Micromechanics Simulation Directly on CT Scans

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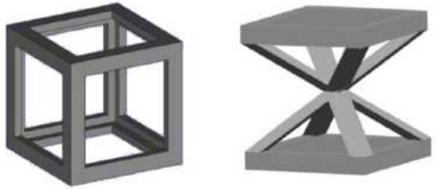
Overview

- **Complex Materials and Components with Defects**
- Mechanical Simulation of Complex Structures
- Industrial Computed Tomography (CT)
- Mechanical Simulation Directly on CT Scans
- Application Examples
- Validation
- Practical Use
- Summary

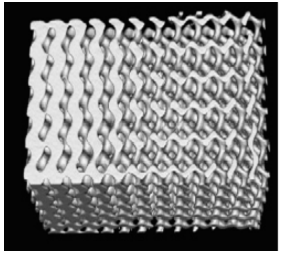
3D Printed Lattice Structures

Material

Periodic



Graded



Applications

- *Structural:* lightweight design with 3D printed components (e.g. aerospace components, orthopedic implants)

Microstructure

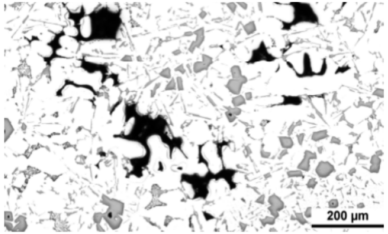
- Different unit cell geometries (e.g. cubic, diamond, dodecahedron, truncated cuboctahedron, gyroid)
- Pore sizes typically 500 – 1000 µm
- Strut sizes typically 100 – 500 µm

Images: D. Mahmoud, M. Elbestawi: Lattice Structures and Functionally Graded Materials: Applications in Additive Manufacturing of Orthopedic Implants: A Review. J. Manuf. Mater. Process. 2017, 1, 13; doi: 10.3390/jmmp1020013

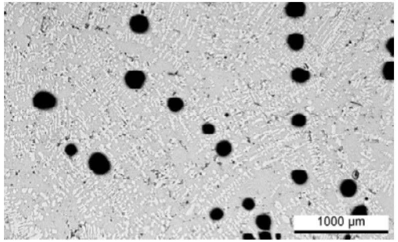
Microporosity in Cast (Al) Components

Material

Shrink Holes



Gas Pores



Applications

- *Functional:* powertrain components, e.g. motor blocks, cylinder heads
- *Structural:* vehicle chassis and body components

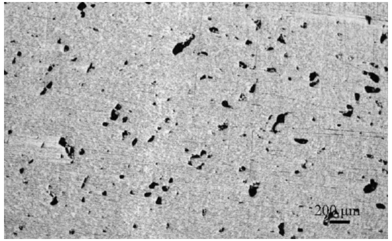
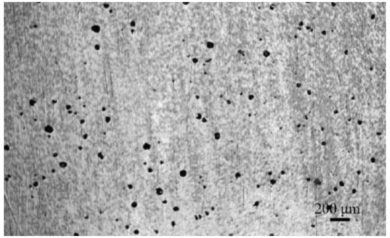
Microstructure

- Porosity resulting from inhomogeneous shrinkage during solidification
- Pores with irregular shapes and lengths of up to ≈ 1000 µm
  (> 500 µm := macroporosity)

- Porosity resulting from gas evaporation from the melt, sand cores (non-spherical) or from inclusion of external gases (spherical)
- Evenly distributed across larger areas
- Diameters of up to ≈ 300 µm

Images: BDG Richtlinie P202: Volumendefizite von Gussstücken aus Aluminium-, Magnesium- und Zinkgusslegierungen. Stand September 2010.

Porosity in 3D Printed Metal Components

Material	Applications	Microstructure
Irre-gu-lar 		▪ Porosity of ≈ 1 - 3 % resulting from incomplete melting ▪ Pores with irregular shapes and lengths of ≈ 25 - 250 µm
	▪ *Structural:* aircraft, aerospace, automotive components, medical implants, …	
Sphe-ri-cal 		▪ Porosity of ≈ 1 - 3 % resulting from excessive energy / speed (leading to evaporation of hydrogen or metal) ▪ Near spherical pores with diameters ≈ 25 - 100 µm

Images: http://www.insidemetaladditivemanufacturing.com/blog/how-do-slm-process-defects-impact-ti64-mechanical-properties

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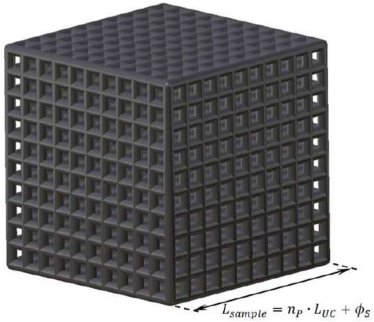
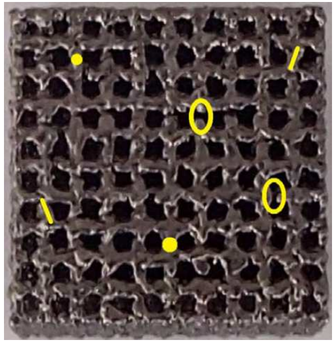
FEM Simulation of Lattice Structures

- FEM simulation typically **overestimates stiffness by 10-30%** compared to experimental measurements due to neglection of manufacturing deviations (strut diameter variation, strut inclination, fractured struts) [1]
- In principle, such manufacturing deviations can be taken into account in FEM [2]
- However: Low practicability due to high effort:





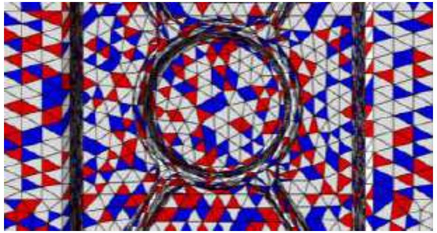
- "Although these methods will reduce the significant gap between numerical and experimental results if successfully applied, the application of such methods on different unit cells **requires significant dimensional characterization and may be challenging to achieve**" [1]

[1] D. Mahmoud, M. Elbestawi: Lattice Structures and Functionally Graded Materials: Applications in Additive Manufacturing of Orthopedic Implants: A Review. J. Manuf. Mater. Process. 2017, 1, 13; DOI: 10.3390/jmmp1020013
[2] F. Quevedo Gonzalez: Finite element modeling of manufacturing irregularities of porous materials. Biomaterials and Biomechanics in Bioengineering. Vol. 3, No. 1 (2016) 1-14. DOI: 10.12989/bme.2016.3.1.001. Images from [2]

Mechanical FEM Simulation Including Porosity

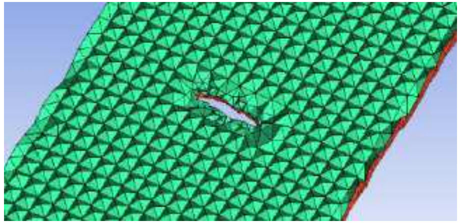
Various approaches (examples) – none of which exactly represents locations and shapes of all pores

Stochastic Distribution [1]



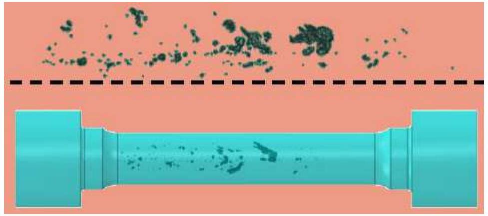
- Stochastic assignment of 3 aggregate porosity levels (e.g. 0 / 2 / 20%) and corresponding material parameters to the cells of an FEM model
- – Individual pores not captured at all

One Pore Only [2]



- + (surface → volume) mesh represents pore location and shape
- + Validated by experiments
- – but only for one large pore (d = 3050 µm, h = 580 µm)

Lego Brick Model [3]



- + includes larger pores and their locations
- – but only as coarse “lego brick model” with large voxel size (400 or 100 µm), potentially leading to stress artefacts

[1] FAT (2015): Modellierung der Einflüsse von Porenmorphologie auf das Versagensverhalten von Al-Druckgussteilen mit stochastischem Aspekt für durchgängige Simulation von Gießen bis Crash. FAT Schriftenreihe 277.

[2] F. Esposito (2016): Structural Simulation of Real Defects with Industrial Computed Tomography. International CAE Conference 2016, Parma

[3] P. Tempel, C. Eichheimer (2017): Digitalisierung von komplexen Volumendefektverteilungen am Beispiel von Stahlguss für die Festigkeitsbewertung unter quasi-statischer Zugbeanspruchung.

Limitations of FEM Simulations

STOP High Effort

- High effort required for the generation of geometry-conforming meshes, if possible at all
- High computational cost

↔

STOP Approximation Errors

- Errors associated with approximation of irregular surfaces with regular geometries (eg. tetra-hedrons, pyramids, hexahedrons, …)

