the build conditions and also of the build patterns. Residual stresses are not equi-biaxial. Analytical (simulation) prediction proves to be important when building slender structures as excessive deformation from layer to layer could lead to unacceptable departure from the intended geometry...”

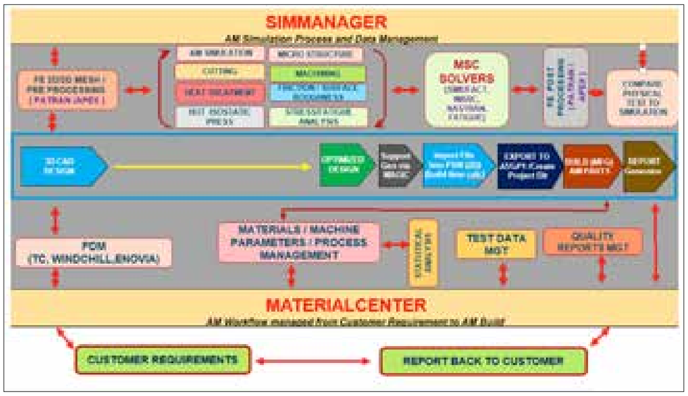


Figure 9: Additive Manufacturing End to End Analytical Framework

MSC Software's AM analytical framework demonstrates the ability to perform the following:

- Management of all customer functional requirements during various lifecycle stages;
- Repository of all simulation processes and data (models and results);
- Central database of all materials property, process and machine/build info;
- Storage of all forms of experimental and quality control information related to AM parts;
- Transfer of the optimized high quality topology back to CAD for geometry processing leading to final build;
- Archive all reports.

Fig. 9 presents the workflow of the end to end AM simulation framework.

Modeling AM processes requires a broad range of simulation capabilities that addresses heat profile, fluid flow, microstructure phase changes, residual stress and distortion modeling, optimized topology, etc. In the simulation of AM processes, engineers/designers are dealing with particles in the order of 10 to 25 microns in diameter, an object that is 40 to 80 mm long and a laser path that could be as long as a kilometer. Though the heat source (thermal profile) remains in contact for a few micro seconds, the total build time may take up to several days.

The complete capabilities of the simulation toolkit (set of solutions) in the framework are broken down into two categories:

1. Before AM printing process

- Search a database of thousands of materials and their associate properties. Choose the material type that is optimal for the design.
- Capture and store material for the next build.
- Simulate the manufacturing method, energy input, speed, material deposition, welding path, heat treatment, microstructure residual stresses, and mechanical properties.
- Automatic optimization of part design including performance and weight to account for manufacturing.
- Optimize machine parameters for repeatable producibility.

2. After AM printing process

- Analyze output to gain a better understanding of which parameters led to the final shape.
- Study the sensitivity matrix and optimize the parameters for better selection criteria in future builds.
- Predict product performance, resilience and life expectancy.

AM FRAMEWORK ANALYTICAL COMPONENTS

MSC Software's framework, comprised of a set of simulation tools, is an enterprise-scalable next generation system. The intuitive web-based interface allows engineering organizations to virtualize material or part/machine/process/additive manufacturing behavior. The framework enables accurate transmission of information to other stakeholders in a given organization.

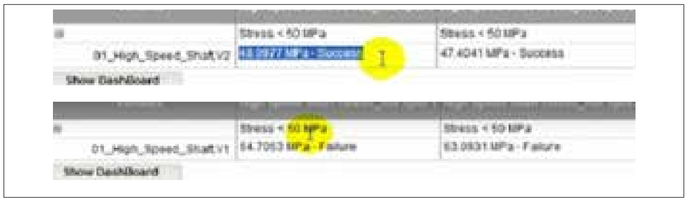
The important elements of the framework/toolset are explained below:

1. Process and Data Management: SimManager and MaterialCenter

A. SimManager

This system is a Simulation Process & Data Management system (SPDM) that integrates customer applications, both commercial tools as well as in-house developed programs. It has a proven track record of managing hundreds of simultaneous users running thousands of simulations and operations every day. The information is securely shared among all the information silos within the enterprise and further extended to the supply chain network throughout all the product lifecycle stages.

Figure 10 (a): Management of Simulation Processes and Data



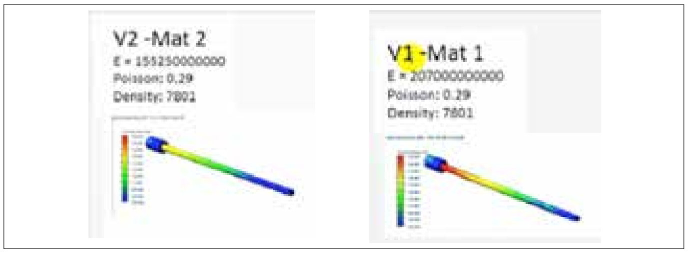
	Stress < 50 MPa	Stress < 50 MPa
01_High_Speed_Shaft.V2	48.0977 MPa - Success	47.4041 MPa - Success

Show Dashboard

	Stress < 50 MPa	Stress < 50 MPa
01_High_Speed_Shaft.V1	54.7053 MPa - Failure	53.0831 MPa - Failure

Show Dashboard

Figure 10(b): Track Targets and Requirements Across All Variants



V2 -Mat 2
E = 155250000000
Poisson: 0.29
Density: 7801

V1 -Mat 1
E = 207000000000
Poisson: 0.29
Density: 7801

Figure 10(c): Variance Between Two Sets of Materials

Fig. 10 (a) presents the management of simulation processes and 3D AM part data in the virtual domain. Fig. 10 (b) tracks the targets and requirements across all variants. Fig 10 (c) shows the variance between the two sets of materials.

