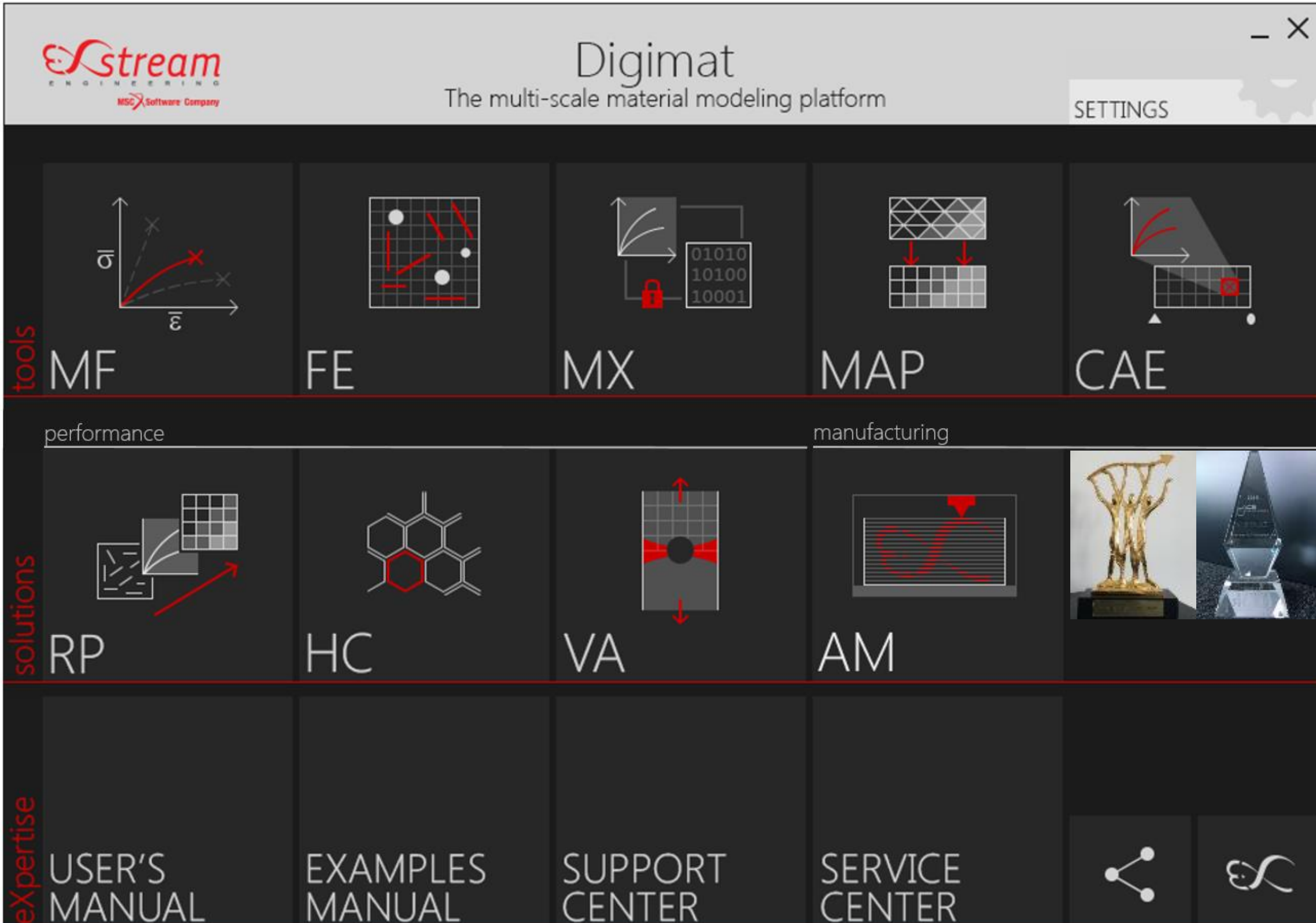
Digimat for Additive Manufacturing

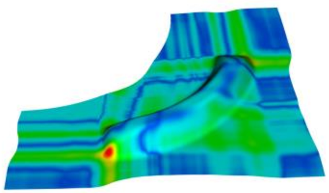
March 2017

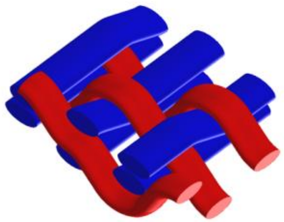
e-Xstream ENGINEERING
MSC Software Company

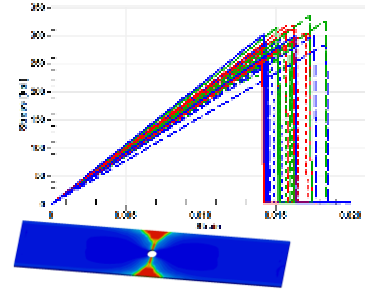
e-Xstream, an MSC Software Company
50+ Engineers that are 100% dedicated to Material Modeling

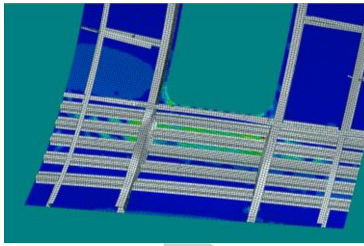

e-Xstream
ENGINEERING
MSC Software Company
Digimat
The multi-scale material modeling platform
SETTINGS
tools
MF
FE
01010
10100
10001
MX
MAP
CAE
performance
manufacturing
solutions
RP
HC
VA
AM
eXpertise
USER'S MANUAL
EXAMPLES MANUAL
SUPPORT CENTER
SERVICE CENTER

From Manufacturing Processes to End Product Performance







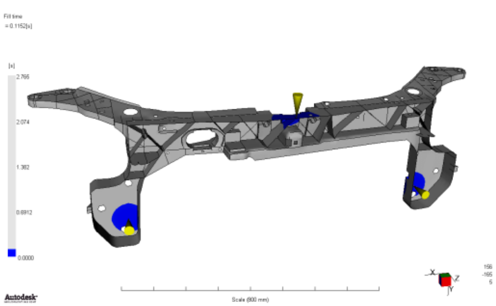


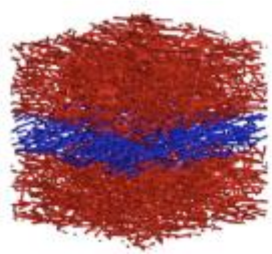
Manufacturing Process

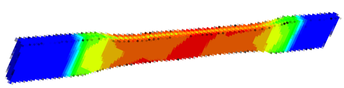
Material microstructure (chopped fibers, UD, woven, etc.)

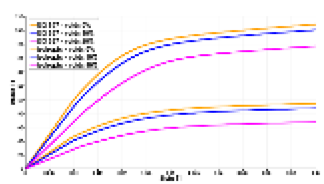
Material characterization (mechanical, thermal, electrical)

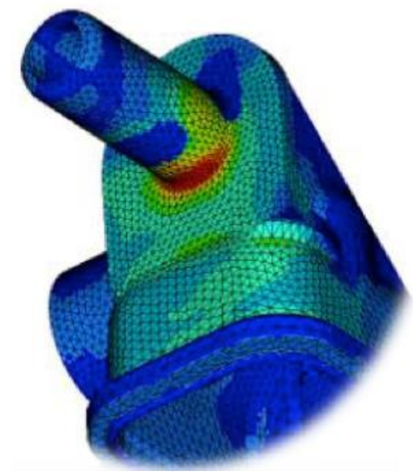
Engineering of Composite Parts & Systems