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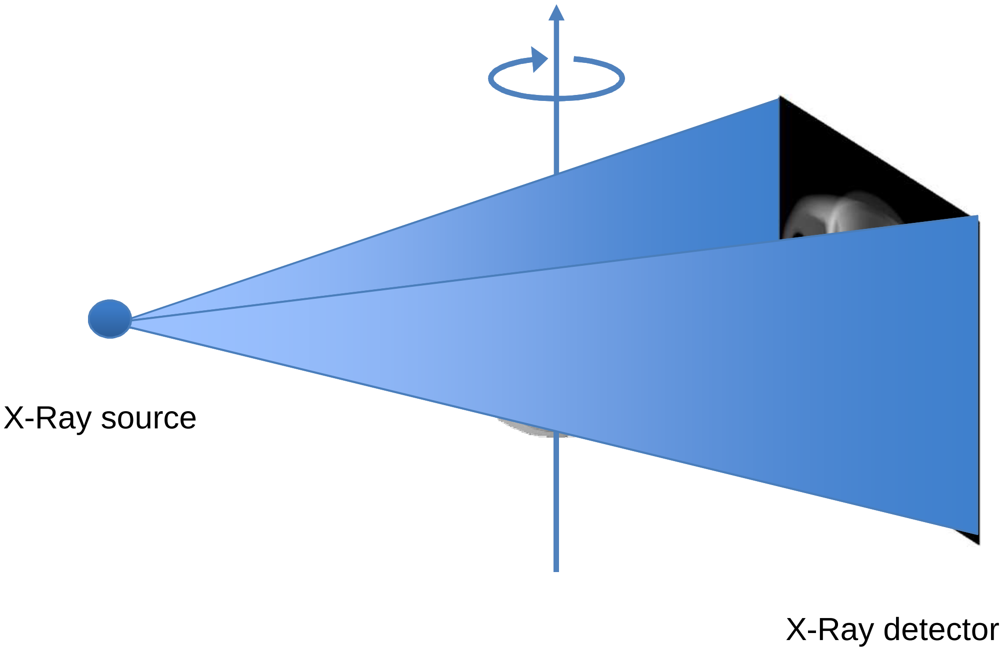
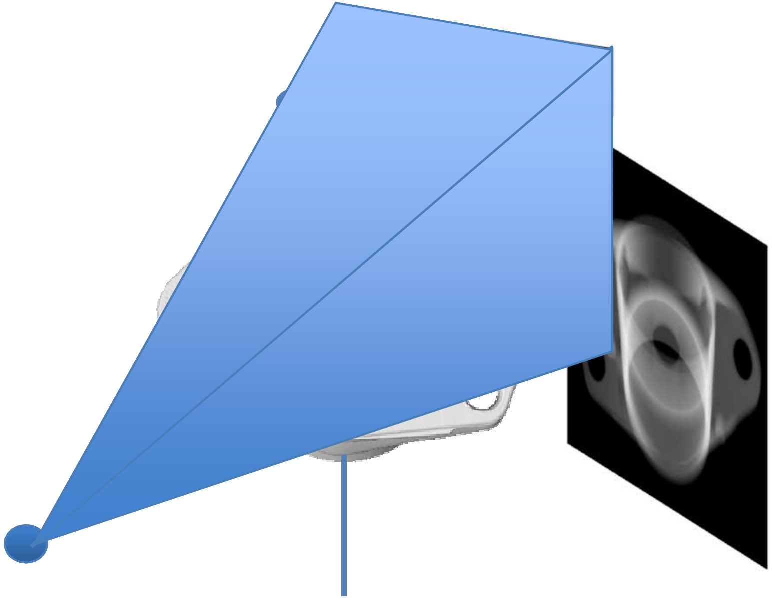
Industrial X-Ray Computed Tomography (CT)



Industrial X-Ray Computed Tomography (CT)



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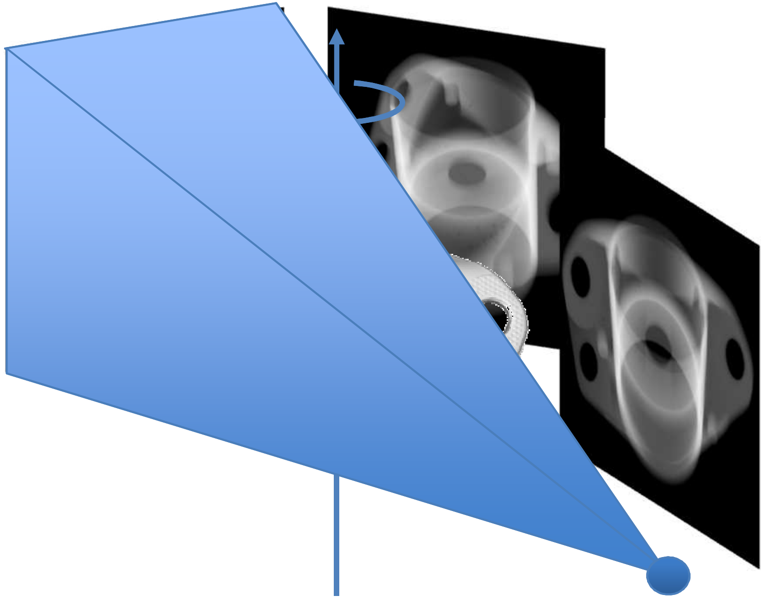

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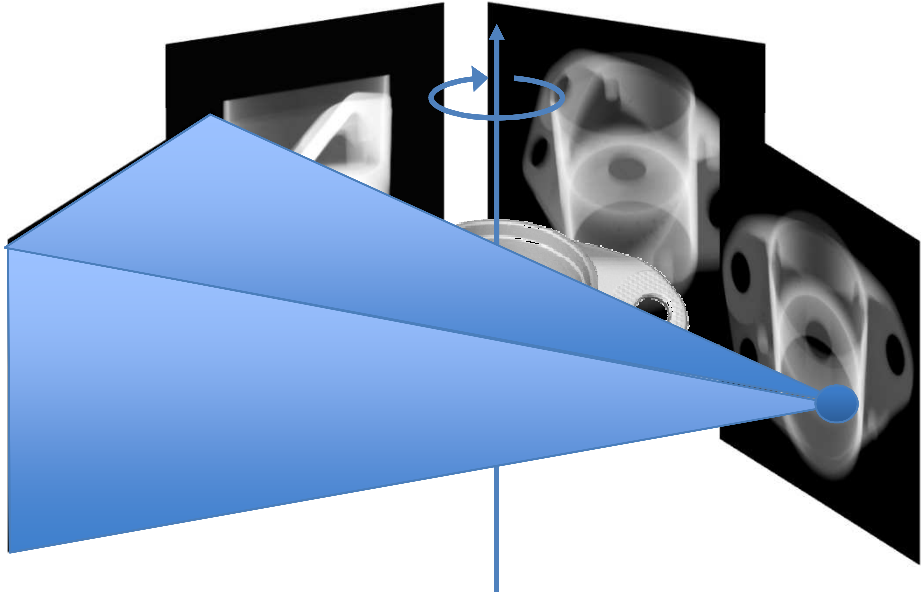

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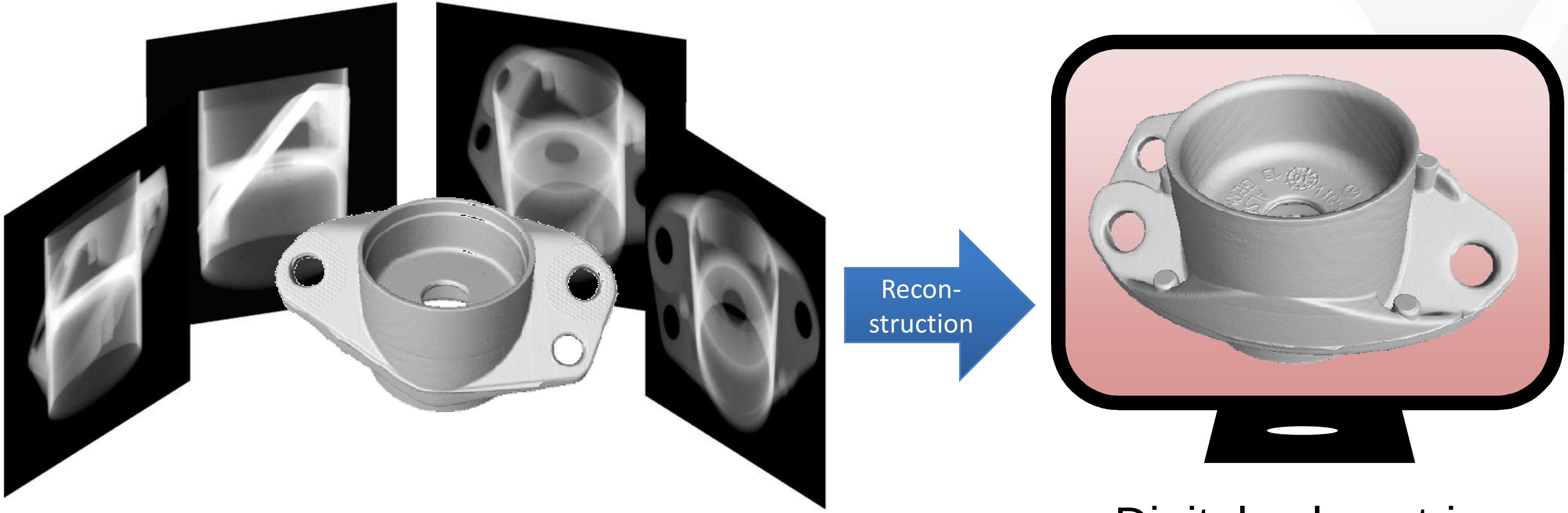
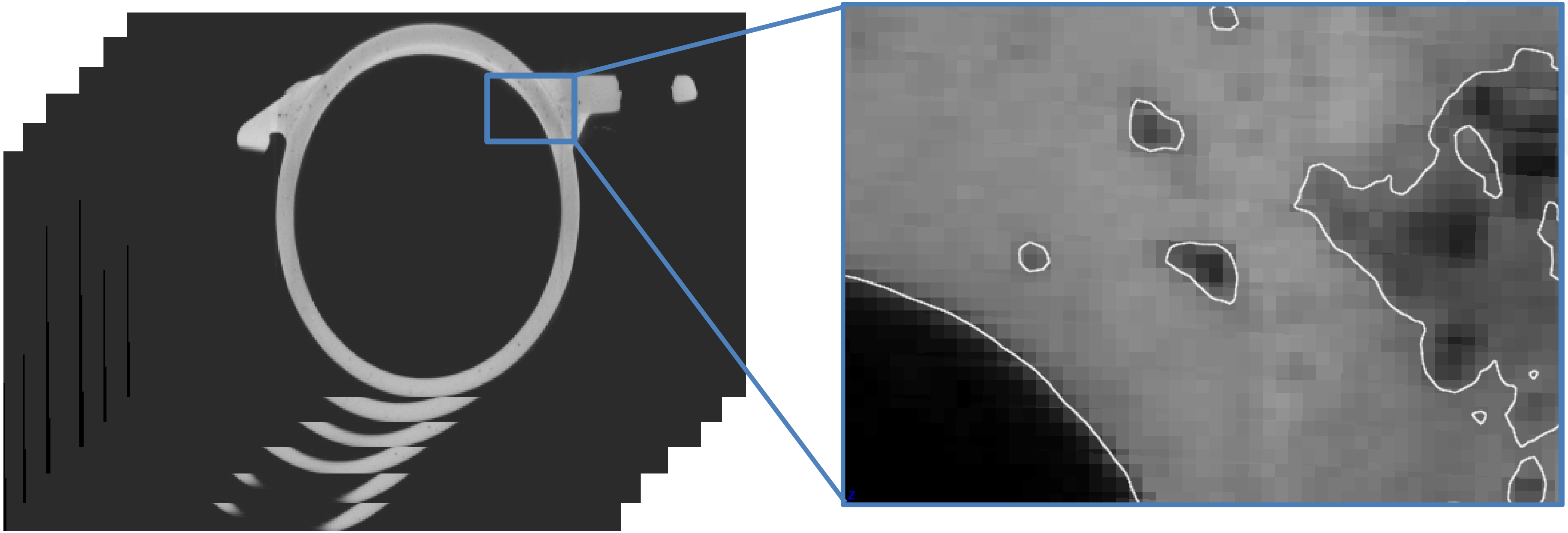