B. MaterialCenter

MaterialCenter is a complete solution for the current and future needs of materials data and process management. It manages the complete materials process, from physical test to design allowables (integrated process management, automated traceability, robust workflow and approval processes, etc.). Fig. 11 (a) presents the workflow of MaterialCenter.

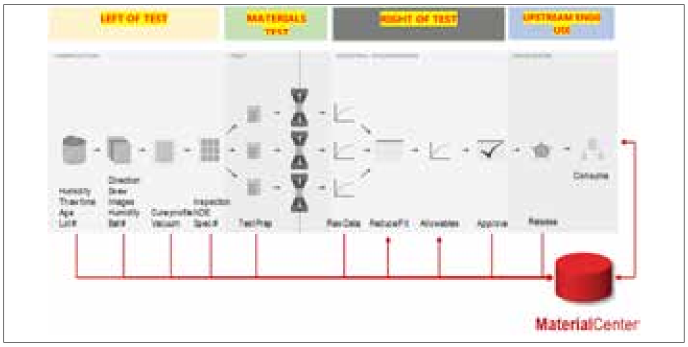


Figure 11 (a): Workflow of MaterialCenter

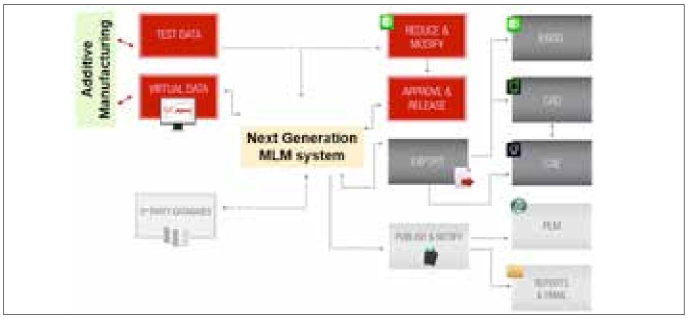


Figure 11 (b): Ecosystem and Integration Touchpoints of MaterialCenter

It is also designed to handle next-generation needs through the enablement of ICME (Integrated Computational Materials Engineering) and virtual allowables. The system has a built-in database of 2500 materials and their associated properties. 10% of the materials in the database are plastics. Fig. 11 (b) displays the ecosystem of MaterialCenter.

The automatic capture of results for comparison, confidence and certification – all with complete traceability in MaterialCenter – brings a new dimension to Additive Manufacturing. It provides a comprehensive workflow tool which enables the capture of information at every step of the manufacturing process from concept to final build. A sample of benefits of this advanced, web-based tool are as follows:

1. Workflow management from customer to engineering/manufacturing;
2. Database of CAD/STL information;
3. Record of all environmental/manufacturing conditions;
4. Repository of all machine/process/build parameters;
5. Statistical analysis of samples, machine/process parameters to perform “what if“ studies;
6. Pedigree information of material/machine/process/prototype build and test actions;
7. Develop predictive part behavior model to quantify part performance (stiffness, strength and life);
8. Generate machine qualification scheme and control library;
9. Reverse engineer material properties via integrated FEA solvers (MSC Digimat);
10. Usage of all stored data to guide emerging R&D and future method development.

The standard AM workflow (from importing a customer’s requirement to managing all tasks in an automated mode and finally reporting back to the customer) can be achieved via MaterialCenter. Industrial clients have reported a return of investment (ROI) in excess of 40% by utilizing MaterialCenter in the management of AM processes. Management of the AM workflow in the MaterialCenter environment is shown in Fig. 12.

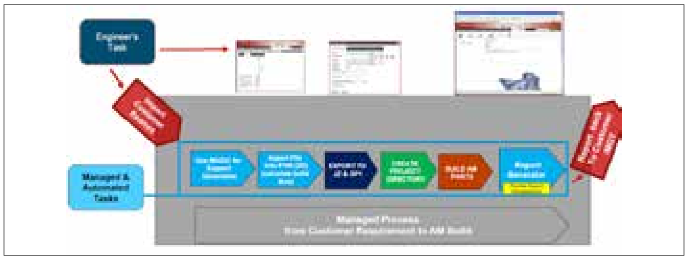


Figure 12: Management of Additive Manufacturing Workflow in MaterialCenter

MaterialCenter’s AM schema is derived from years of research conducted at Penn State University and the United States Army. It includes metallic, non metallic and plastic AM processes. The system can be used as a repository of manufacturing attributes and machine and process qualification parameters.

The built-in template builds up or imports material/machine/process/test data. Excel integration can be utilized in order to map and import custom templates for AM and various test methods. For example:

- AM Electron beam deposition;
- AM Directed laser beam deposition;
- AM Powder bed fusion;
- AM Fused Deposition Modeling;
- Various Tensile Tests (Fracture Toughness K1C);
- Various Hardness Test (Charpy Impact).

A sample of a laser-based powder based fusion template is shown in Fig. 13.