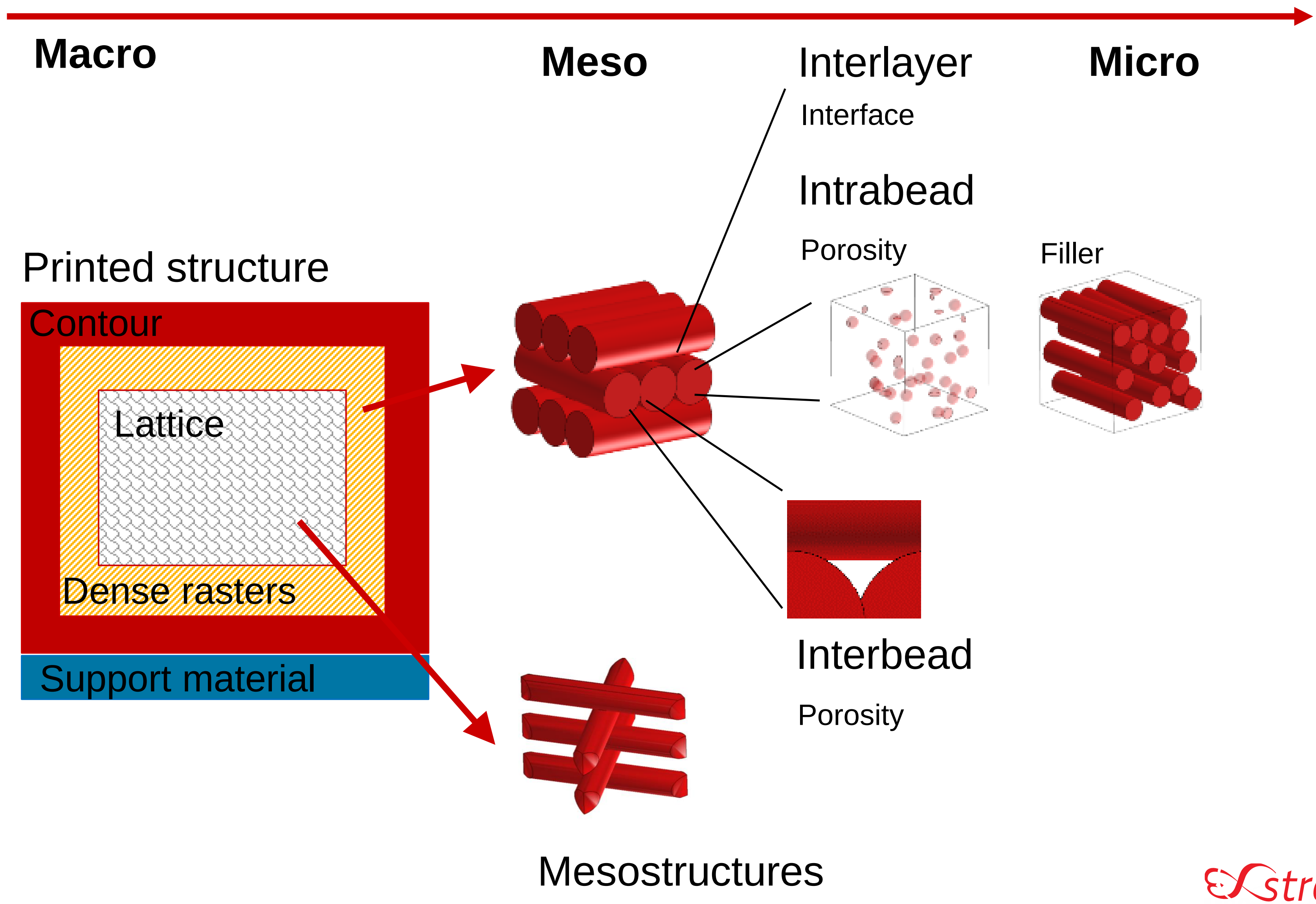




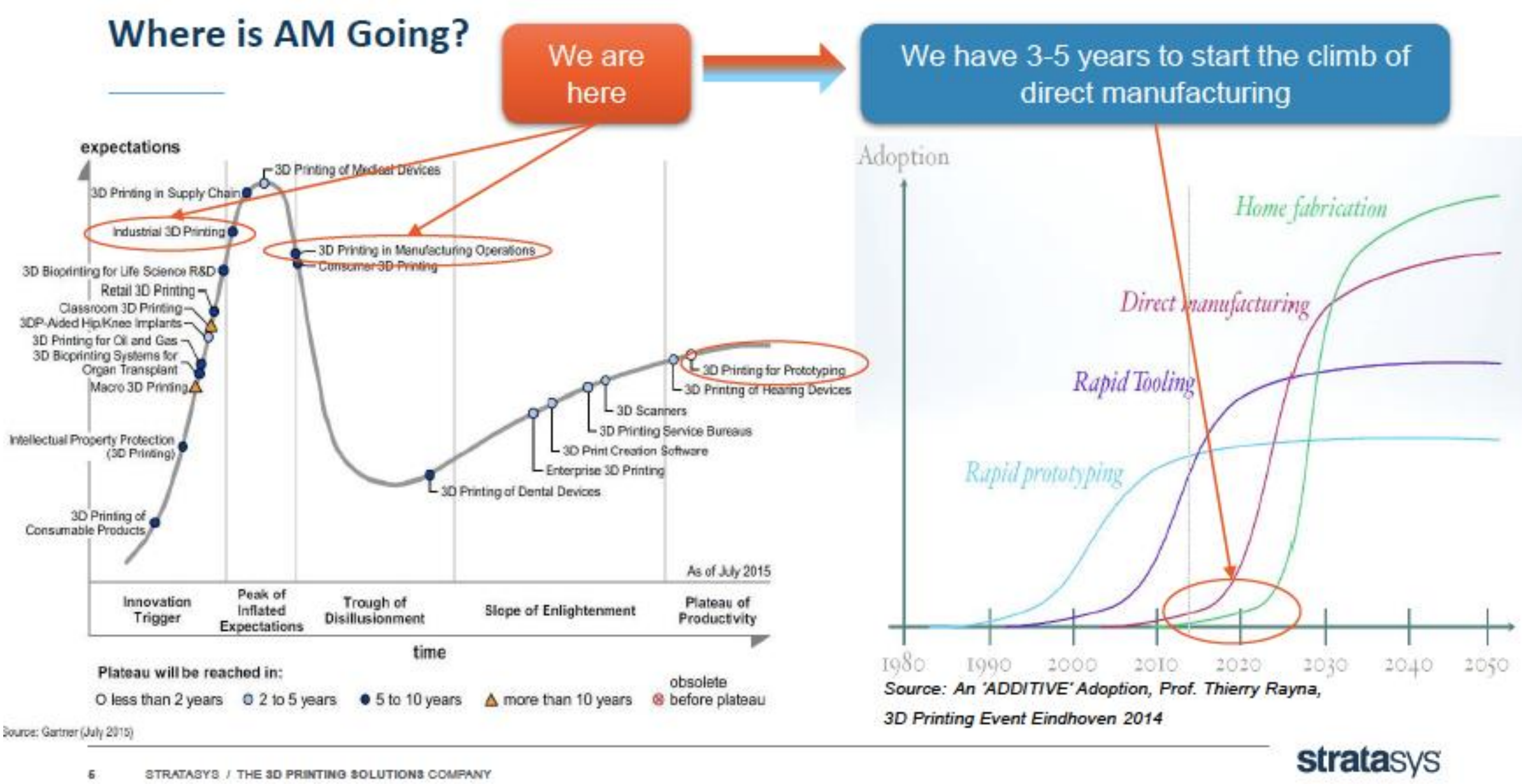




Additive manufacturing modeling is a true multiscale challenge



Digimat is being developed to support the AM market move from rapid prototyping to direct manufacturing



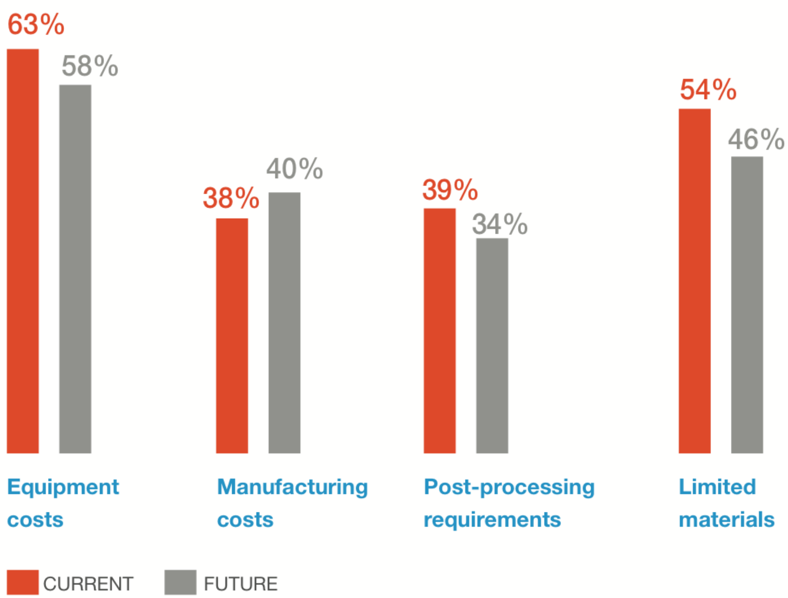
<u>Source:</u> Multi-Material Voxel based 3D Prnting. A New Horizon in Composition Fredom, Oren Zoran (Stratasys), DigimatUM16, oct 2016

Print it right the first time!

According to [Wohlers Report 2016, the additive manufacturing (AM) industry grew 25.9% (CAGR – Corporate Annual Growth Rate) to $5.165 billion in 2015.] *The CAGR for the previous three years was 33.8%. Over the past 27 years, the CAGR for the industry is an impressive 26.2%*

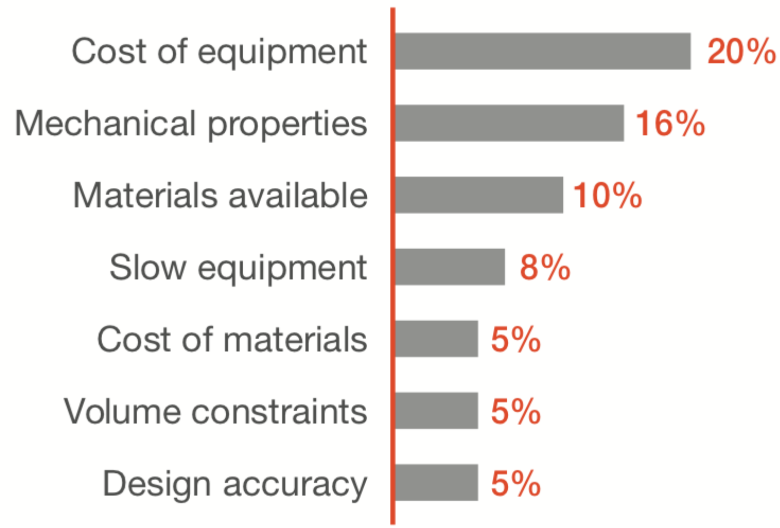
Source: Forbes.com

FIGURE C



Respondents were asked what they perceive as the top challenges their company faces in using AM now and will face in the future. The 4 most common responses are shown in this graph.

FIGURE F



Respondents were asked what one issue they feel will have the greatest impact on the AM market. Interestingly, no one issue stands out significantly more than another.

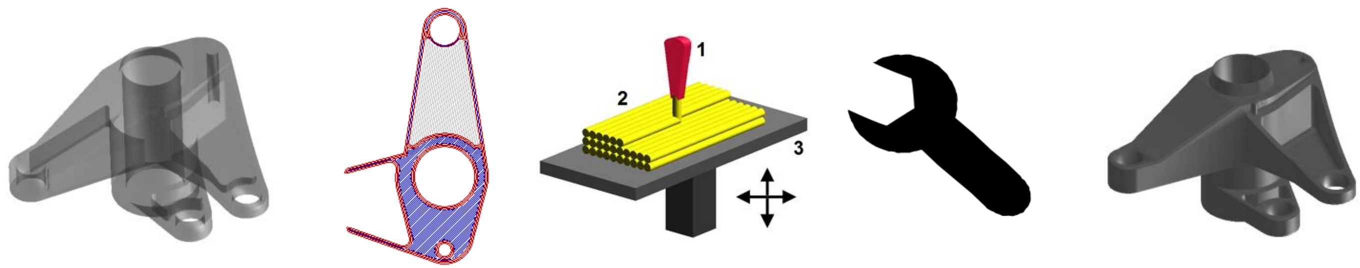
Source: stratasys.com

Additive Manufacturing industrial pains

- **Cost of manufacturing equipment**
- **Long development time for each new grade**
  - Determine mechanical properties of the material
- **Reliability of printed part**
  - Design accuracy (warpage)
  - Defects
  - Impact of the printing direction
  - Support
- **Process speed & robustness**
- **Large number of process parameters**
  - Effect of each parameter
  - Optimize process
- **Prove part performance**
  - Mechanical tests are expensive!

Current additive manufacturing workflow

- **Test based**



Design → Printer pre-processing → Printing → Post-processing → Final part → Test

Design
- Initial CAD

Printer pre-processing
- .stl
- Material
- Toolpath
- Process parameters

Printing
- Material deposition
- **Printing issues**

Post-processing
- Heat treatment
- Surface finish

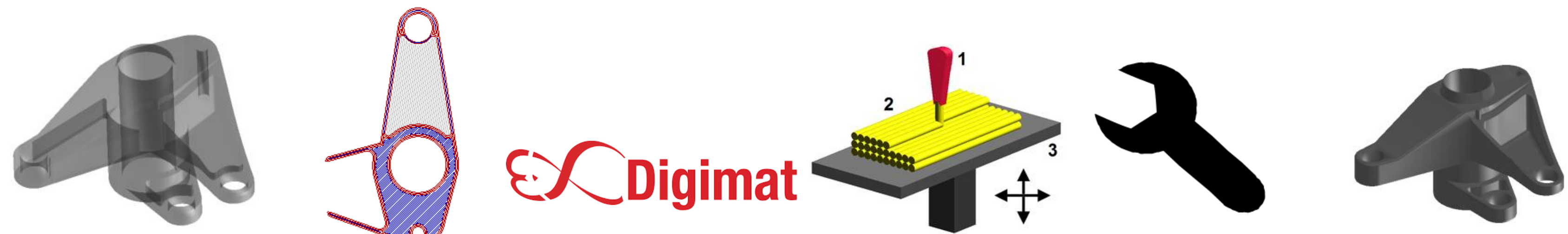
Final part
- Warpage
- Residual stresses
- Porosity

$$

Trial and error methodology

Optimized additive manufacturing workflow

- **Simulation based**



Design → Printer pre-processing → Simulation → Printing → Post-processing → Final part

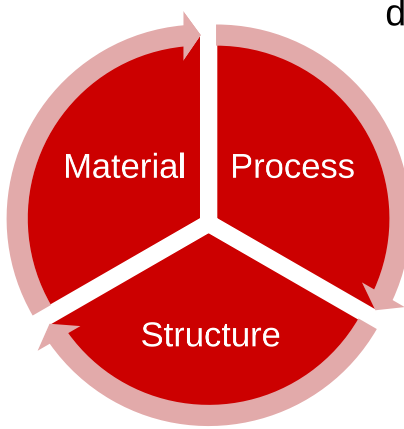
Design
- Initial CAD

Printer pre-processing
- .stl
- Material
- Toolpath
- Process parameters

Printing
- Material deposition

Post-processing
- Heat treatment
- Surface finish

Final part
- Minimized Warpage
- Minimized Residual stresses
- Mastered porosity
- **Mastered performance**