Digital volumetric representation of scanned part

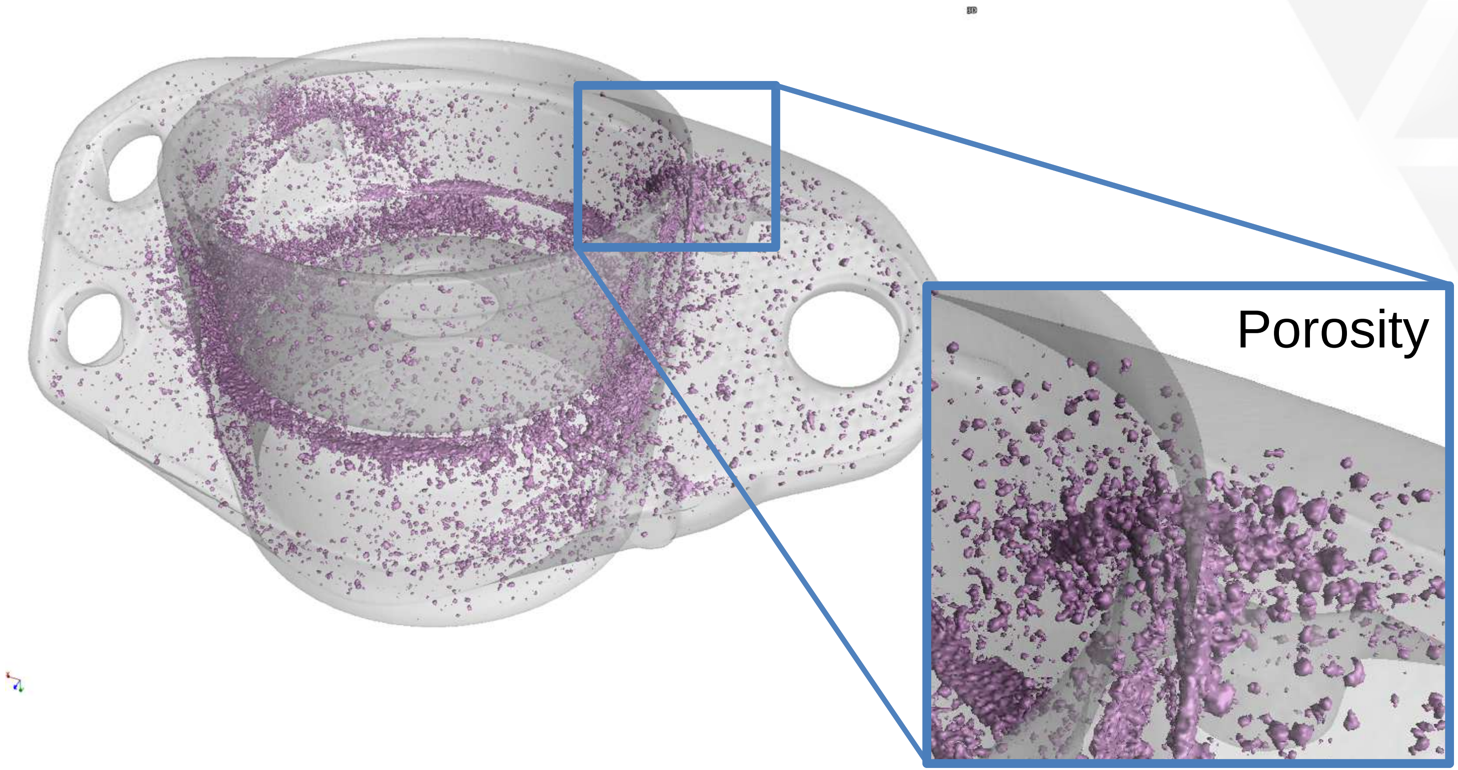
Segmentation of All (Internal and External) Surfaces



CT image data

Determined surface

Accurate Representation of Complex Geometry



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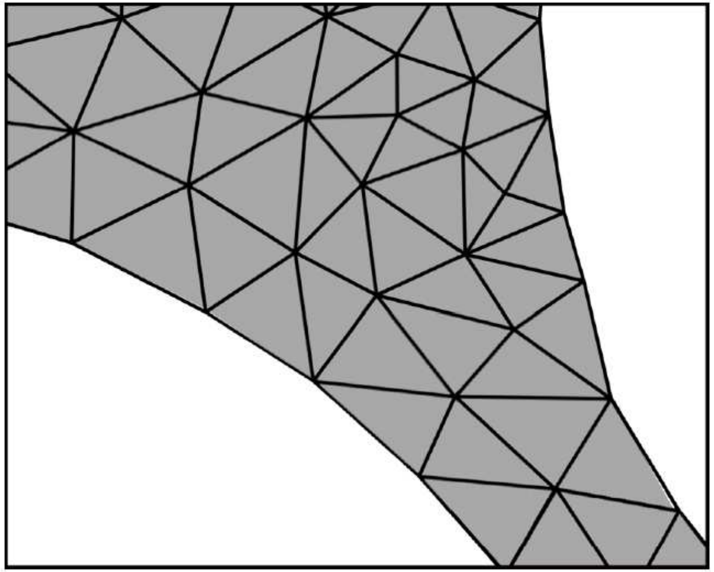
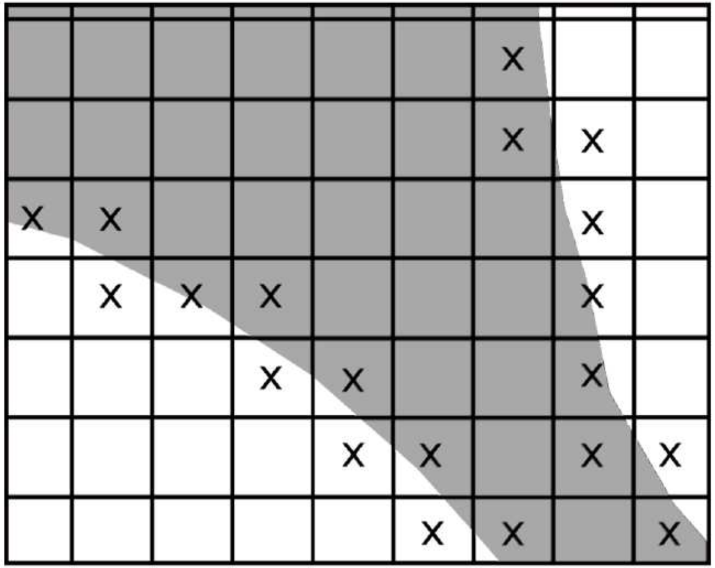
Immersed Boundary Method

Classical FEM

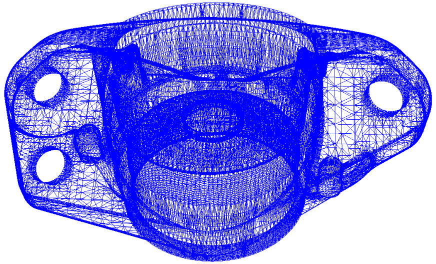


Immersed Boundary



Immersed-boundary FEM in VGSTUDIO MAX

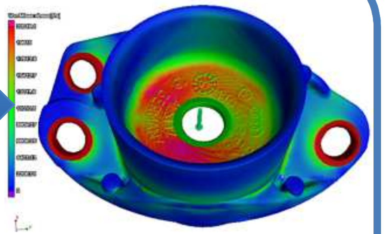
CT Scan



3D surface models (CAD, STL)