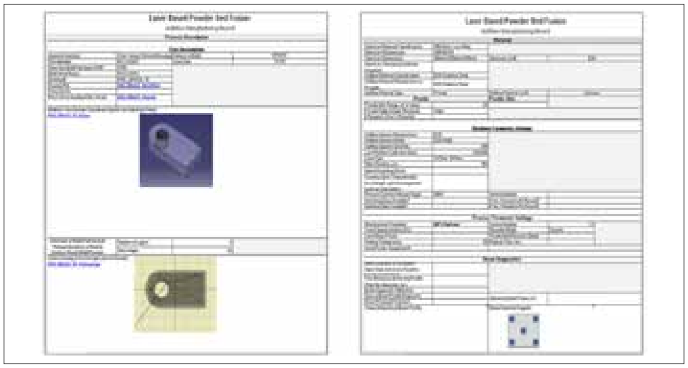


Figure 12: Management of Additive Manufacturing Workflow in MaterialCenter

Built in Analyzers in MaterialCenter perform various forms of statistical analyses and enrich the machine/process qualification. Fig. 14 (a) and 14 (b) trace the analysis and postprocessing of AM data. Some of the analytical capabilities are presented below:

1. Computation of average mass, thickness, peak load, peak stress, strain at break and modulus;
2. Standard deviation of all parameters listed in A;
3. Generates property curves:
    - Peak Load Vs. % Infill;
    - Peak Stress Vs. % Infill;
    - Modulus Vs. % Infill;
    - Peak Stress Vs. Mass;
4. Reduced steps in dynamic data analysis process;
5. Sequential process automation;
6. Integration of custom reduction algorithms via Python, JAVA, MATLAB or 3rd party CAE software.

Figure 14(a): Analysis/Post Processing of Data in MaterialCenter

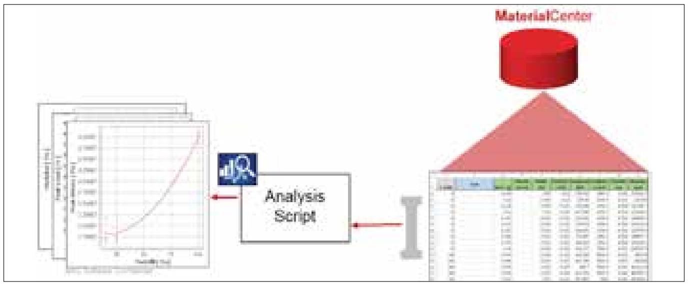


Figure 14(b): Statistical Analysis of AM Material/Machine/Process Data in MaterialCenter

2. Finite Element (FE) Pre & Post Processing: MSC Patran and Apex

MSC's industry-leading pre & post processors Patran and Apex read in the 3D AM part CAD data from corporate CAD Managers (i.e. PDM system), perform FE mesh generation and process the part/assemblies with necessary boundary conditions for subsequent analysis and afternalysis result visualization.

Industrial partners have used the MSC Patran/Nastran toolkit to automatically generate 2D/3D microstructure models based on grain size, shape, orientation, texture, void, grain boundary defects, multiphase and volume fractions. The toolkit predicted micro stress and macro strain distribution in each grain with high accuracy. A typical workflow for micro structure modeling and analysis steps is presented in Fig. 15.

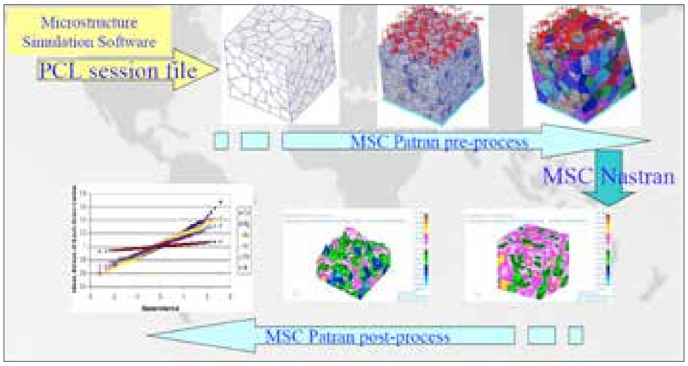


Figure 15: Micro Structure Modeling and Analysis Process

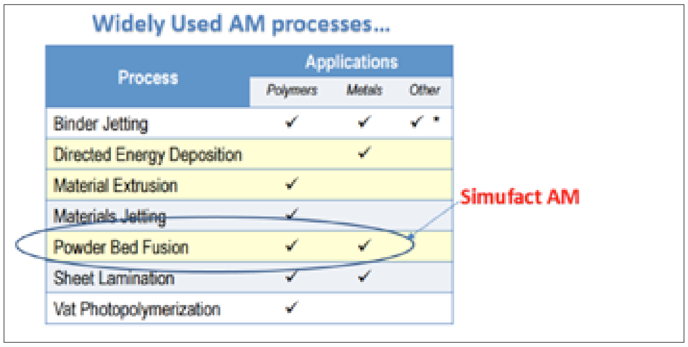
3. MSC Analytical Toolset: Simufact, Digimat, Marc, Nastran and Fatigue

MSC's analysis toolset (Simufact, Marc, Digimat, Nastran and Fatigue) is applied to perform all forms of simulation work throughout various lifecycle stages (from concept to sustainment) on the 3D AM part. A series of simulation and "what if" studies eventually optimizes the shape and size of the design and transfers the information back to the CAD system for subsequent processing. The application of each software is presented below.

A. Simufact:

Simufact is MSC Software's flagship analytical toolset in the manufacturing space. It simulates the virtual manufacturing process during AM build. The multi-scaling approach takes into account the flexible material data structure, based on a phase model. It takes advantage of Marc's solver technology and provides the platform for modeling, solving and result viewing.

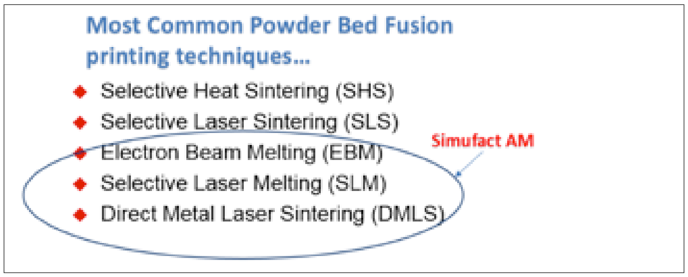
Fig. 16 (a) and (b) detail the widely used AM processes in the industry and the application of Simufact. Fig. 16 (c) presents the schematic of a sample powder bed fusion chamber.