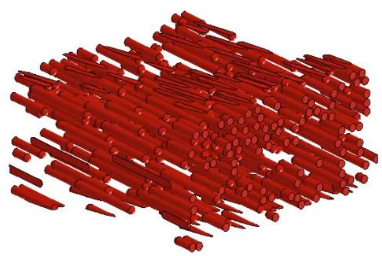
Optimization

Digimat Additive Manufacturing Solution

Additive Layer Manufacturing

FDM/SLS

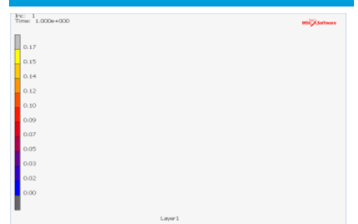
Material Engineering



- Mechanical
- Thermal
- Electric

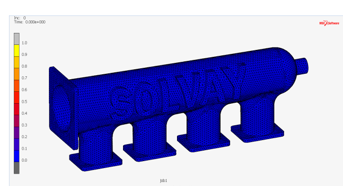
Digimat Material

Process Simulation



- Warpage
- Residual Stress
- Porosity

Part Performance



- Stiffness
- Failure
  - Print Direction
  - Reinforcement

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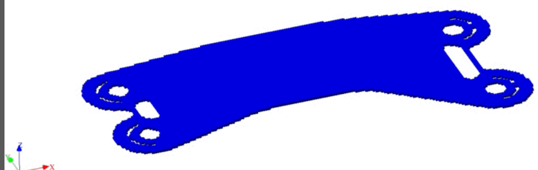
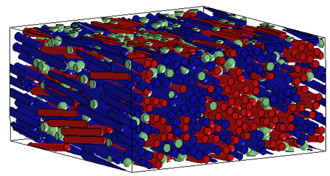
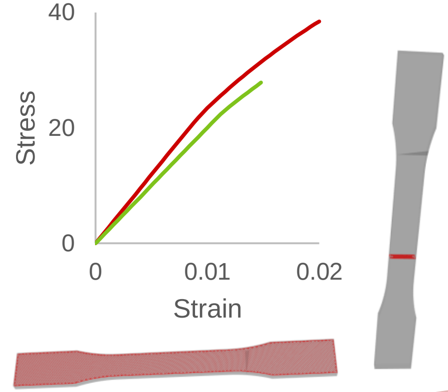
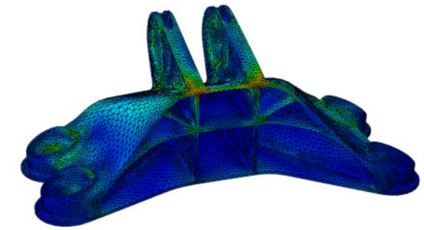
From Manufacturing Process to End Product Performance







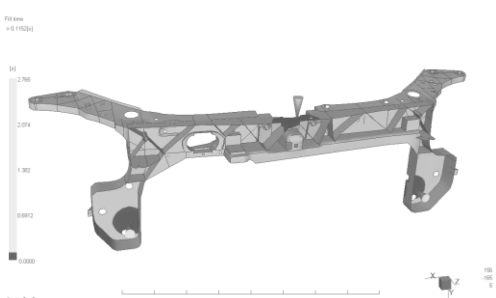


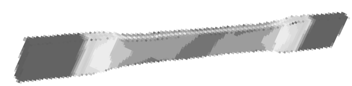
Manufacturing Process Simulation

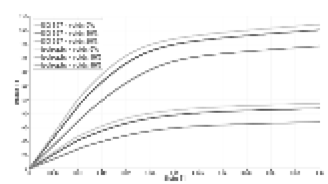
Material microstructure

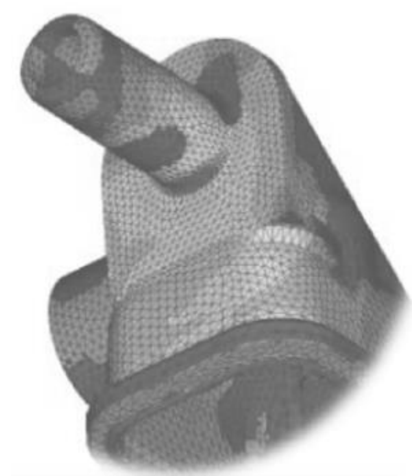
Material characterization (mechanical, thermal, electrical)

Engineering of AM Parts & Systems









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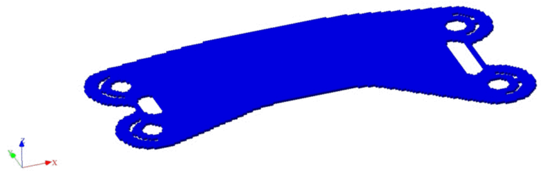
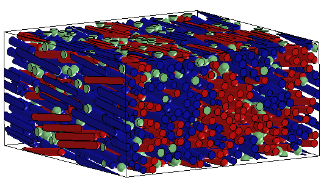
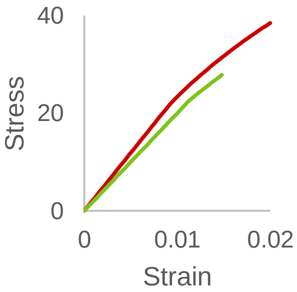
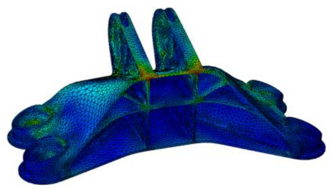
Digimat Additive Manufacturing Solution: modeling to support fast ideas to the market

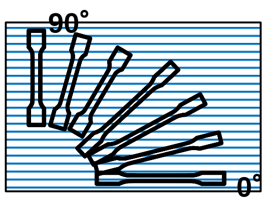
- **Comprehensive modeling solution developed in partnership with the complete ecosystem**
- **Simulate the manufacturing process**
  - Improve part quality
  - Anticipate printing issue with simulation
  - Time & material saving
  - Capture AM technology potential
- **Virtual testing of efficient materials**
  - Design, understand, test (new) systems
  - Reinforced materials and advanced material models
- **Accurate, efficient and predictive FEA to guide design**
  - Design & validate parts by accounting for the microstructure
  - Reduces physical productions and testing

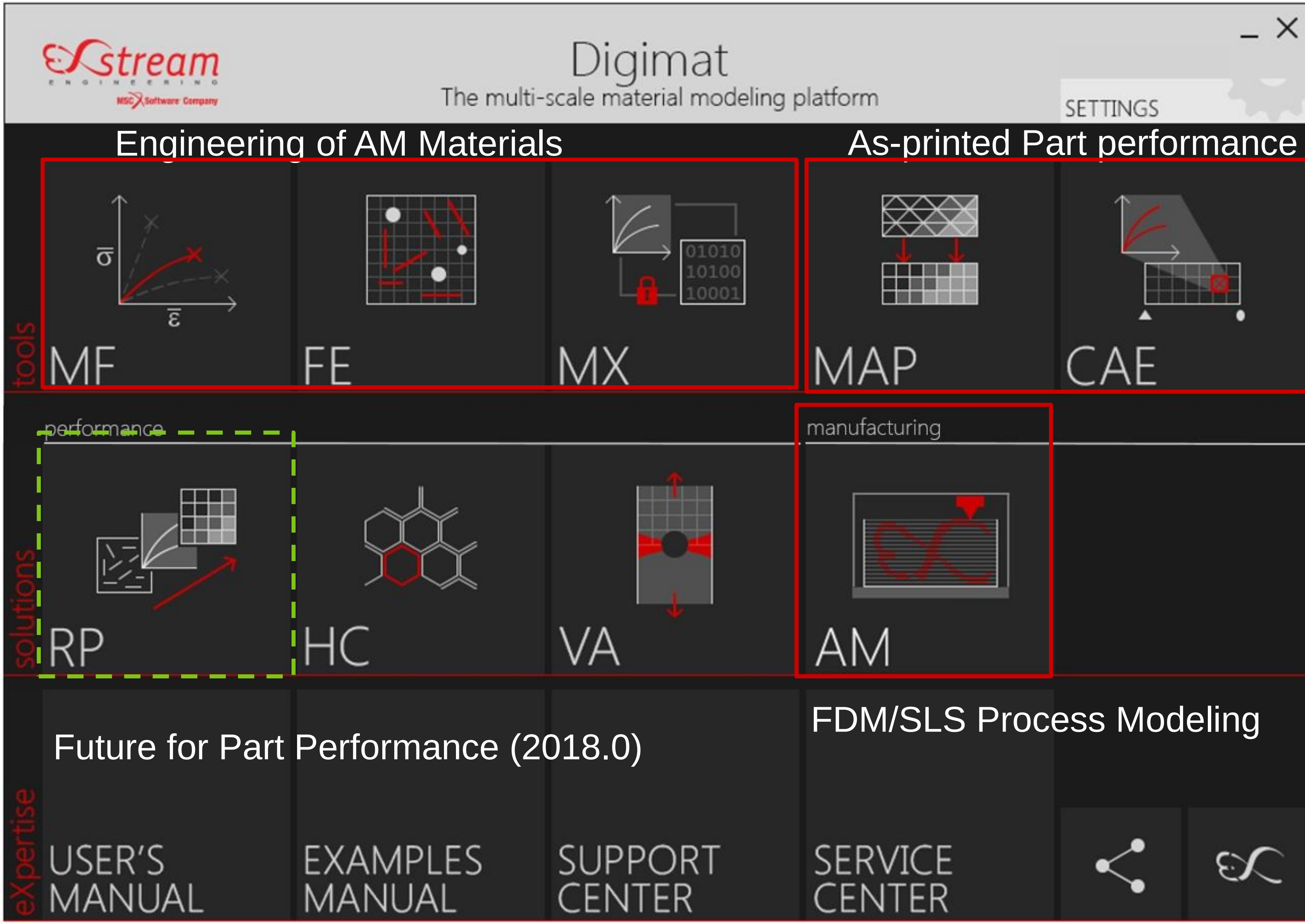












Digimat
The multi-scale material modeling platform
SETTINGS
Engineering of AM Materials
As-printed Part performance
tools
MF
FE
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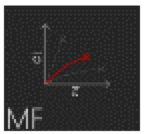
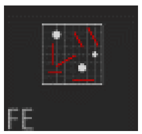
performance
manufacturing
solutions
RP
HC
VA
AM
Future for Part Performance (2018.0)
FDM/SLS Process Modeling
eXpertise
USER'S MANUAL
EXAMPLES MANUAL
SUPPORT CENTER
SERVICE CENTER

Material Engineering

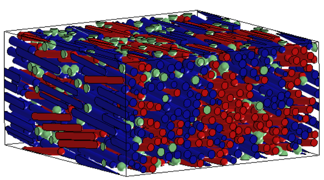
Digimat to support AM material needs

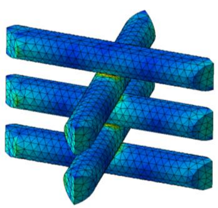
Simulation tools for material development and performance optimization

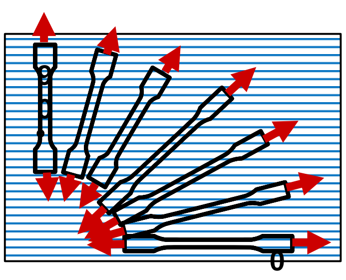


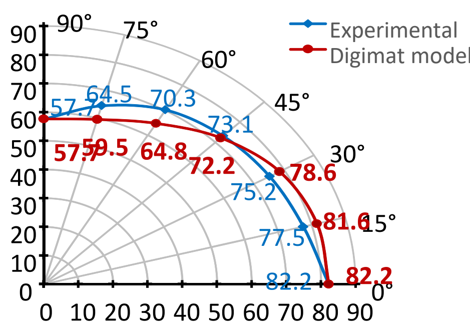


Analyze and control
Effect of filler
Effect of defects
Failure
New material system