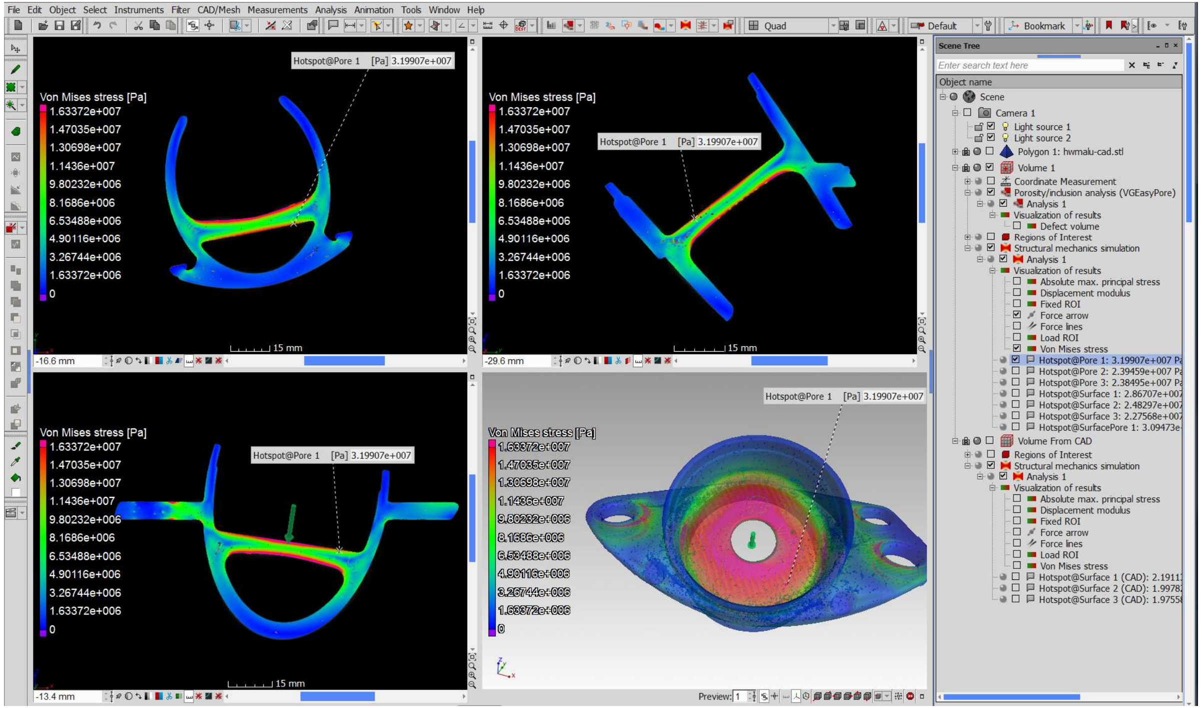
Surface segmentation

Immersed boundary solver



VOLUME GRAPHICS VGSTUDIO MAX

Immersed-boundary FEM in VGSTUDIO MAX



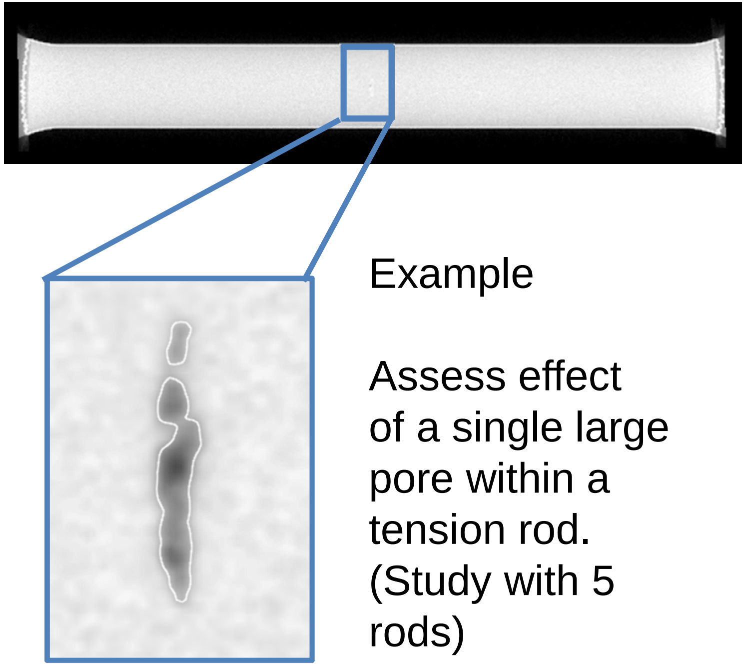
Structural mechanics

- Static load cases (force, torque, pressure)
- Linear elastic material behavior
- Supports distributed computing

No meshing required!

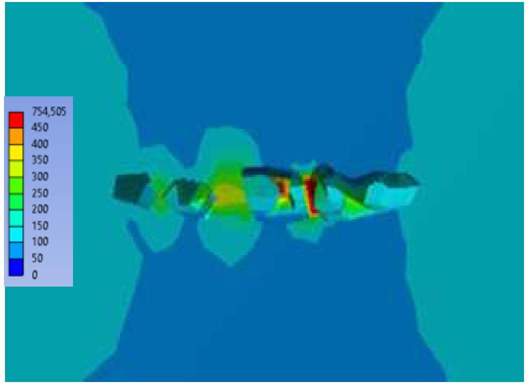
Example: Tension Rod with just 1 Pore

Comparison between classical FEM and immersed boundary FEM

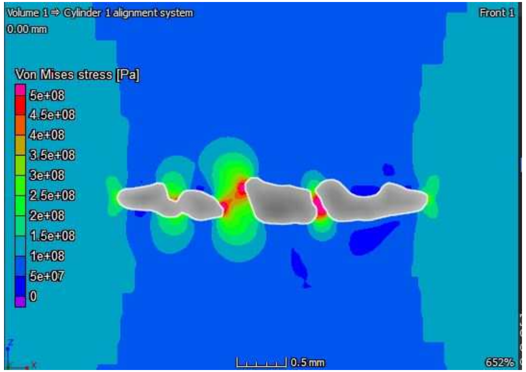


Example

Assess effect of a single large pore within a tension rod. (Study with 5 rods)



ANSYS
- CT -> STL
- Volume meshing (1 h)
- Solve (5 min)



VGSTUDIO MAX
- Solve (13 min)

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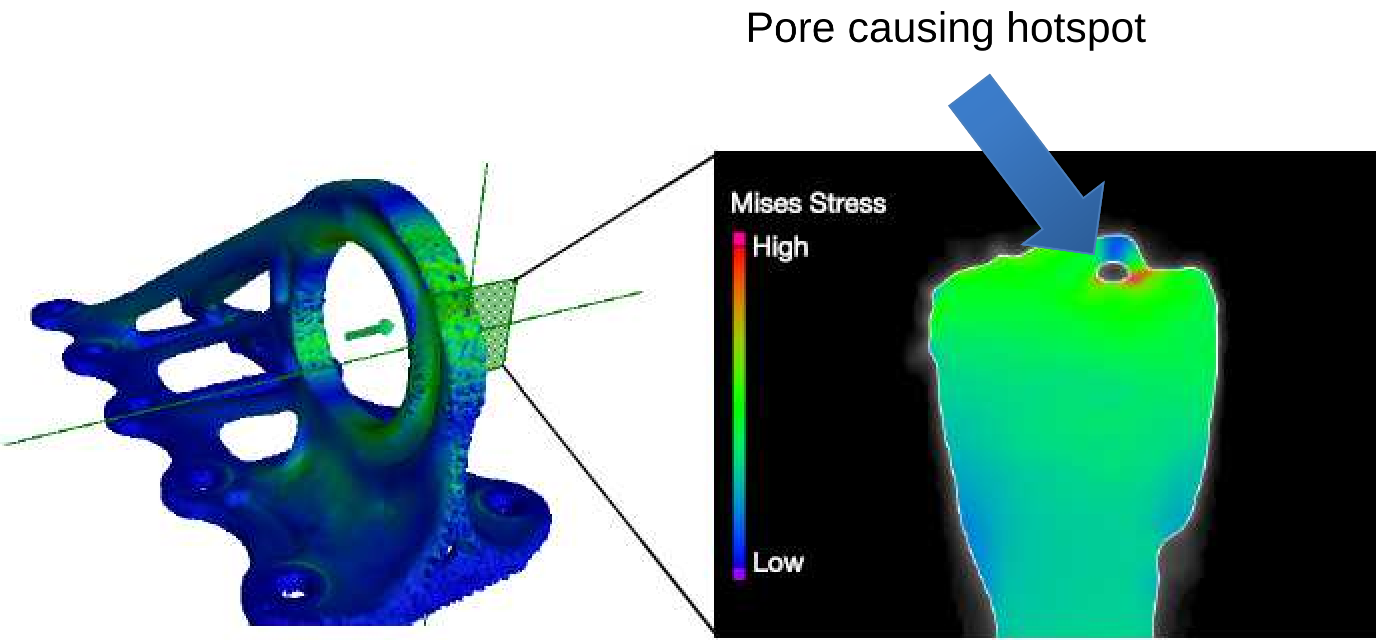
Example: 3D Printed Component with Pores (1)

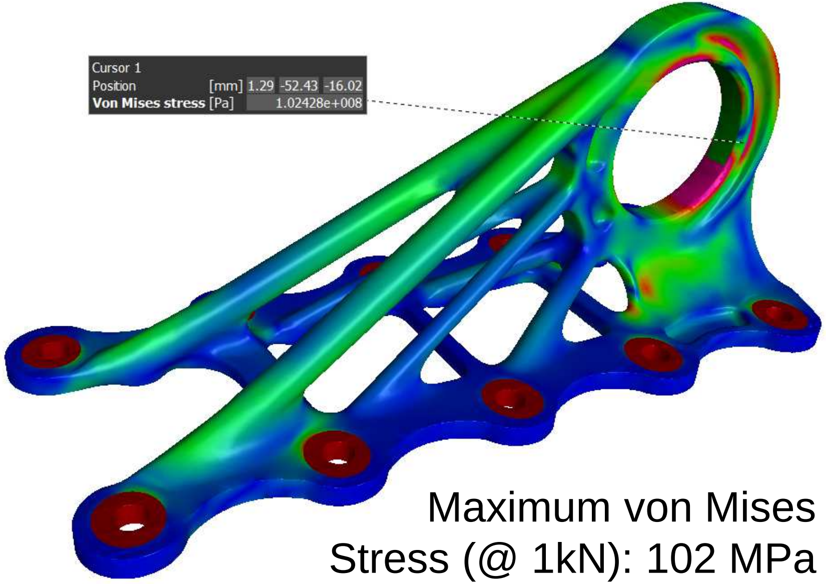
Stress concentration caused by a pore



Example: 3D Printed Component with Pores (2)