Widely Used AM processes...

Process	Applications		
	Polymers	Metals	Other
Binder Jetting	✓	✓	✓ *
Directed Energy Deposition		✓	
Material Extrusion	✓		
Materials Jetting	✓		
Powder Bed Fusion	✓	✓	
Sheet Lamination	✓	✓	
Vat Photopolymerization	✓		

Figure 16 (a): Widely Used AM Process



Most Common Powder Bed Fusion printing techniques...

- Selective Heat Sintering (SHS)
- Selective Laser Sintering (SLS)
- Electron Beam Melting (EBM)
- Selective Laser Melting (SLM)
- Direct Metal Laser Sintering (DMLS)

Figure 16 (b): Powder Bed Fusion Technique

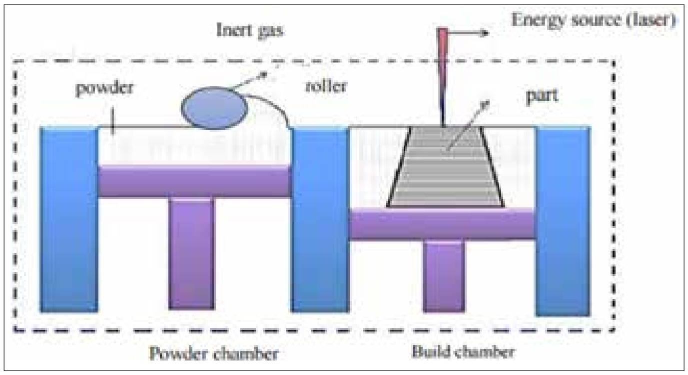
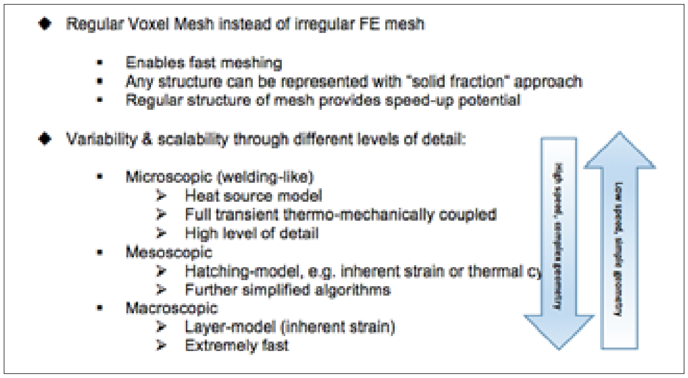


Figure 16 (c): Schematic of a Sample Powder Bed Fusion Chamber

Typically, a given 3D AM part (work piece) is meshed and preprocessed in the Patran or Apex environment. Users assign boundary conditions or influencing parameters to the FE mesh in Simufact. The parameters are as follows:

- Energy input (coupling; equivalent heat source)
- Speed
- Material deposition/melting rate
- Welding path
- Powder characteristics
- Supports
- Heat treatment
- Manufacturing method (indirectly considered via input parameters; powder bed/material deposition via powder/wire).



- Regular Voxel Mesh instead of irregular FE mesh
    - Enables fast meshing
    - Any structure can be represented with "solid fraction" approach
    - Regular structure of mesh provides speed-up potential
- Variability & scalability through different levels of detail:
    - Microscopic (welding-like)
        - Heat source model
        - Full transient thermo-mechanically coupled
        - High level of detail
    - Mesoscopic
        - Hatching-model, e.g. inherent strain or thermal cy
        - Further simplified algorithms
    - Macroscopic
        - Layer-model (inherent strain)
        - Extremely fast

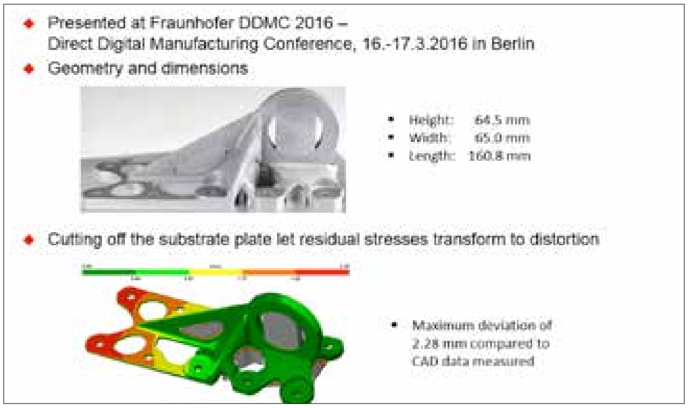
Figure 17: Simufact Solution Approach

Several solution approaches are available in Simufact, based on the desired results. A macroscopic approach with the inherent strain method is used for fast simulations to predict overall distortion and residual stresses. A detailed study at the macroscopic level requires a full transient simulation with moving heat sources and metallurgical models. All the simulation methods are seamlessly integrated in the same environment and can also be changed interchangeably. Typical solution approaches are presented in Fig. 17.