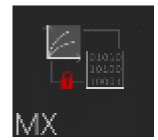








Support material end-user with advanced predictive material models



Public Data Providers

	Grades	DAF	DMF	DEF
DuPont Performance Polymers	10	30	0	0
EMS-GRIVORY	11	0	0	22
EVONIK Industries AG	4	0	0	14
Lanxess Deutschland GmbH	2	7	0	0
LyondellBasell	17	0	0	74
Radici	3	18	0	0
SABIC	14	36	0	0
SOLVAY Engineering Plastics	44	9101	0	0
Solvay Specialty Polymers	15	39	0	0
Ticona GmbH	3	0	0	6
Trinseo	7	12	0	0
Victrex Polymer Solutions	3	6	0	0
e-Xstream	36	192	0	54

Off-the-shelf Digimat model for predictive simulation of printed parts

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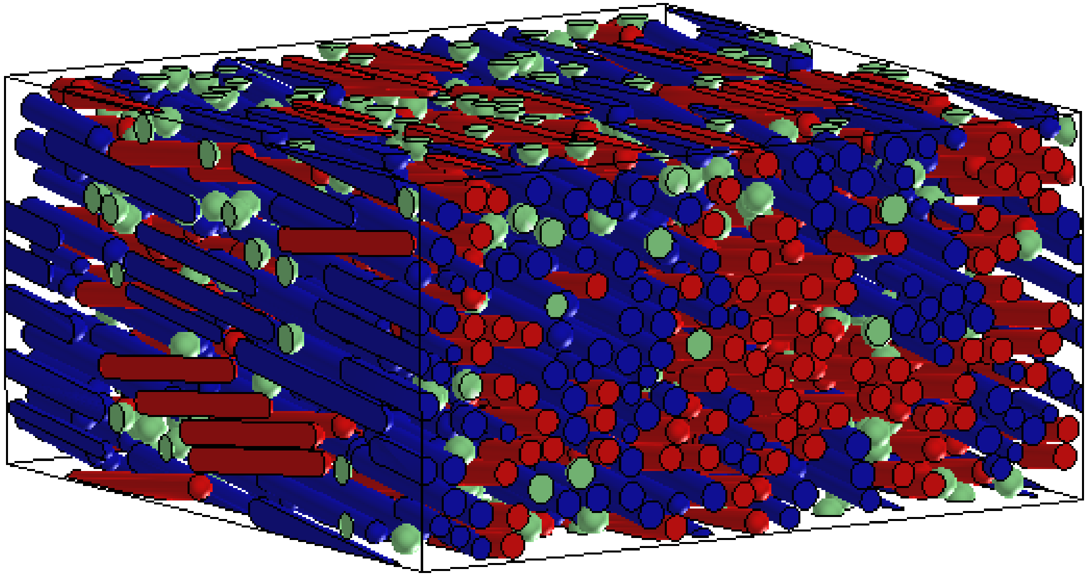
PEKK + CF
Effect of Porosity



	PEKK	CF	Porosity
Young Modulus (MPa)	3,600	250,000	0,01
Poisson ratio	0,38	0,2	0
Thermal Expansion (K^{-1})	2,1E-5	1,8E-6	0
Thermal Conductivity (W/mK)	0,25	17	0,0001
Electric Conductivity (S/mm)	2,04E-18	500	E-20
Volume Fraction		30%	2%
Aspect Ratio		10	1
Orientation		+7°/-7°	

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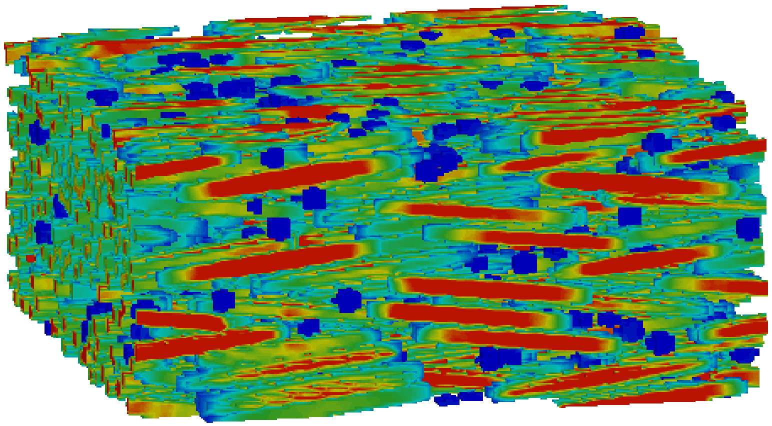
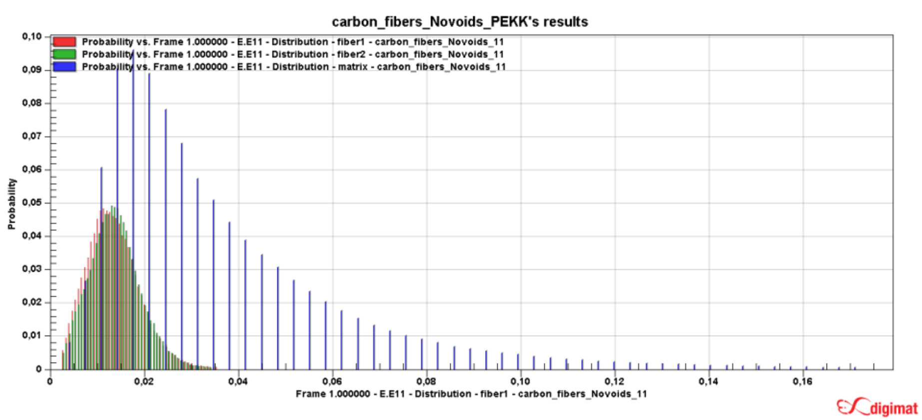
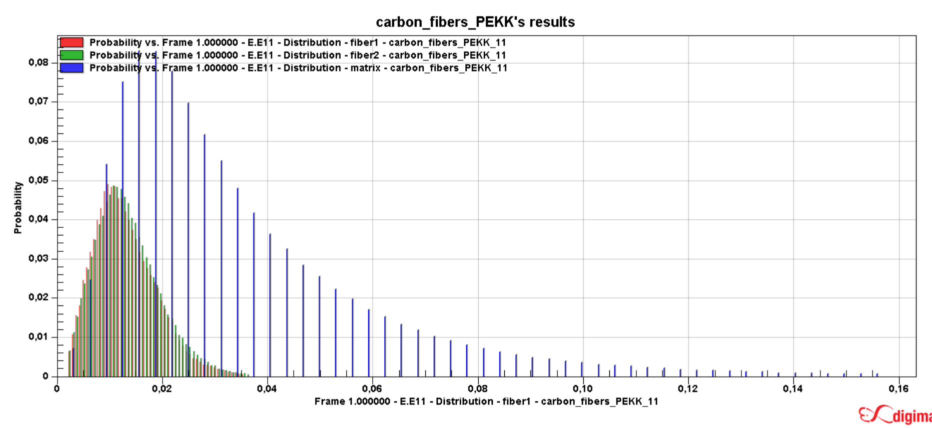
PEKK + CF : Effect of micro porosity

Prediction of the Thermo/Mechanical/Electric Properties



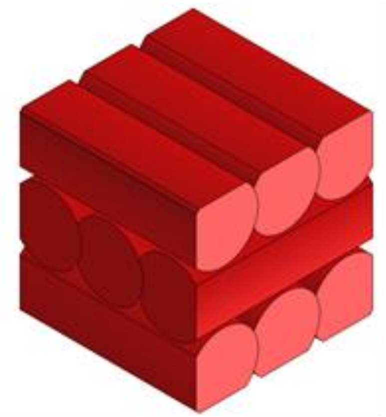
	No Porosity	Porosity
Young Modulus (MPa)	36930.8	32765.6
Poisson ratio	0.363	0.357
Max Matrix Strain	18%	15%
Thermal Expansion(K^{-1})	3.60E-006	4.0E-006
Thermal Conductivity (W/mK)	3.572	3.021
Electric Conductivity (S/mm)	74.87	53.45



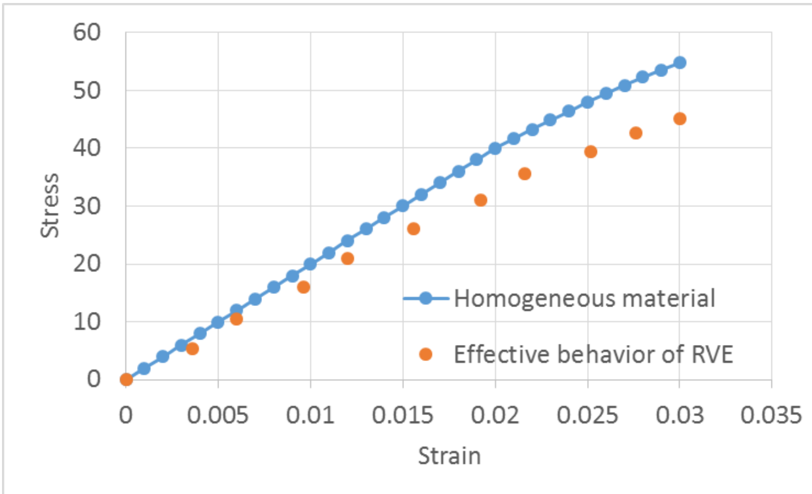


RVE of FDM material samples

- **Study effect of printing pattern and porosity on material behavior**



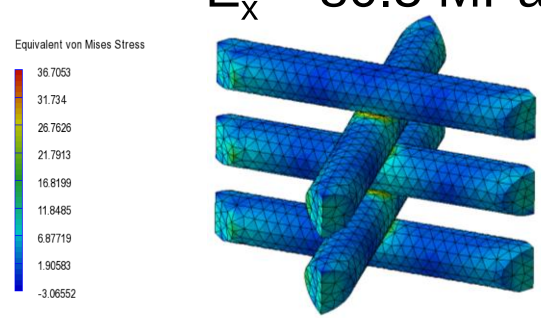
6% of inter-beads voids



- **Predict lattice structure response**

Bulk axial modulus
E = 2000 MPa

Equivalent axial modulus
E_x = 80.5 MPa



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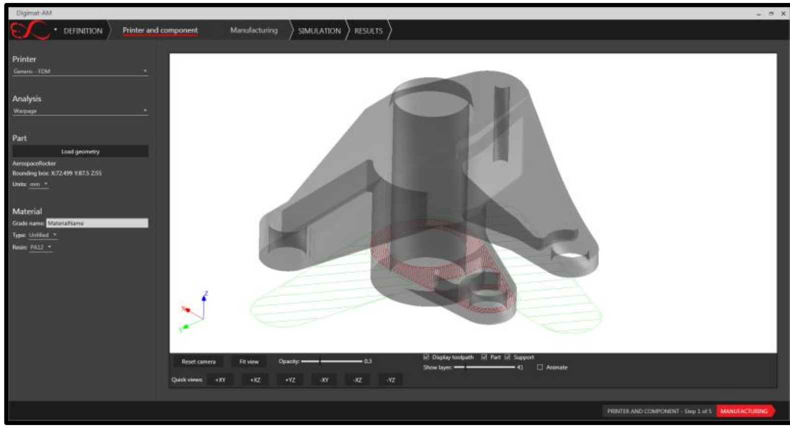
Process simulation