Distribution on Ideal vs. Real Component

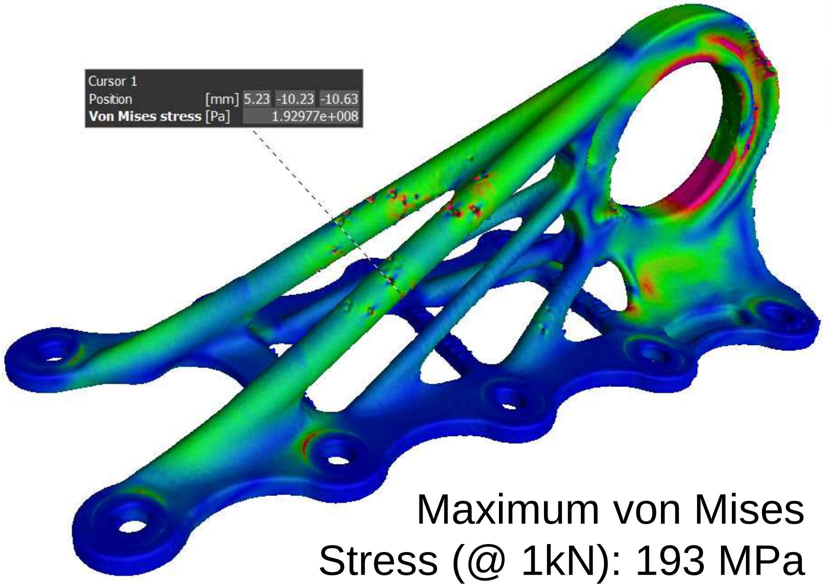
CAD



Maximum von Mises
Stress (@ 1kN): 102 MPa

CT Scan

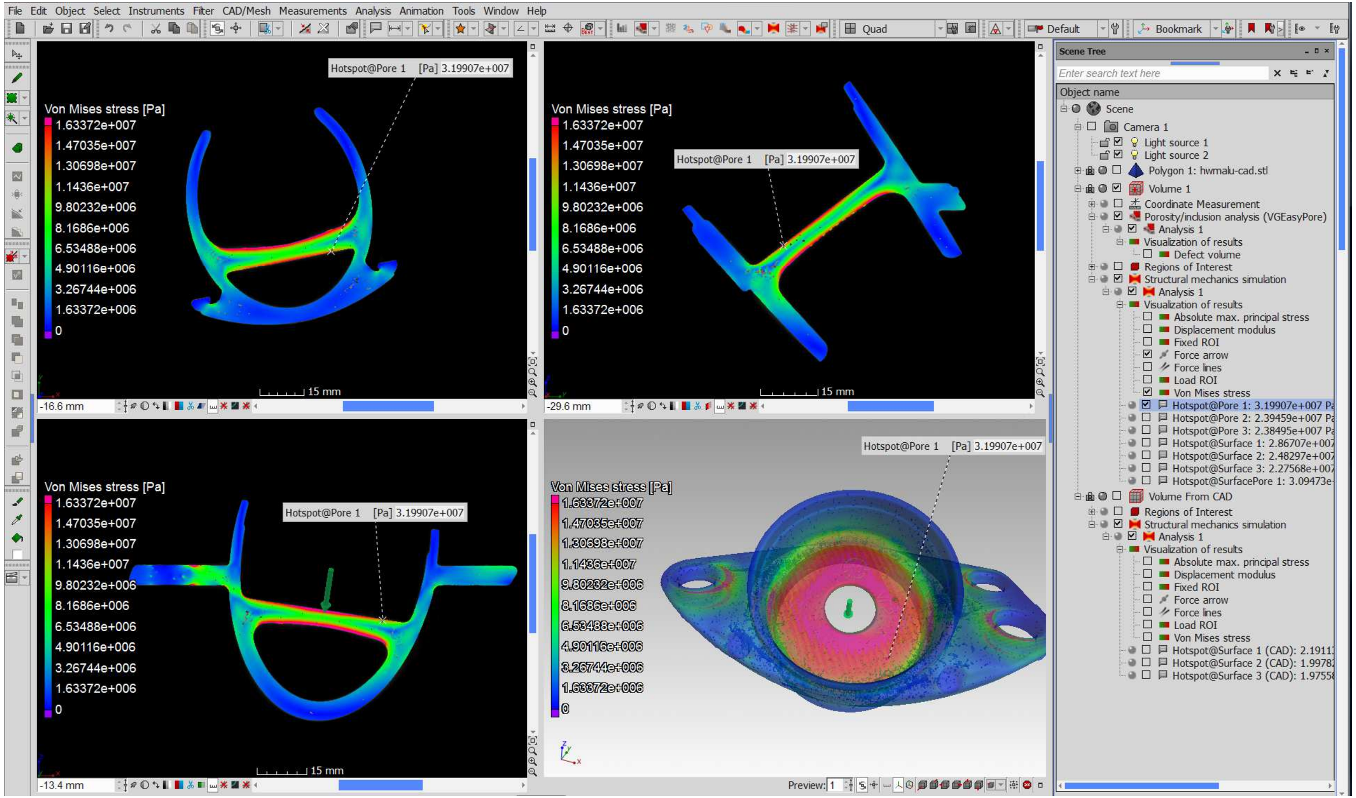
(or result of process simulation)



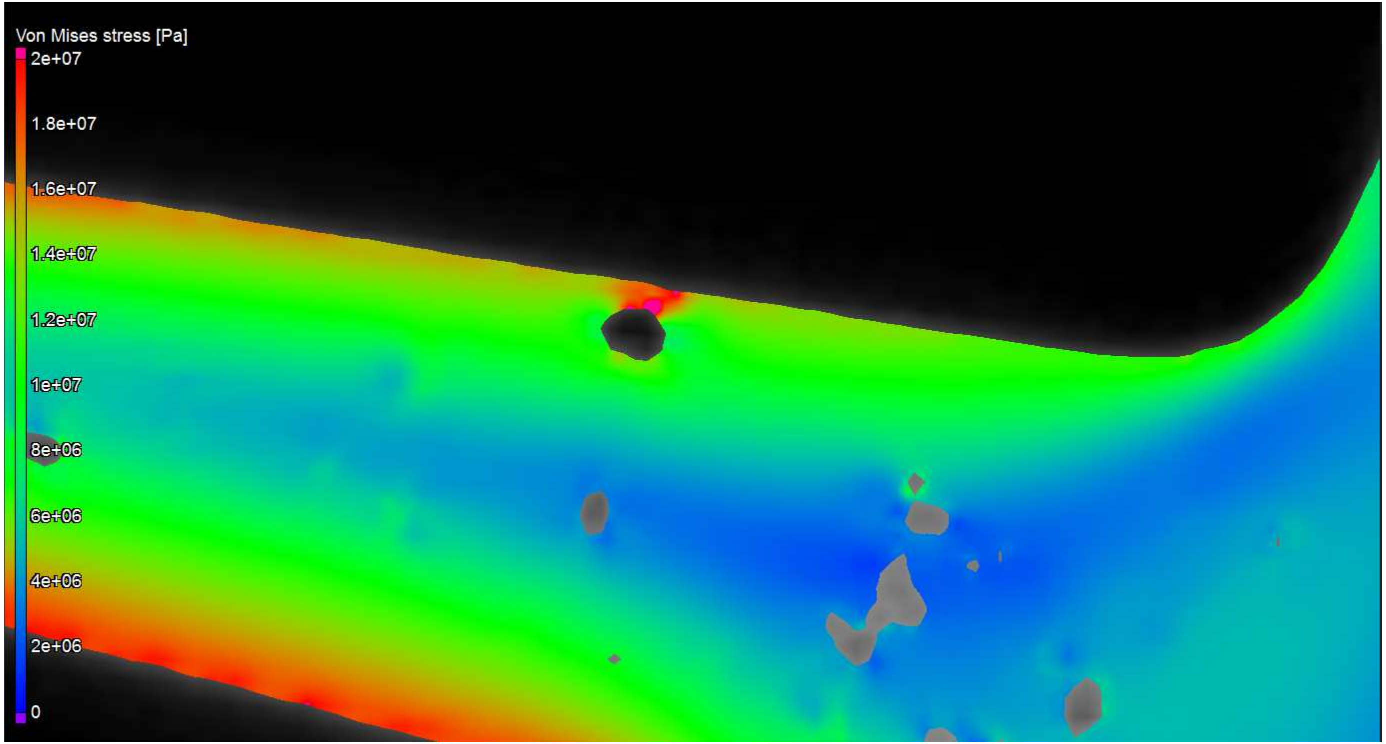
Maximum von Mises
Stress (@ 1kN): 193 MPa
(+ 89%)

Example: Cast Al Part with Porosity (1)

Structural Mechanics Simulation taking the porosity and shape deviations into account



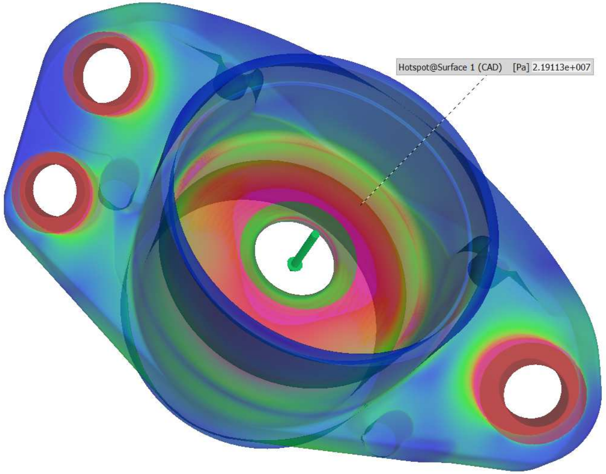
Stress Concentration Around Pores



Example: Cast Al Part with Porosity (2)

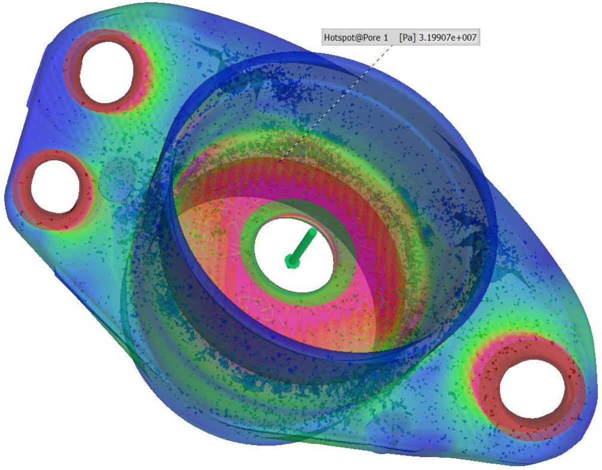
Stress Distribution on Ideal vs. Real Component

CAD



Maximum von Mises Stress (@ 1kN): 22 MPa

CT Scan

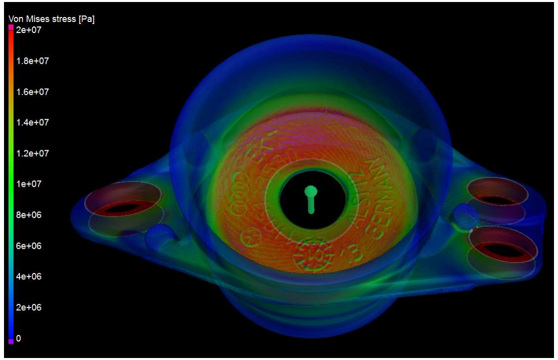


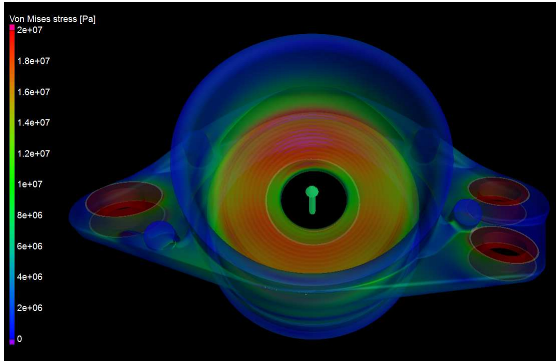
Maximum von Mises Stress (@ 1kN): 32 MPa **(+ 45%)**