The targeted results of Simufact simulation are as follows:

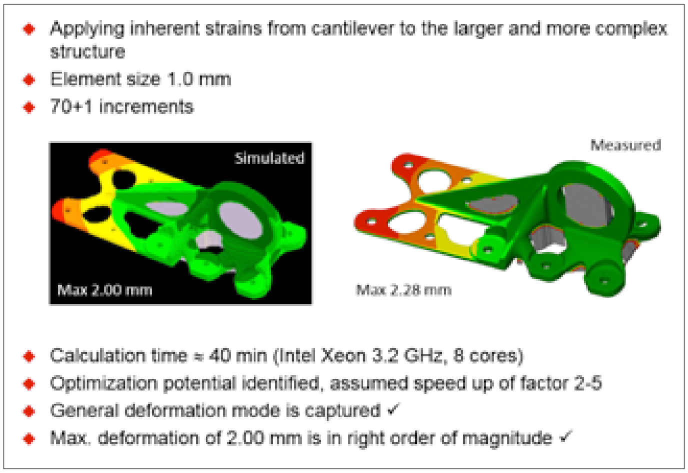
- Distortion and residual stresses during the buildup process;
- Microstructure (phases and grain size);
- Location and strength/stiffness of support;
- Failure modes prediction;
- Insufficient support structure;
- High risk areas for crack propagation;
- Final shape after manufacturing.

Simufact was recently used in the simulation of an aerospace AM part by a leading AM manufacturer. The simulation process and results were presented in March 2016 at the DDMC conference in Berlin, Germany. Fig. 18 (a) and (b) present the highlights.



- Presented at Fraunhofer DDMC 2016 –
  Direct Digital Manufacturing Conference, 16.-17.3.2016 in Berlin
- Geometry and dimensions
    - Height: 64.5 mm
    - Width: 65.0 mm
    - Length: 160.8 mm
- Cutting off the substrate plate let residual stresses transform to distortion
    - Maximum deviation of 2.28 mm compared to CAD data measured

Figure 18(a): Highlights of Simufact Solution of an AM Part



- Applying inherent strains from cantilever to the larger and more complex structure
- Element size 1.0 mm
- 70+1 increments

- Calculation time ≈ 40 min (Intel Xeon 3.2 GHz, 8 cores)
- Optimization potential identified, assumed speed up of factor 2-5
- General deformation mode is captured ✓
- Max. deformation of 2.00 mm is in right order of magnitude ✓

Figure 18(b): Highlights of Simufact Solution of AM Part

Simufact has a built-in database of commonly used industry leading AM materials. Some metals are listed below.

1. Titanium Alloys (TiAl6V4, TiAl6Nb7, and pure Titanium);
2. Cobalt Chrome Group (CoCrMo);
3. Nickel Alloys (Inconel 625, 718, 939) and Hastelloy X;
4. Aluminum Alloys (AlSi10Mg, AlSi12, AlSi7Mg, AlSi9Cu3);
5. Steel Group (1.2709, 17-4PH, 15-5PH, 316L).

B. Digimat:

MSC Software's e-Xstream engineering team has developed simulation tools within the Digimat software suite for two specific additive manufacturing applications:

1. Selective Laser Sintering (SLS);
2. Fused Deposition Modeling (FDM) – as shown in Fig. 19 (a).

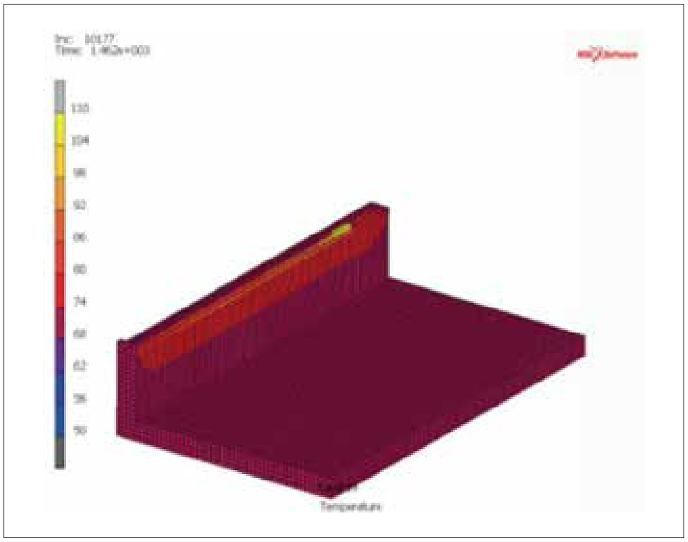


Figure 19(a): Temperature Field While Printing a Corner AM Part with FDM Technology

Digimat's AM simulation tools were successfully applied by Solvay, the global leader in advanced polymer solutions, in the Polimotor 2 project. The project's goal was to open the way for a technological breakthrough in the automotive sector by replacing up to 10 metal parts with plastic materials in the Polimotor 2 engine. The AM part (plenum) was produced through selective laser sintering using a Sinterline Technyl polyamide 6 (PA6) powder grade reinforced with a 40% loading of glass beads.

A multiscale thermo-mechanical material reinforced plastic was modeled in Digimat and subsequently processed for layer-by-layer Additive Manufacturing. The static boundary condition of operational load was applied to the component. Analytical calculations predicted low distortion and maximum sustained pressure of 9.1 bars. In addition, the printing direction was optimized such that the ultimate sustainable load could be increased by 40% without adjusting the geometry. Fig 19 (b) illustrates the part, distortion and critical failure spots.