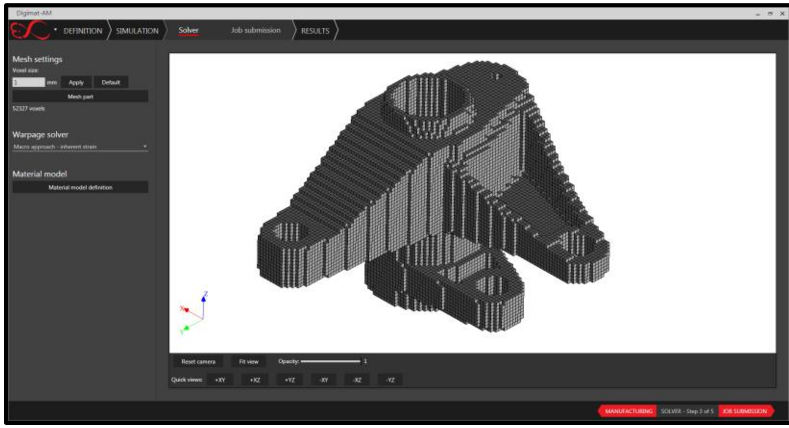
Process simulation – Digimat-AM

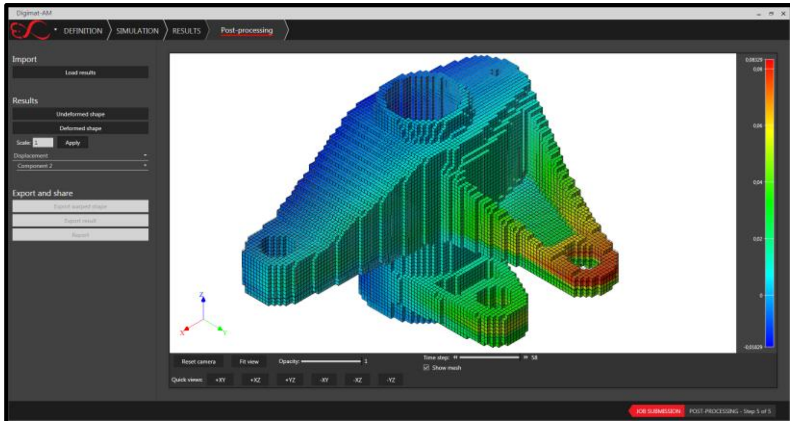
- **Additive manufacturing processes :**
  - SLS
  - FFF

- **Materials :**
  - Filled & unfilled polymers

- **Predictions :**
  - Warpage & residuals stresses
  - Micro/meso structure





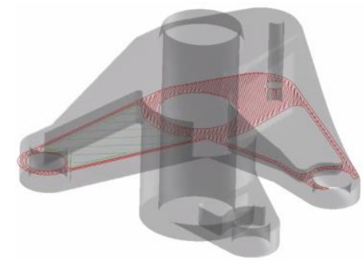


Digimat-AM process simulation workflow

Initial geometry
Material specification

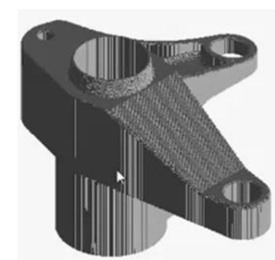
User input

Toolpath
Process parameters
Parts positioning

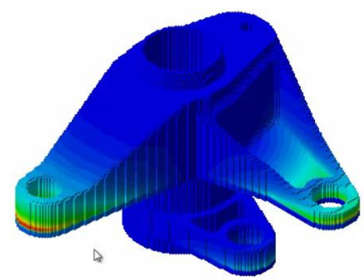


Printer
pre-processing

Beads deposition
Materials state evolution
Stress build-up
Stress relaxation



Process



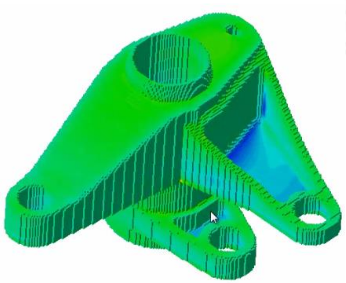
Residual stress distribution

Material properties distributions

Final deformed shape

Post-processing & heat treatments

Microstructure



Link to Part performance:

- porosities
- toolpath
- process parameters

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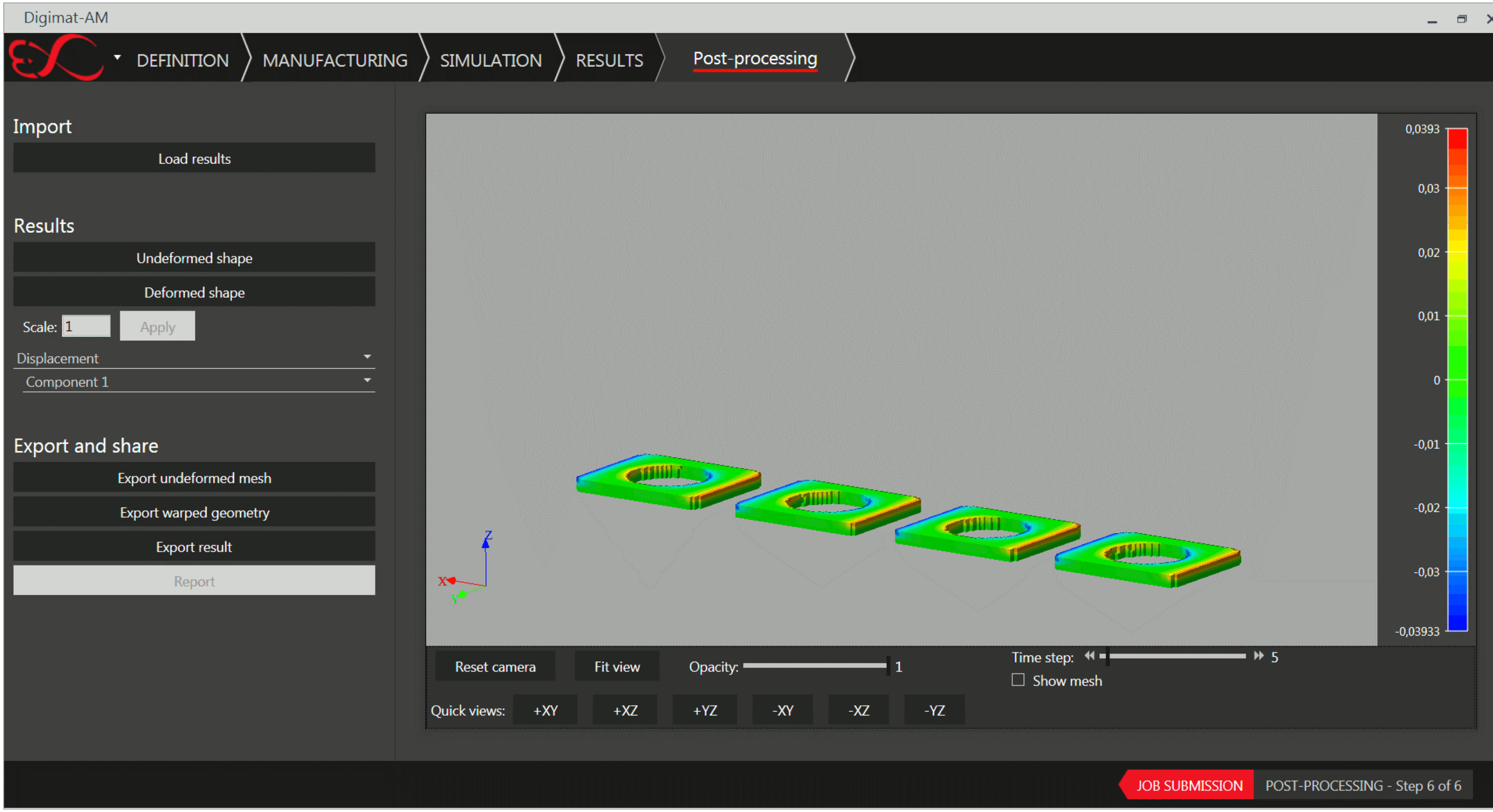
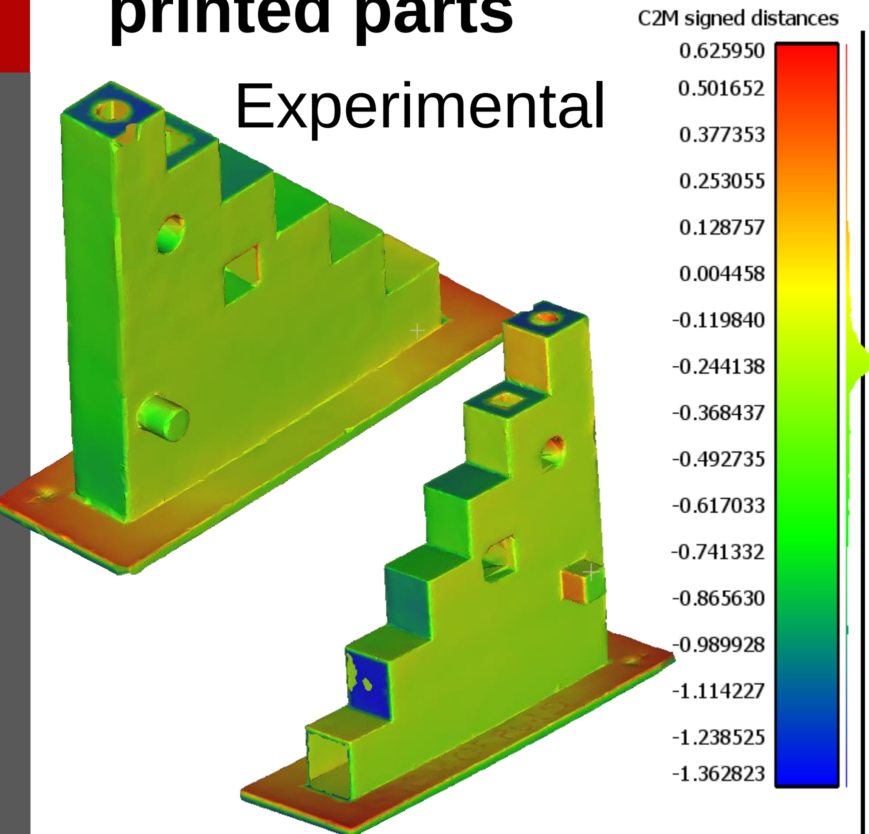
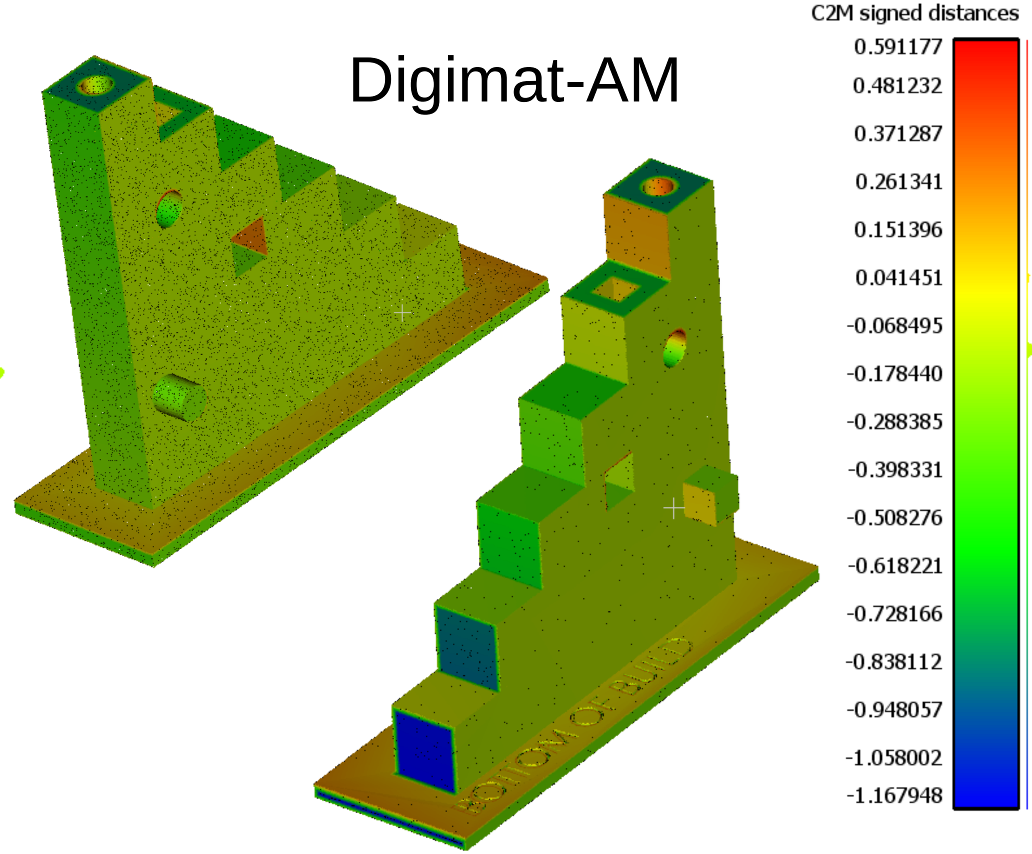
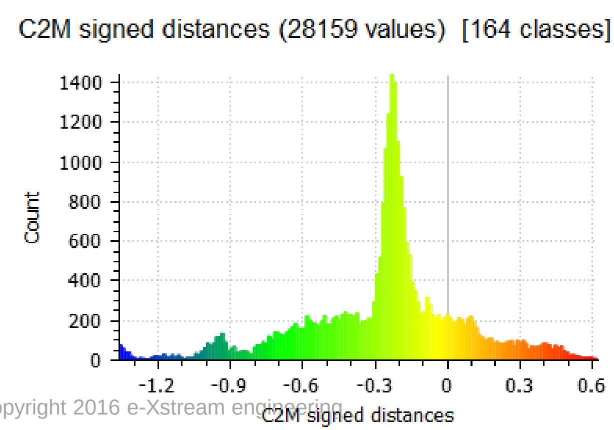
Warpage prediction in Digimat-AM