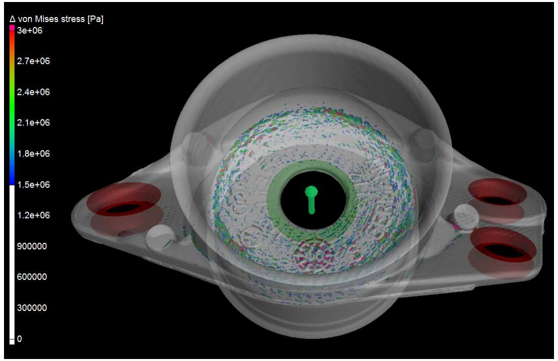
Comparison with Reference Simulation

- Calculate and visualize differences in results to a reference simulation

Stress on CT Scan - **Stress on CAD** = **Δ Stress from Defects**

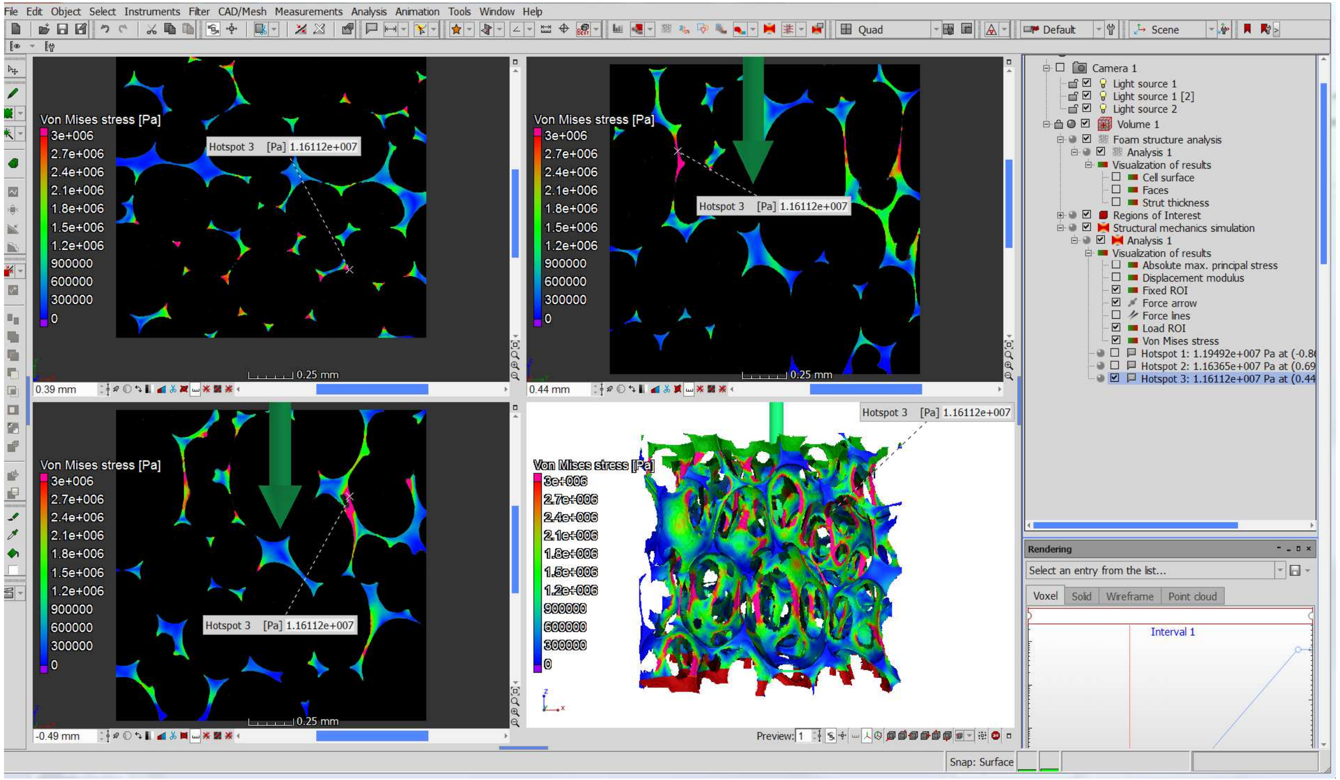






Example: Foam Structure (1)

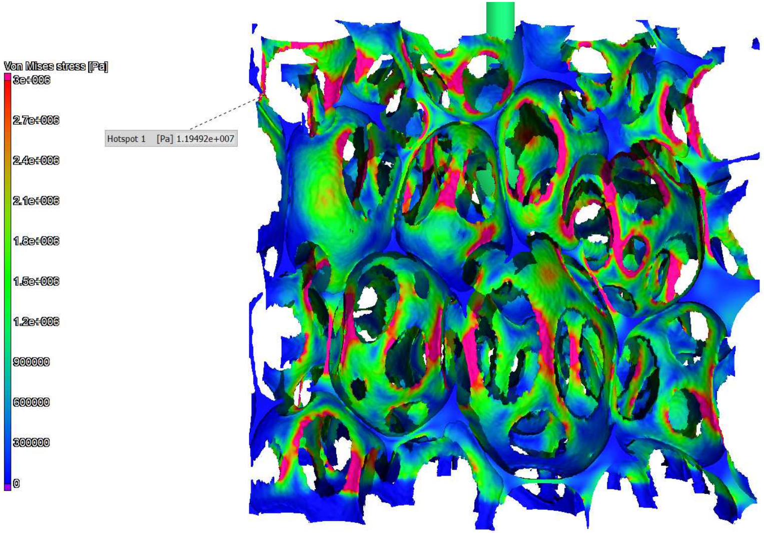
Mechanics Simulation of a Foam Structure Material Probe



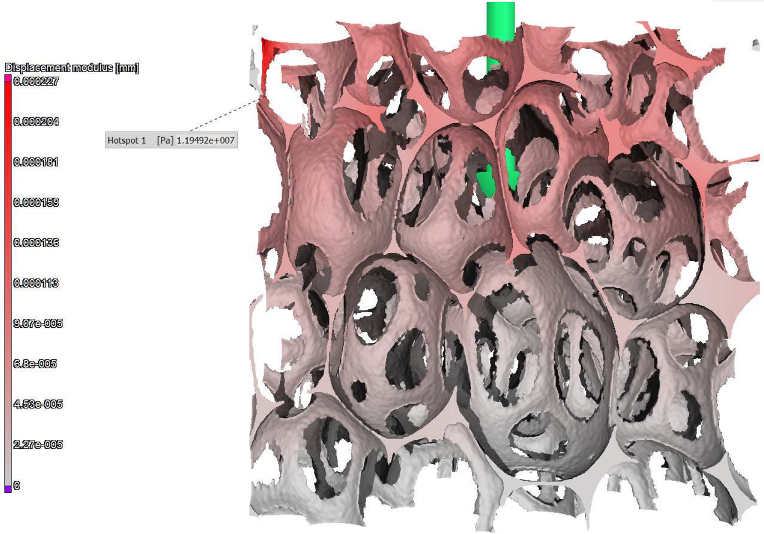
Example: Foam Structure (2)

Effective Young's Modulus

Stress Field



Displacement Field



→ Effective Young's Modulus

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Validation Experiments: Test Specimen

A—250A (specimen 1 of 3)

B—125A (specimen 1 of 3)

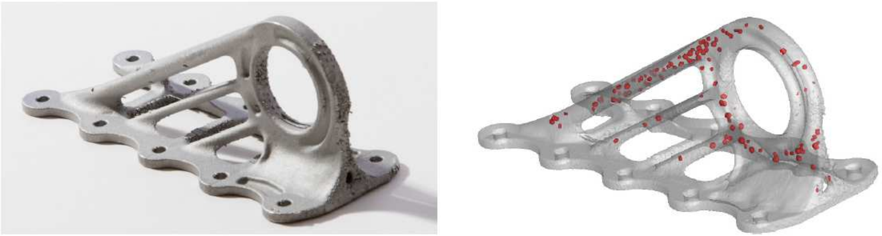
C—75A (specimen 1 of 3)

18 Tension Rods

(3D printed AlSi10Mg, d = 5 mm, l = 50 mm
3 samples each with 75 / 125 / 250 pores
in 2 different random distributions A / B)

18 Aeronautic Brackets

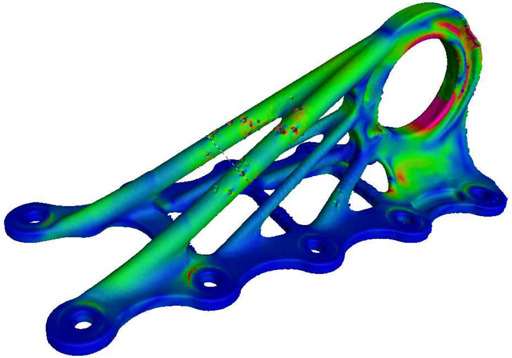
(3D printed AlSi10Mg, 75 x 30 x 30 mm
3 samples each of 6 different pore distributions)



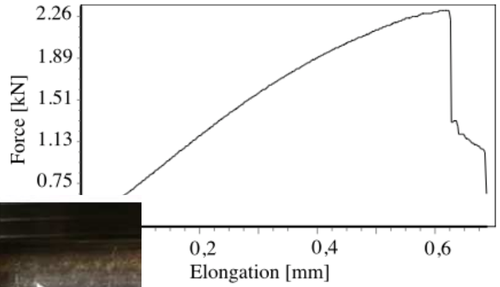
D—250C (specimen 1 of 3)

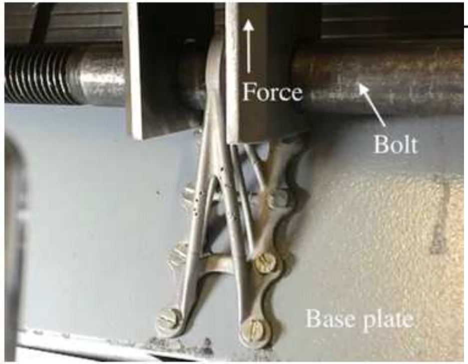
E—Bars200 (specimen 2 of 3)