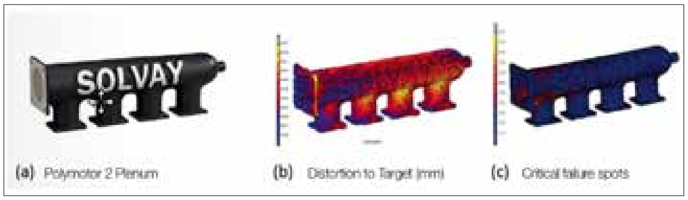


Figure 19(b): Polymotor 2 Printed with Sinterline

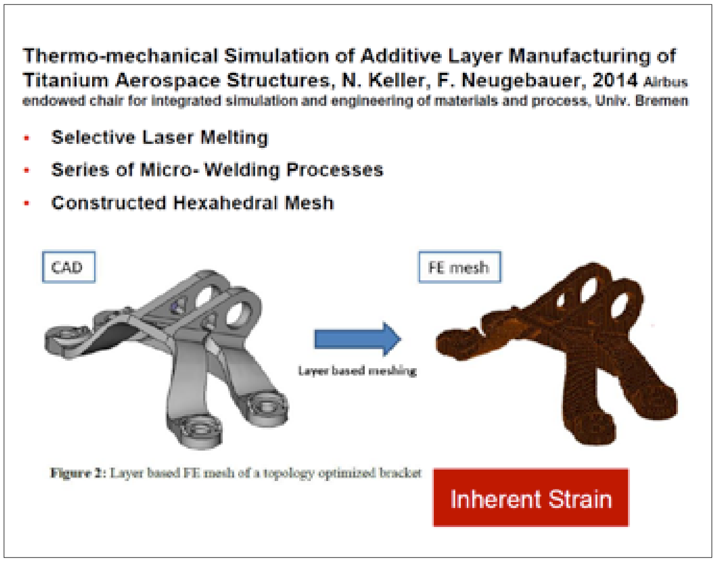
Digimat has a large database of more than 10,000 material (reinforced plastics) properties and micromechanical analysis features. This is built on years of experience, laboratory coordinated tests and publicly available certified/validated data.

C. Marc:

FE analysts apply the Marc Explicit Nonlinear algorithm to study AM processes for a variety of reasons. The reasons are as follows:

- Competency dealing with nonlinear manufacturing processes;
- Scalability (DDM, performance)
- Direct layer and elemental activation
- Direct laser scan path and parameter modeling
- Thermal-dependent thermal and mechanical properties and plasticity modeling
- Coupled transient thermos-mechanical analysis.

Recently, Marc simulated thermo-mechanical behavior of additive layer manufacturing of a Titanium aerospace structure at University of Bremen, Germany. The research team's primary interest was to study heat transfer during the AM process and distribution and magnitude of residual stress. The team reported their assumptions/predictions in Fig. 20 (a), (b) and (c).



Thermo-mechanical Simulation of Additive Layer Manufacturing of Titanium Aerospace Structures, N. Keller, F. Neugebauer, 2014 Airbus endowed chair for integrated simulation and engineering of materials and process, Univ. Bremen

- Selective Laser Melting
- Series of Micro- Welding Processes
- Constructed Hexahedral Mesh

Figure 2: Layer based FE mesh of a topology optimized bracket

Inherent Strain

Figure 20(a): Thermo-Mechanical Simulation in Marc

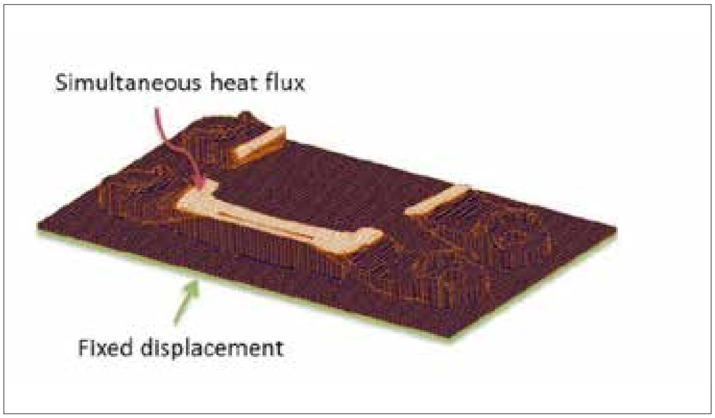


Figure 20(b): Boundary Conditions in the Marc Simulation

Recent applications of Marc have included the simulation of machining and surface roughness of AM parts.

D. MSC Nastran and Fatigue:

Cyclical stress history becomes important when it occurs at a potential crack initiation site of an AM part. This can be any macroscopic level defect or void inherent to material or introduced by additive manufacturing process. Damage is accumulated during

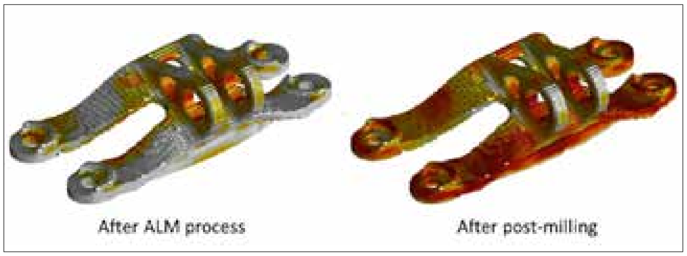


Figure 20(c): Residual Stresses Predicted by Marc Simulation

the service life of the part. If damage grows beyond a critical limit, crack will initiate and minimize service life. Fatigue cracks are often observed far below strength limitations. The lifetime in AM parts under fatigue loading can be divided into the two following areas:

1. Crack initiation
2. Fatigue crack propagation

Following Fig 21 (a) shows a typical cyclic stress variation. Stress amplitude oscillates about a mean stress level. Stress cycle occurs between adjacent peaks. The number of stress cycles, together with the stress amplitude, dictates the fatigue life of the structure.