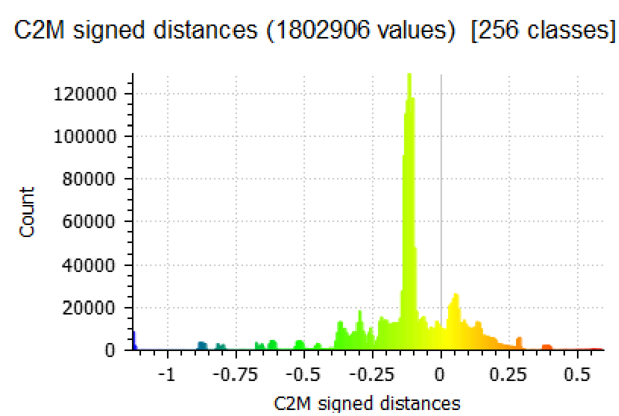


Digimat-AM warpage prediction compares well with printed parts





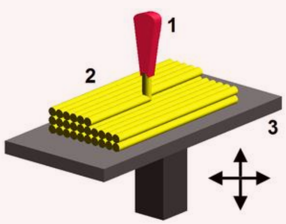




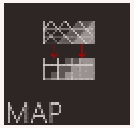
Structural Engineering

Structural engineering of AM components

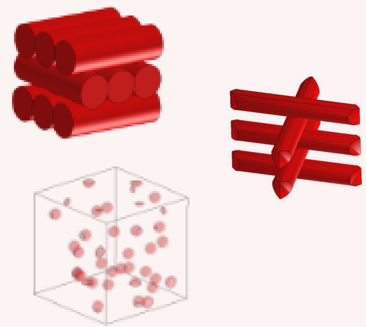
Process data transfered to structural mesh

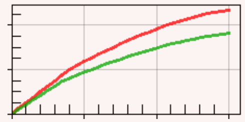


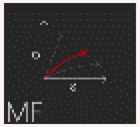
- Residual stresses
- Local printing direction
- *Local porosity*
- *Local filler microstructure*

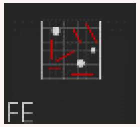


Multiscale non-linear material model

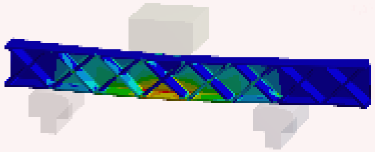


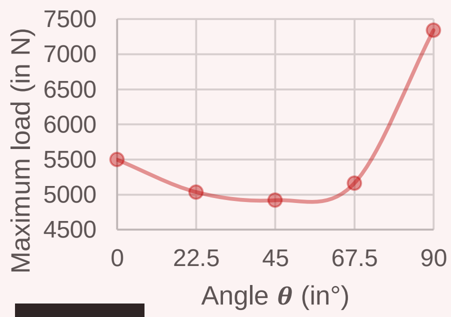


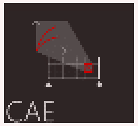




As-manufactured part performance



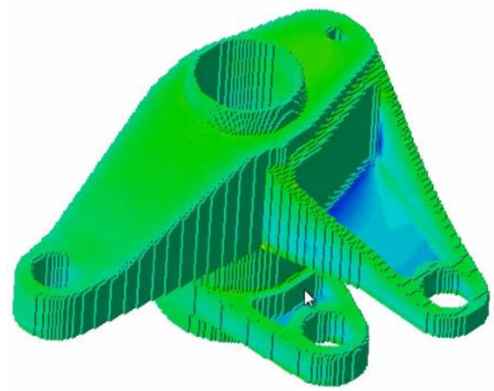




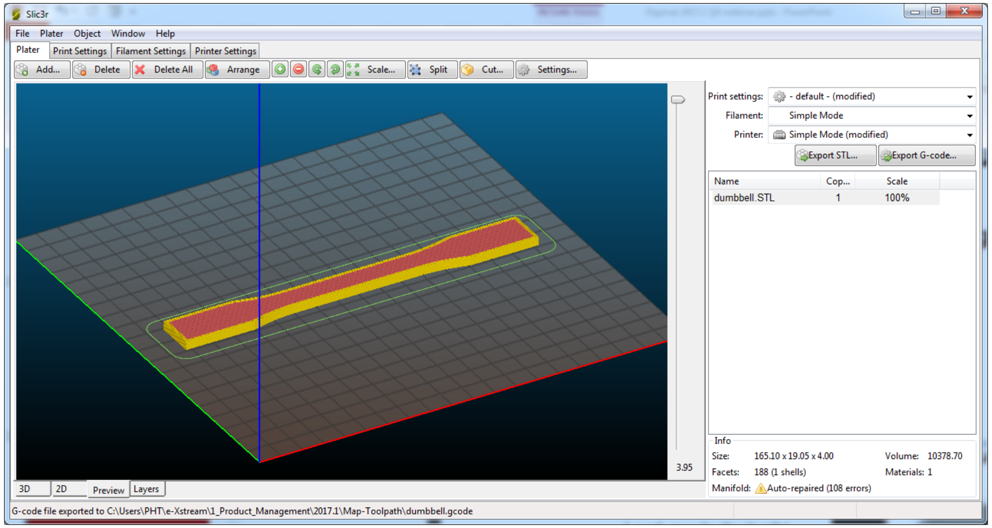
Strong coupling

Connect manufacturing with structure for AM

- **AM produces several types of manufacturing effects**
  - Residual stresses (SLS/FFF)
    - From Digimat-AM

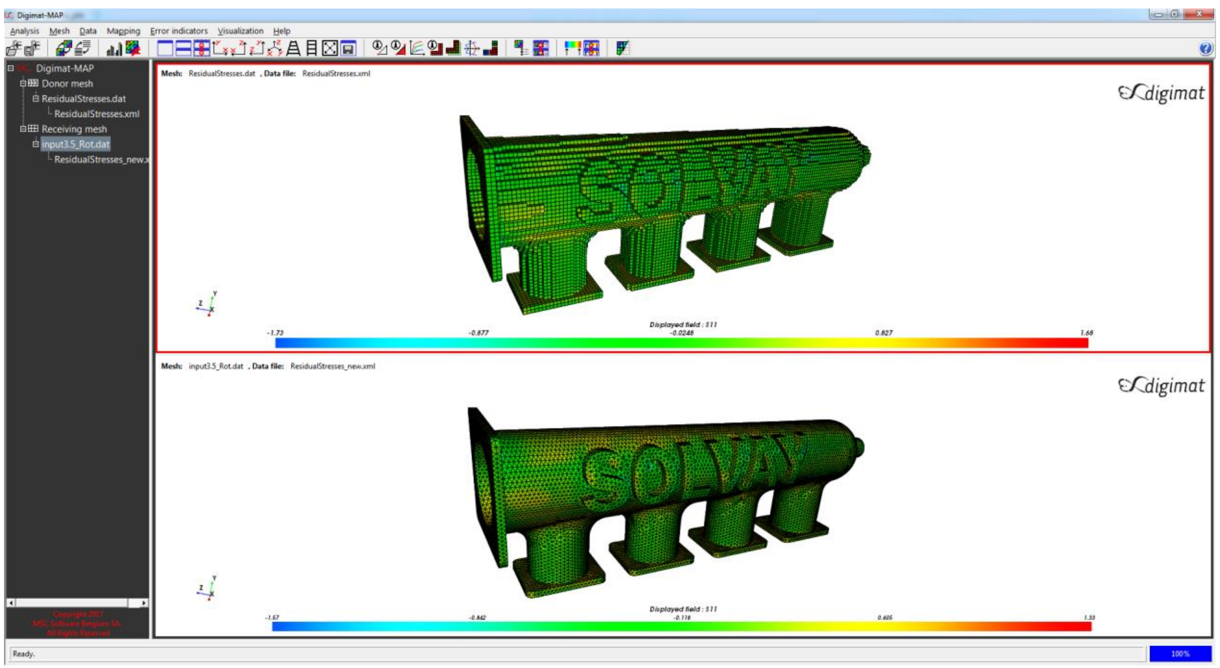


  - Toolpath (FFF only)
    - From slicing software



Digimat-MAP connects residual stresses from Digimat-AM to structural FEA

- **AM produces several types of manufacturing effects**
  - Residual stresses (SLS/FFF)
    - From Digimat-AM
      - Load Marc mesh
      - Load Initial stresses



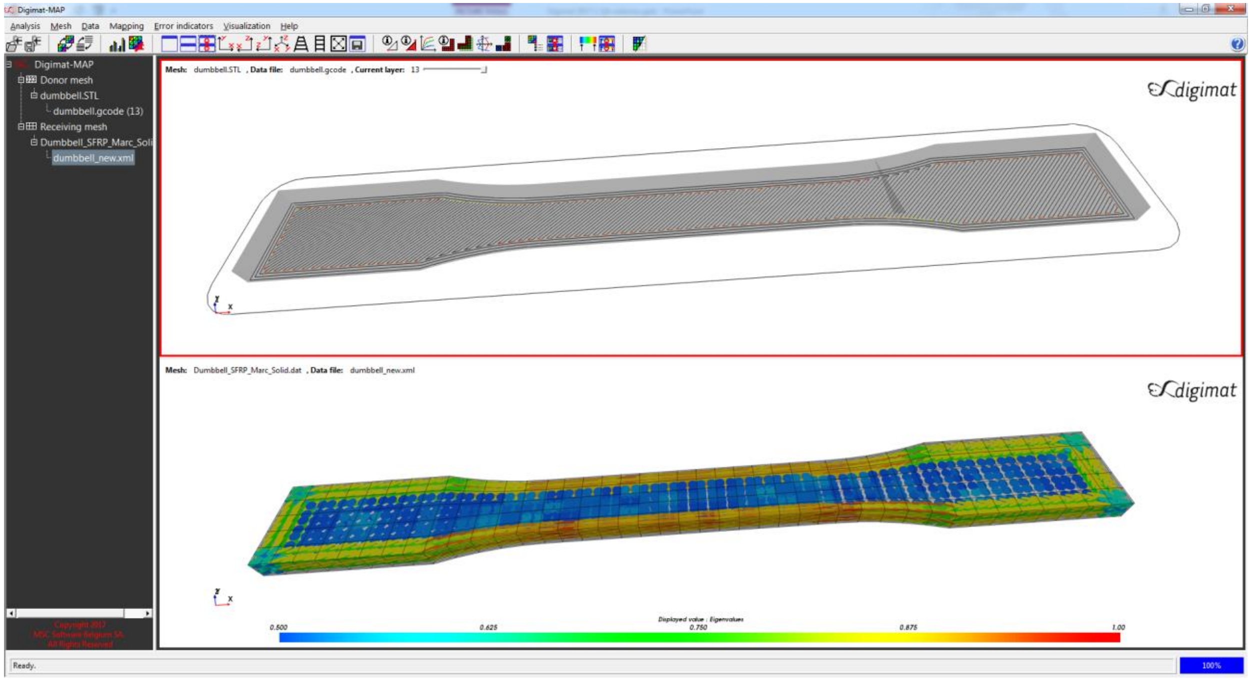
Digimat-AM results

Initial stresses mapped to structural FEA

- Abaqus
- Ansys

Digimat-MAP transfers toolpath information to structural FEA

- **AM produces several types of manufacturing effects**
  - Toolpath (FFF only)
    - From slicing software
      - Load .stl (geometry)
      - Load .gcode (toolpath)