Validation Study



Immersed boundary FE simulation





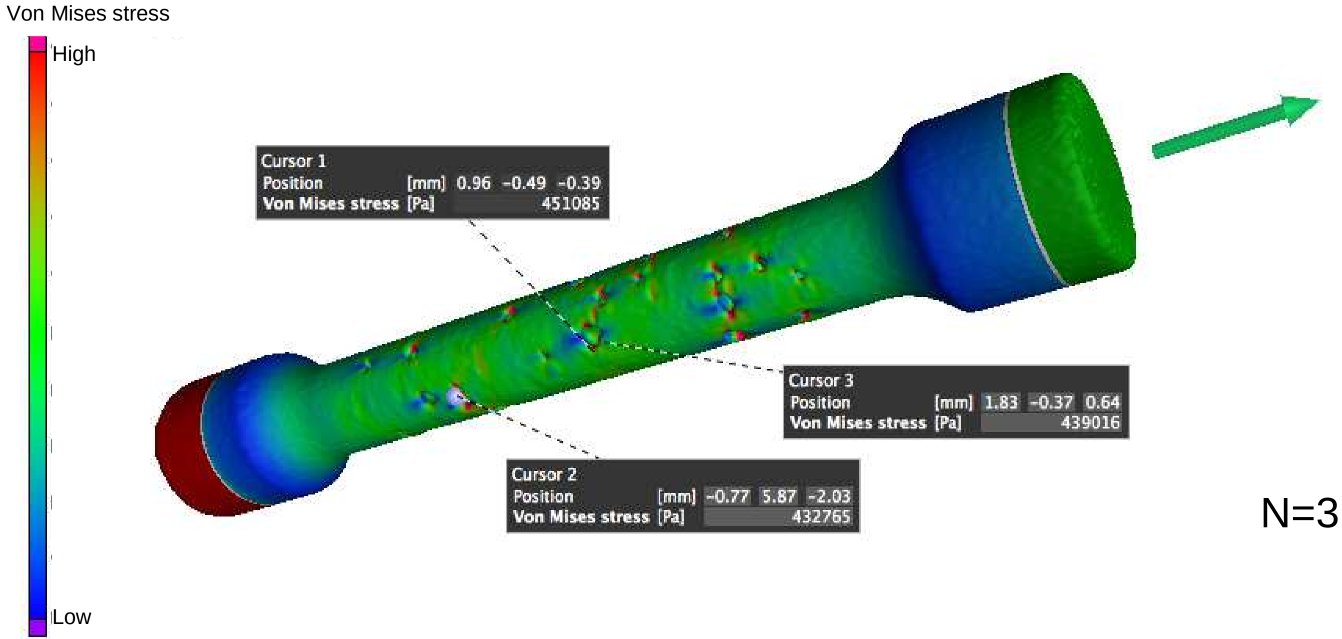
Quasi-static destructive test

Validation Details

Find largest N local maxima of von Mises stress: $\sigma_1 (=\sigma_{max}),\ \sigma_2,\ \ldots\ ,\sigma_N$

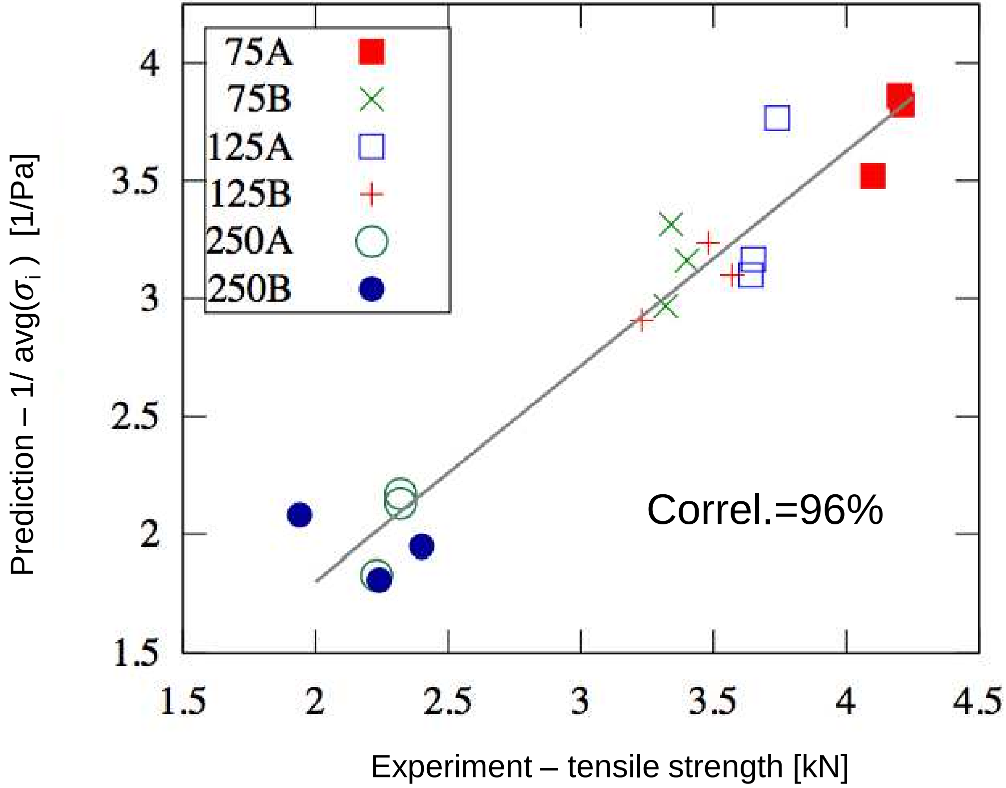
Predictions:

- First crack occurs at either one of these positions
- Ultimate strength $\propto$ 1 / ($\Sigma\sigma_i$ / N)

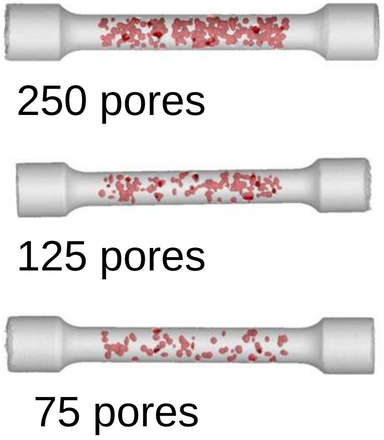


N=3 in this study

Results: Prediction of Tensile Strength

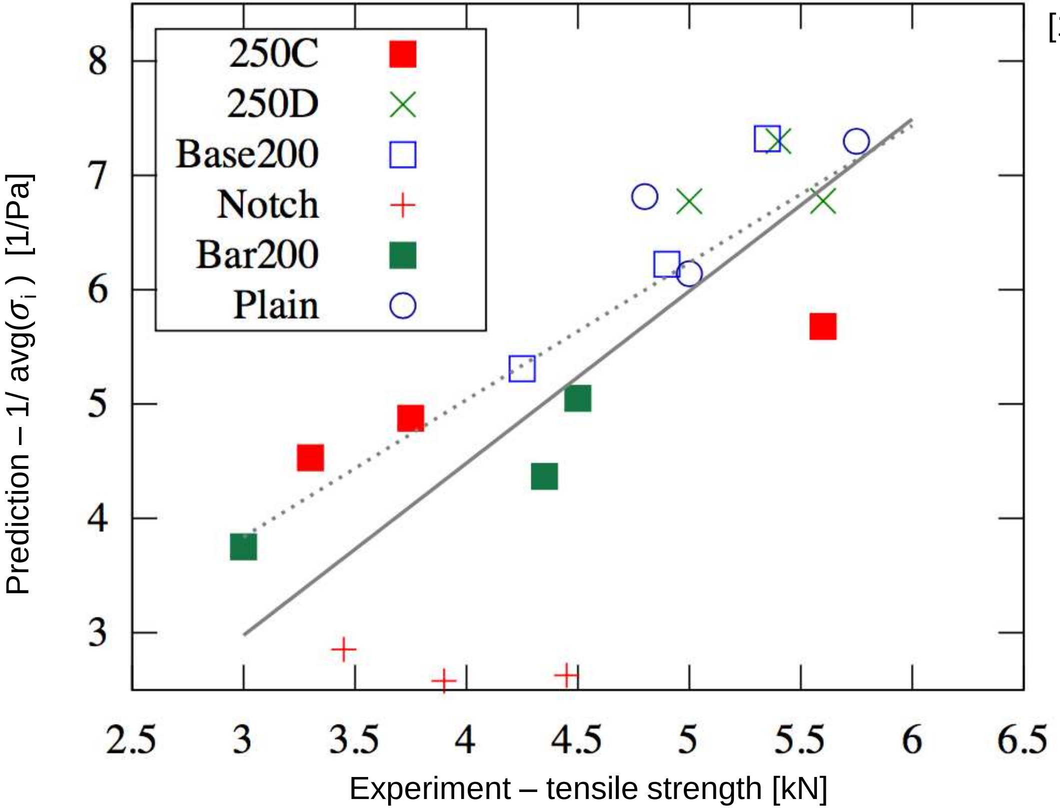


[1]



[1] Fieres et al: Predicting failure in additively manufactured parts using X-ray computed tomography and simulation, 7th intl. conf. fatigue design 2017

Results: Prediction of Tensile Strength

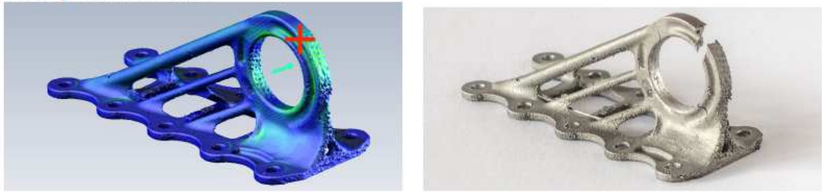


[1]

[1] Fieres et al: Predicting failure in additively manufactured parts using X-ray computed tomography and simulation, 7th intl. conf. fatigue design 2017