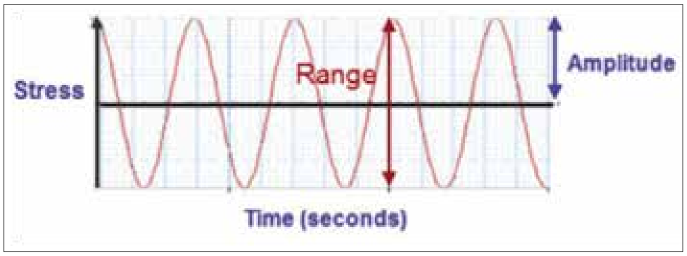


Figure 21(a): Typical Load Stress History

Higher service life can be achieved by applying the crack growth retardation methods. The total lifetime can be extended sometimes by producing notch sections. By varying the size, form, location and orientation of notches, changes in stress distribution will lead to higher fatigue life.

Dr. Hans Albert Richard and his research team at Paderborn University, Germany concluded in 2015 that “significantly higher number of load cycles within the crack initiation period (compared to the number of cycles during crack propagation) can improve service lifetime.”

Dr. Richard and his team’s work on crack initiation/propagation on a sample AM part and its design derivatives is summarized in Fig 21 (b) and (c).

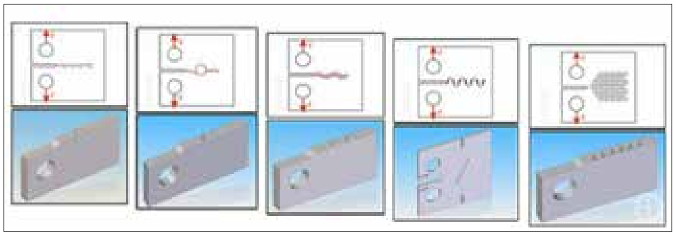


Figure 21(b): Variation of Notch Position, Form and Orientation to Manipulate Fatigue life

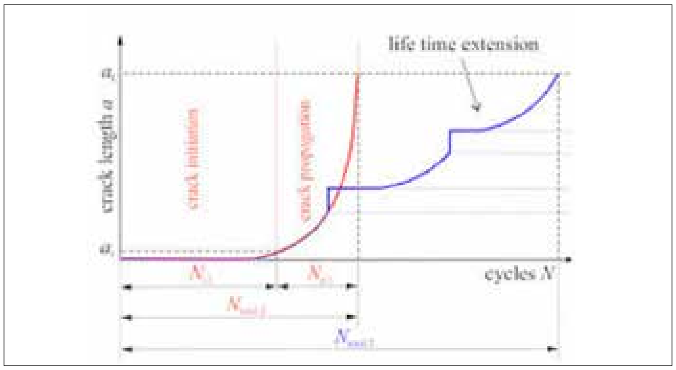


Figure 21(c): Extension of Fatigue Life of a Sample AM Part

MSC Fatigue has been applied to study the following areas of production AM parts:

1. High cycle (S-N) and Low cycle (E-N) Stress Life Fatigue;
2. Deformation and damage analysis using Palmgren – Miner;
3. Crack initiation and growth using Paris;
4. Virtual strain gauge to perform experimental-analytical comparison;
5. Vibration fatigue using random load;
6. Non-proportional multi axial stress state;
7. Multiple simultaneous loads and multiple events;
8. Safety factor analysis.

Recent demonstration of fatigue life calculations under random vibration loads of a sample automotive AM powertrain component produced the following results shown in Fig. 22 (a), (b), (c) and (d).

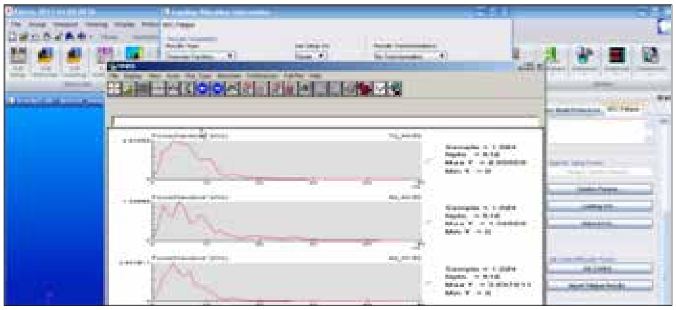


Figure 22(a): Prediction of Fatigue Life of AM Part Subjected to Multiple Inputs (Random Vibration Loads)