Deterministic very detailed layer-by-layer information

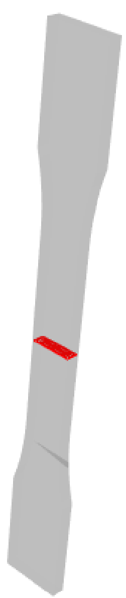
Homogenized into equivalent orientation tensor
→ Export .dof file

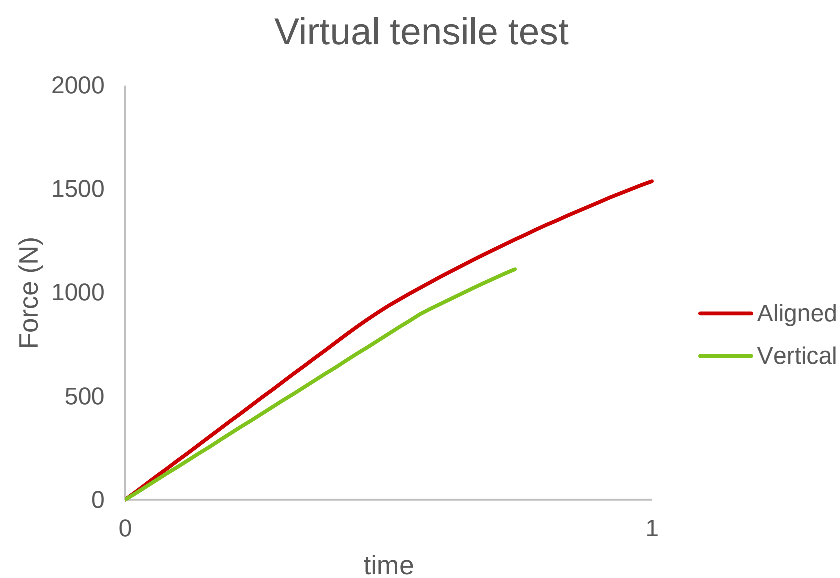
FFF structural FEA shows effect of printing pattern (toolpath)

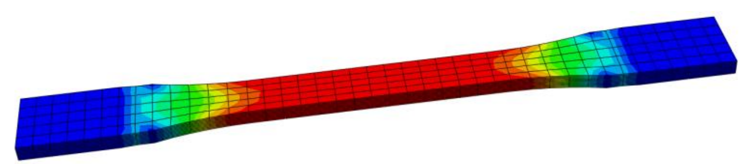
Toolpath

+/-45° infill / Printing Z / Loading X

+/-45° infill / Printing Z / Loading Z

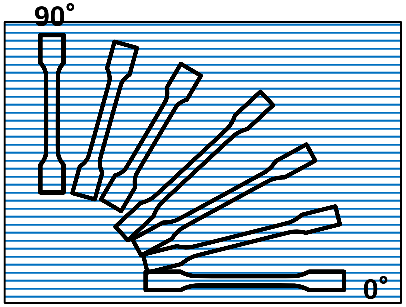






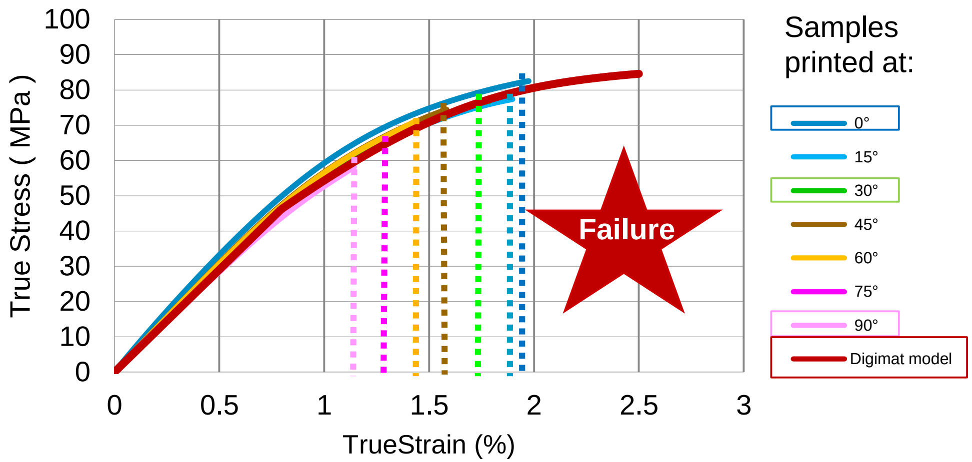
Case study

Characterization of Sinterline Powder

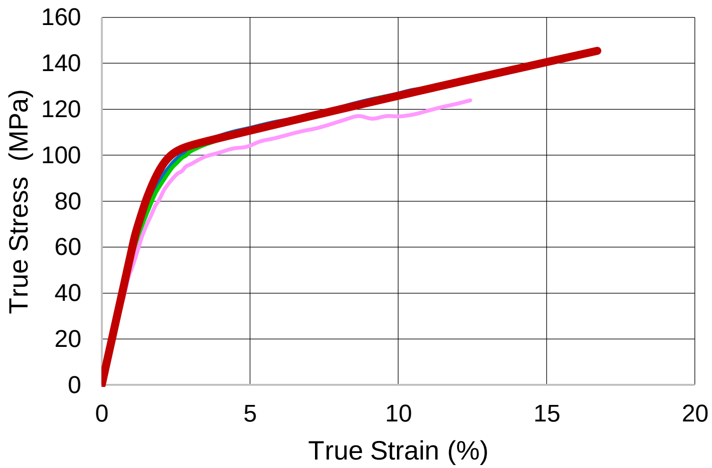


- **Glass beads reinforced polyamide**
- **Tensile + compression test =**
  - Isotropic stiffness of material
  - Traction and compression plasticity dependency → Drucker-Prager model

Tensile test (RH0), depending of printing orientation, compare to Digimat model



Compressive tests (RH0) depending on samples printing orientation, compare to Digimat model



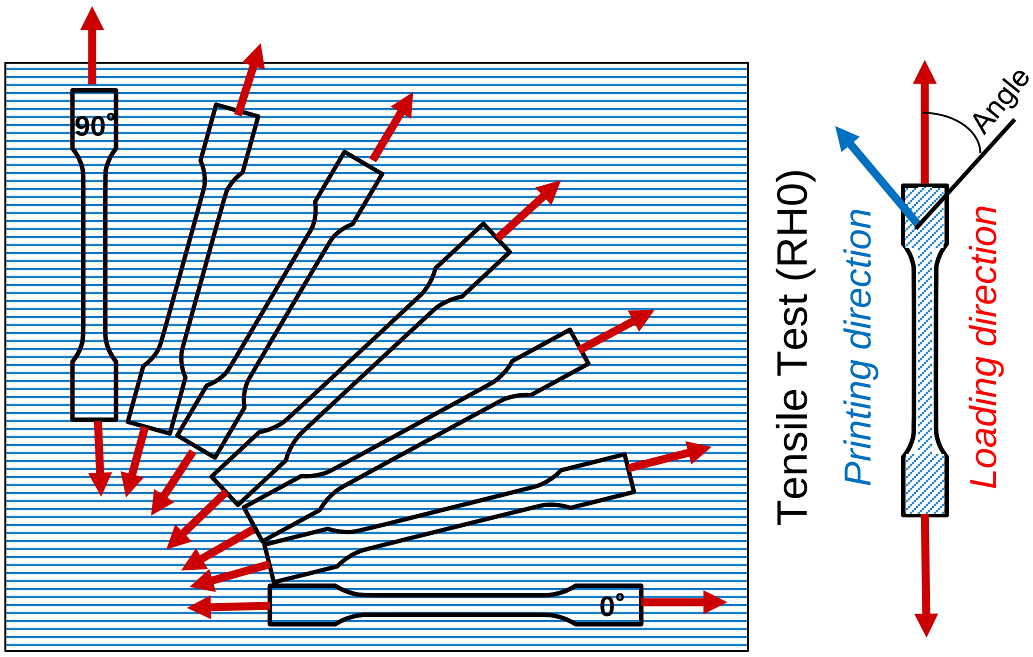
- **Effect of printing direction on:**
  - → Stiffness and stress-strain shape = negligible
  - → Strength (Strain/Stress at Failure) = important

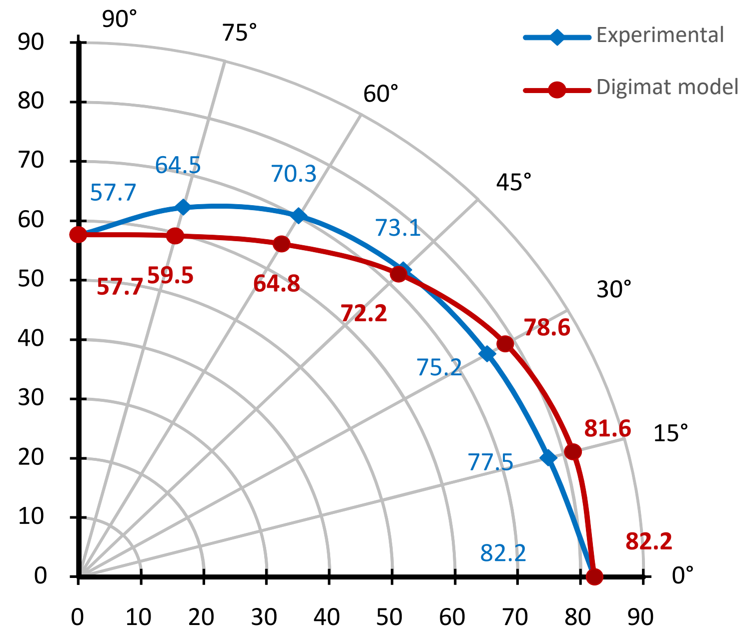
SOLVAY

e-Xstream ENGINEERING MSC Software Company

Multi-Scale Modeling of Sinterline (PA6+40%GB)

- **Modeling failure dependency to printing orientation**





- Tsai-Wu generalized transversely isotropic criterion (stress-based), apply at the composite level.
- Modeling in the gap of measurement : standard deviation max 5.7 MPa.