Simulation vs. Experiment (2): Crack Locations

250C, specimen 1 of 3, HS_1

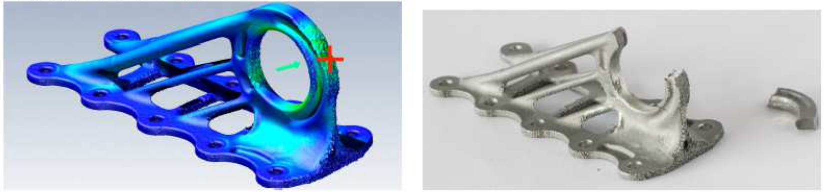


Base200, specimen 2 of 3, HS_2

Notch, specimen 2 of 3, HS_1 and HS_2

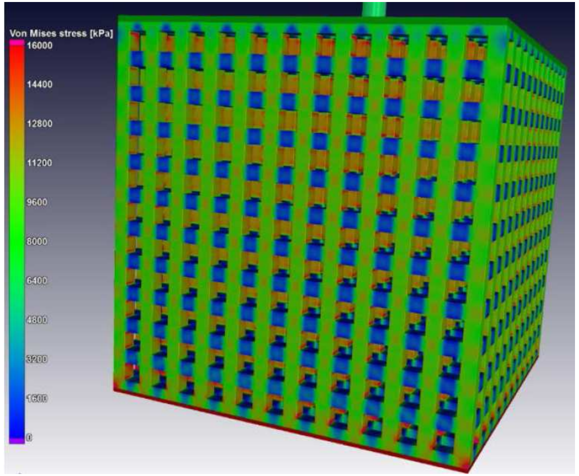
Bar200, specimen 2 of 3, HS_1

Plain, specimen 3 of 3, HS_1



- 12 of 18 specimen cracked at hot spot 1 or 2
- 3 specimen cracked at one of the top 10 hotspots
- 3 specimen cracked elsewhere

Validation Against Classical FEM Simulation



- 20x20x20 mm cubic lattice
- 12 struts of 0.75 mm width and 1 mm spacing between them in every direction
- 57.58 % porosity
- Material parameters of Ti6Al4V (Young's modulus 115 Gpa, Poisson ratio 0.3)
- 1 kN compressive load
- FEM Simulation with Autodesk Fusion 360 (tetrahedral elements, Nastran solver)
- Voxel based simulation with VGSTUDIO MAX

	Ashby-Gibson model	Traditional FEM Autodesk Fusion 360	Voxel-based FEM VGStudioMax
Effective Young's Modulus (GPa)	20.7	28.3	27.6
Max Von Mises stress (MPa)	N/A	16.2	15.8

Source: A. du Plessis et.al: Selection of lattice design for medical implants by additive manufacturing. ASME J. Mech. Design, 2018, submitted

Overview

- Complex Materials and Components with Defects
- Mechanical Simulation of Complex Structures
- Industrial Computed Tomography (CT)
- Mechanical Simulation Directly on CT Scans
- Application Examples
- Validation
- **Practical Use**
- Summary

Practical Use in R&D and Quality Assurance

R&D

(1) Simulate stress distribution $\sigma_{CAD}(\underline{x})$ for CAD model

(2) Simulate stress distribution $\sigma_{CT}(\underline{x})$ for CT scans of early prototypes*

(3) Compare hotspots:

$$\max \sigma_{CT}(\underline{x}) >> \max \sigma_{CAD}(\underline{x}) \ ?$$

→ if yes: change manufacturing process or design
→ if no: OK

Quality Assurance

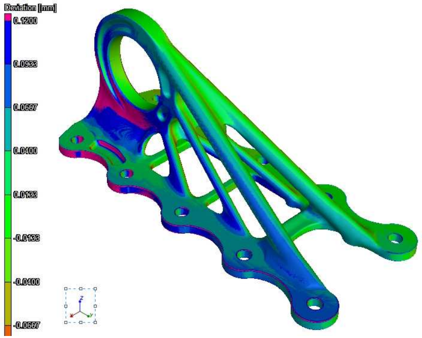
(1) Simulate stress distribution $\sigma_{CAD}(\underline{x})$ for CAD model

(2) Include hotspots of stress distribution $\sigma_{CT}(\underline{x})$ for CT scans of samples from production* in QA criteria (e.g. in pore specifications)

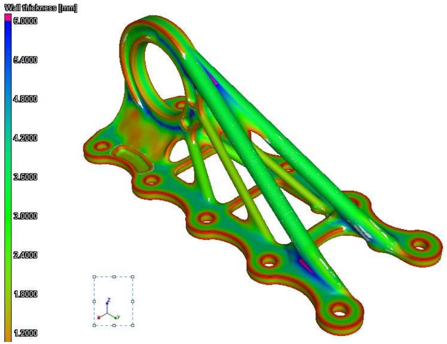
$$\max \sigma_{CT}(\underline{x}) <\approx \max \sigma_{CAD}(\underline{x}) \ !$$

* Focusing on potentially critical regions of interest if necessary

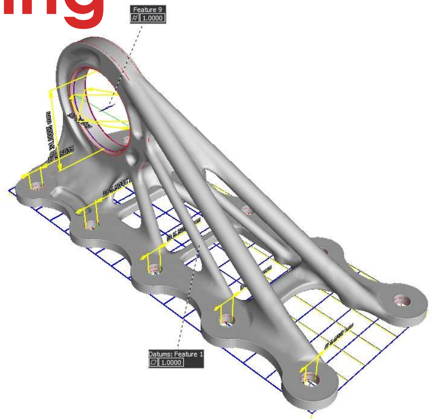
CT for Quality Assurance in 3D Printing



Nominal/Actual Comparison

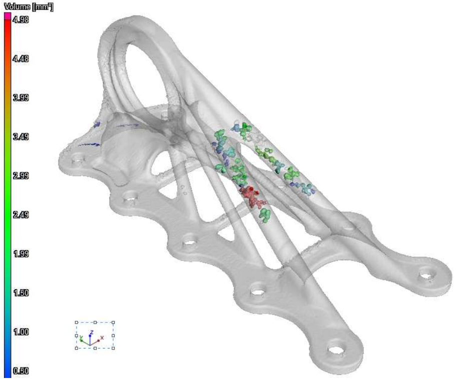


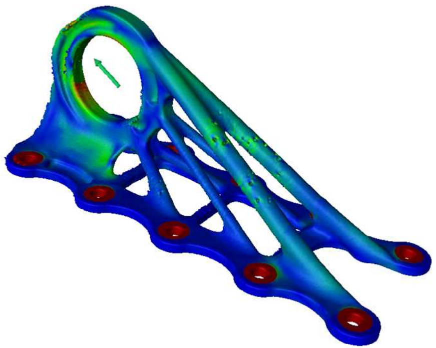
Wall Thickness Analysis



Coordinate Measurement

Porosity Analysis





Mechanical Simulation

Overview

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- Application Examples
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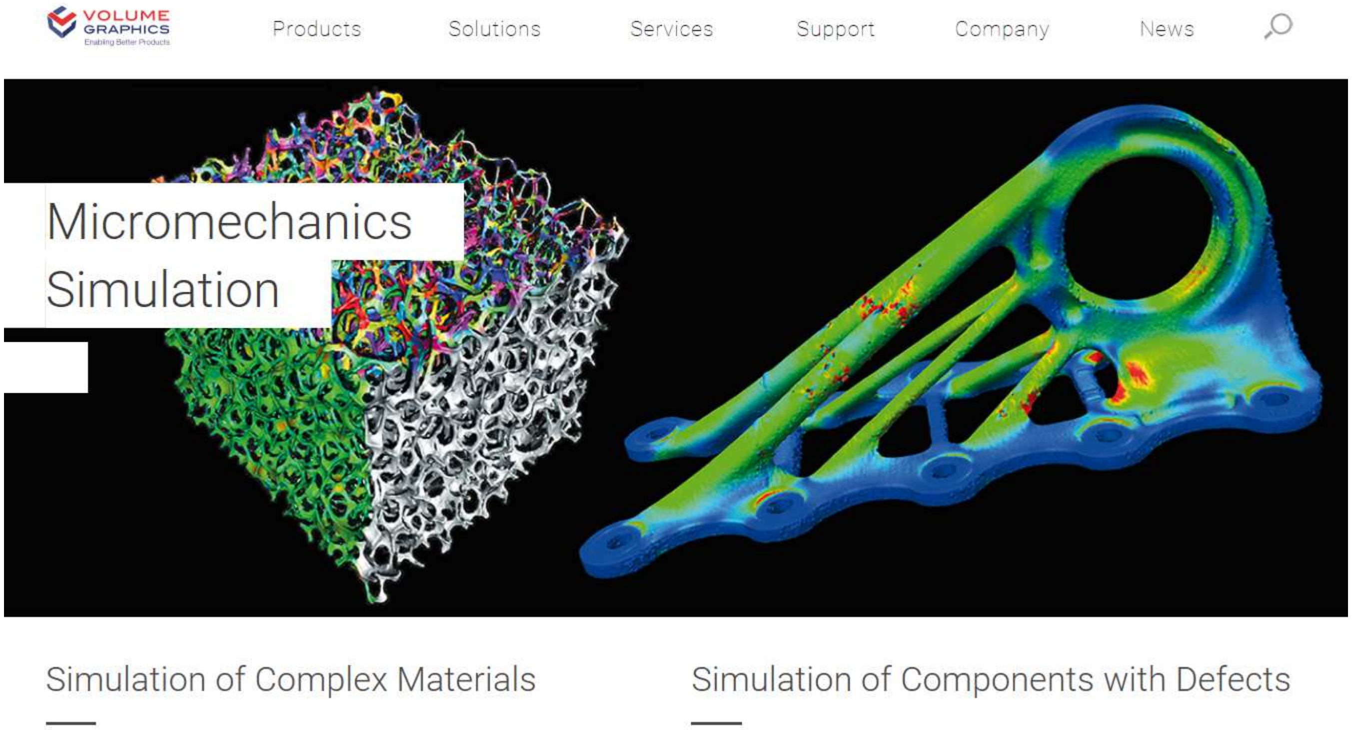
- Practical Use
- **Summary**

Micromechanics Simulation on CT Scans



https://www.volumegraphics.com/micromechanicssimulation

Benefits

Low Effort

- No meshing required
- No simulation expertise required
- Seamless workflow from material segmentation and defect detection to simulation in one software

Realistic

- All microstructural details are captured by a subvoxel-precise material segmentation
- Simulated stresses can be directly related to the underlying material microstructure (e.g. size, location and shape of pores or thicknesses of struts in open-cell foams)

Validated

- Predicted fracture locations and tensile strengths validated in experimental tensile tests of 3D printed components with pores
- Effective elastic properties of a cubic lattice validated against a conventional FEM simulation

Thank You!

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