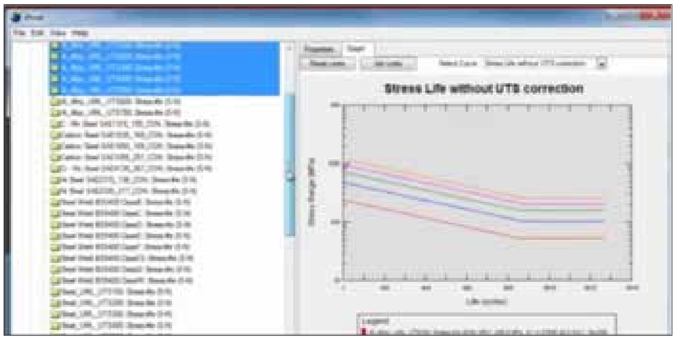


Figure 22(b): Prediction of Stress Life without UTS Correction

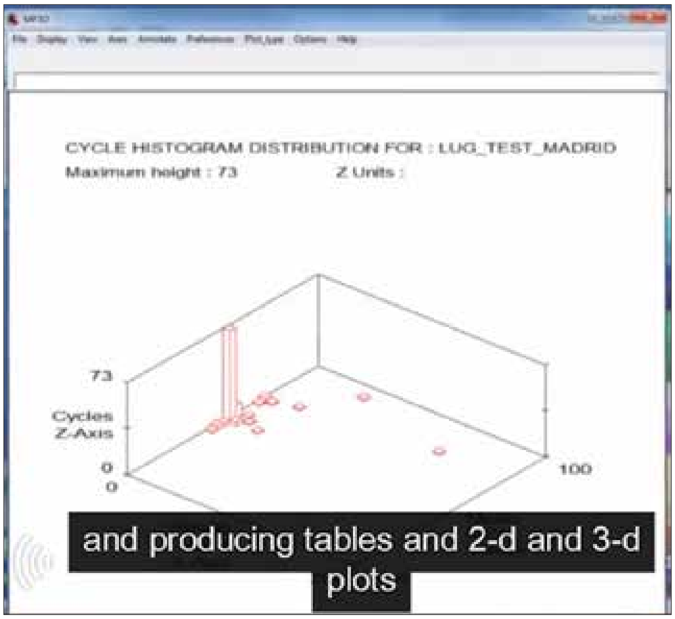


Figure 22(c) and (d): Prediction of Cycle Histogram Distribution under Various Loading

As part of a smaller or larger assembly, any given AM part may have issues with fit/finish, tolerance and functional performance over a period of time. FE analysts simulate all these issues and predict the durability and NVH of a given AM part using MSC Software's world-renowned analytical toolset, MSC Nastran. It is used in the simulation of the following:

1. Areas of high von Mises stress and maximum deflection;
2. Noise and vibration effects of AM parts and assemblies;
3. Areas subjected to high level of buckling;
4. Topology, topometry and topography optimization.

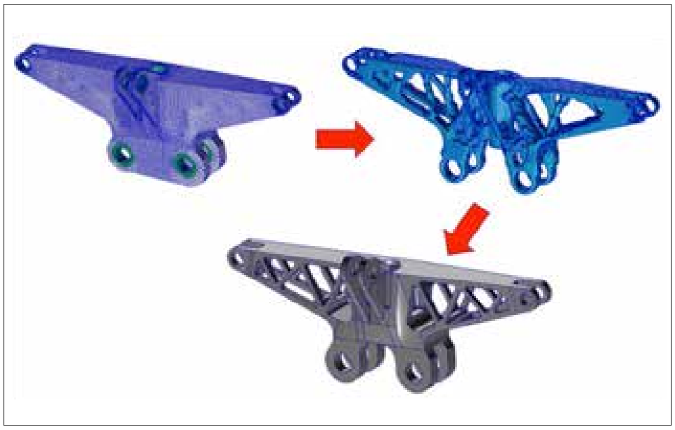


Figure 23: Initial and Optimized (Weight Reduction of 70%) Design of an Aerospace AM Part (Engine Attachment Fitting) made of titanium alloy

Recently, MSC Nastran was applied to simulate the linear static and buckling behavior as well as topology optimization of an aerospace engine attachment fitting AM part made of a Titanium alloy.

MSC Nastran SOL 200 topology optimization reduced the weight of the AM part by 70% while preserving static (stress and distortion) and buckling behavior the same as the initial design. Fig. 23 illustrates the initial and optimized design.

CONCLUSIONS

Over the past 25 years, Additive Manufacturing has grown from a rapid prototyping process into a set of advanced technologies that are becoming more accessible to businesses, government organizations and individual customers worldwide. Although it continues to be a challenge in producing high quality parts, there are commercial systems available to address all shortcomings.

MSC Software's AM End to End Simulation framework has been developed as "backbone" to address AM challenges. This system is applied all across the AM product development lifecycle (design, development, simulation/prototype build, test and after market performance) stages and covers the full scope of materials/machine/process/build qualification from concept to sustainment. Fig. 24 outlines the stages of Additive Manufacturing from part design to part performance in the analytical framework.

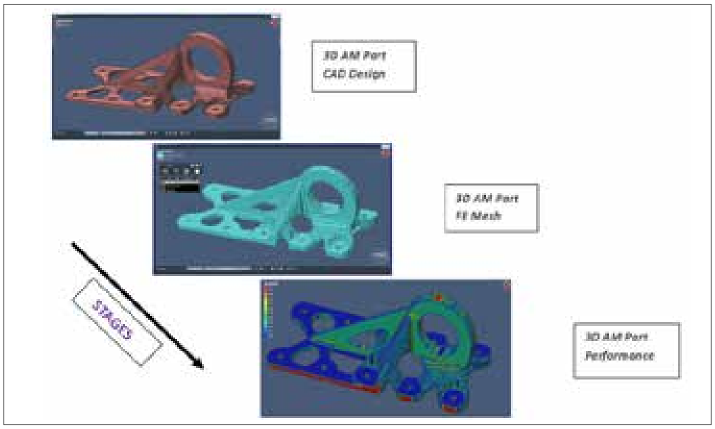


Figure 22: Stages of Additive Manufacturing in the Analytical Framework

ABOUT MSC SOFTWARE

MSC Software is a global leader of multidiscipline simulation solutions that help companies improve quality, save time, and reduce costs associated with designing and testing manufactured products. MSC Software works with thousands of companies worldwide to develop better products faster with engineering simulation technology, software, and services. For additional information about MSC Software's products and services, please visit www.mscsoftware.com. MSC Software's products and services are used by 900 of the top 1000 manufacturers in the world, across several industries including aerospace, defense, automotive, transportation, agricultural equipment, heavy machinery, medical devices, oil and gas, nuclear, consumer products, renewable energy, packaging, electronics, and shipbuilding.

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