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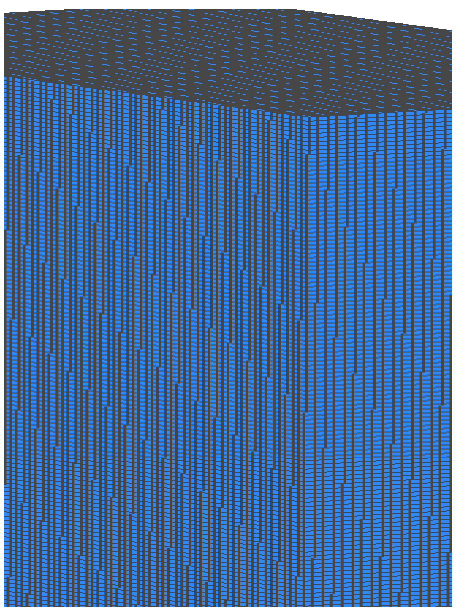
Ultimate failure prediction of a plenum under pressure produced by SLS

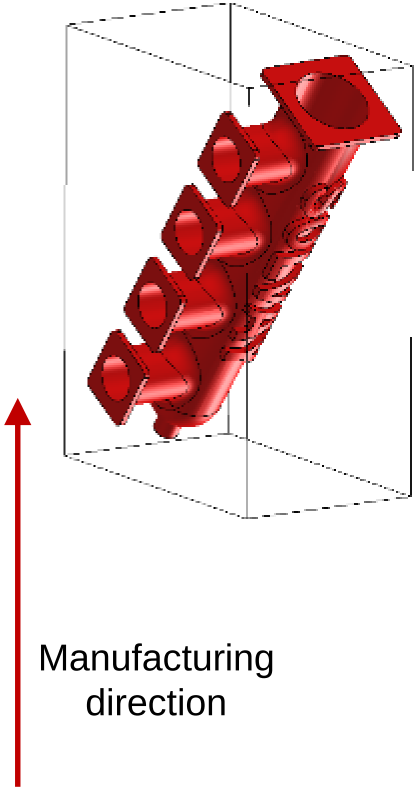
3D printed plenum chamber
of Polimotor 2

Part setup in powder bed

- Neighboring powder is modeled for part support
- A parallelepiped containing the printed part and neighboring powder is generated



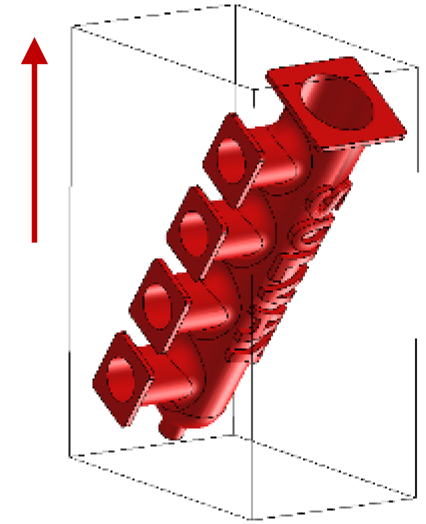
Voxelized RVE

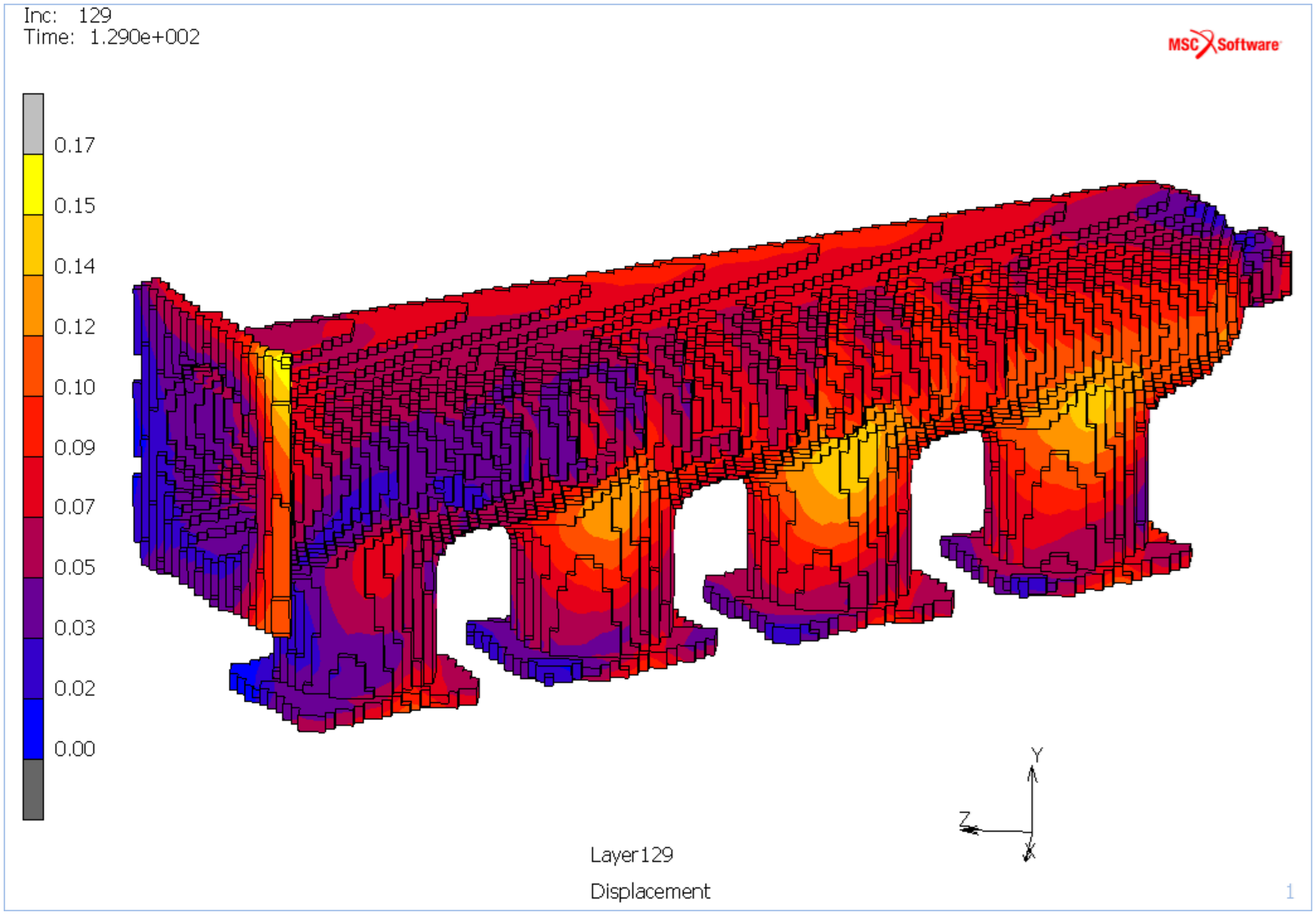


Voxelized Inclusion

Process induced warpage

Manufacturing direction

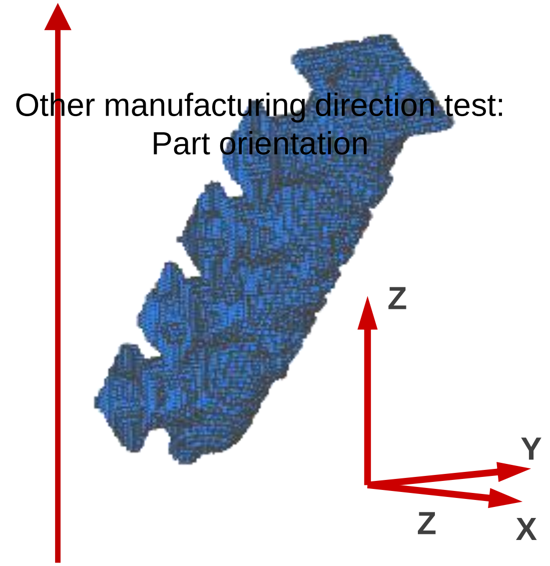




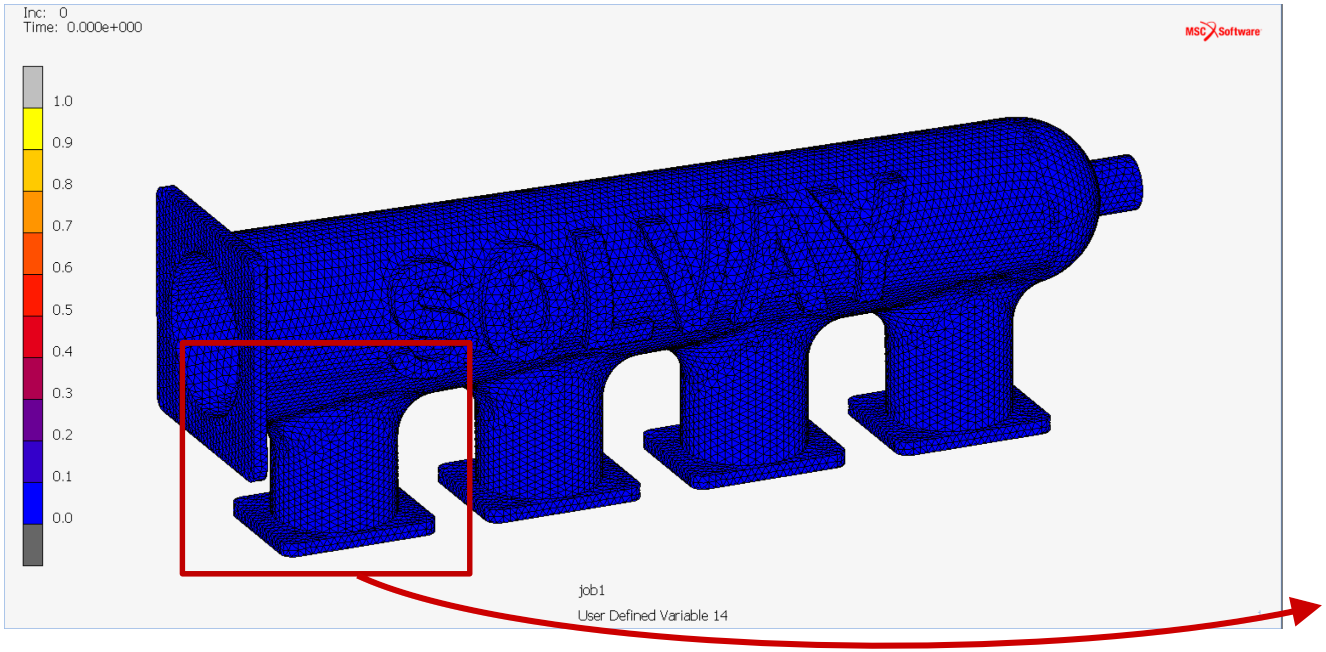
Magnitude of displacement from bed chamber initial position (in mm)

Structural modelling

- **Pressure loading of the plenum chamber until failure**
  - Numerical loading: 9.1 bars → experimental results checked



Manufacturing direction is Z
Rotation around X: 5°
Rotation around Y: 35°



Failure indicator distribution until ultimate failure (MSC Marc)

- **The manufacturing direction is not optimal.**
- **Pressure loading at failure for other manufacturing direction:**
  - X direction: 12.8 bars
  - Y direction: 12 bars
  - Z direction: 8.1 bars

Conclusion

- **A new simulation chain for additive manufacturing of polymers**

Material Engineering	Process Simulation	Structural engineering
Digimat-MF/FE/MX	Digimat-AM	Digimat-MAP/CAE
Mechanical properties	Warped shape	Non-linear stiffness
Thermal properties	Residual stresses	Failure
Electrical properties	Microstructure	

Perspectives

- **Process simulation**
  - Micro-level advanced process simulation with increased polymer physics in Digimat-AM
- **Material and printer database**
  - Continue partnership with material suppliers and printer OEMs
  - More advanced material modeling for lattices, failure, fatigue
- **Digimat-RP for easy and efficient AM part performance simulation**
- **Lightweighting**
  - Dedicated lattice functionalities for lightweighting
  - Connection to topology optimization