Simulation of the Stress Concentration around Pores in 3D Printed Components

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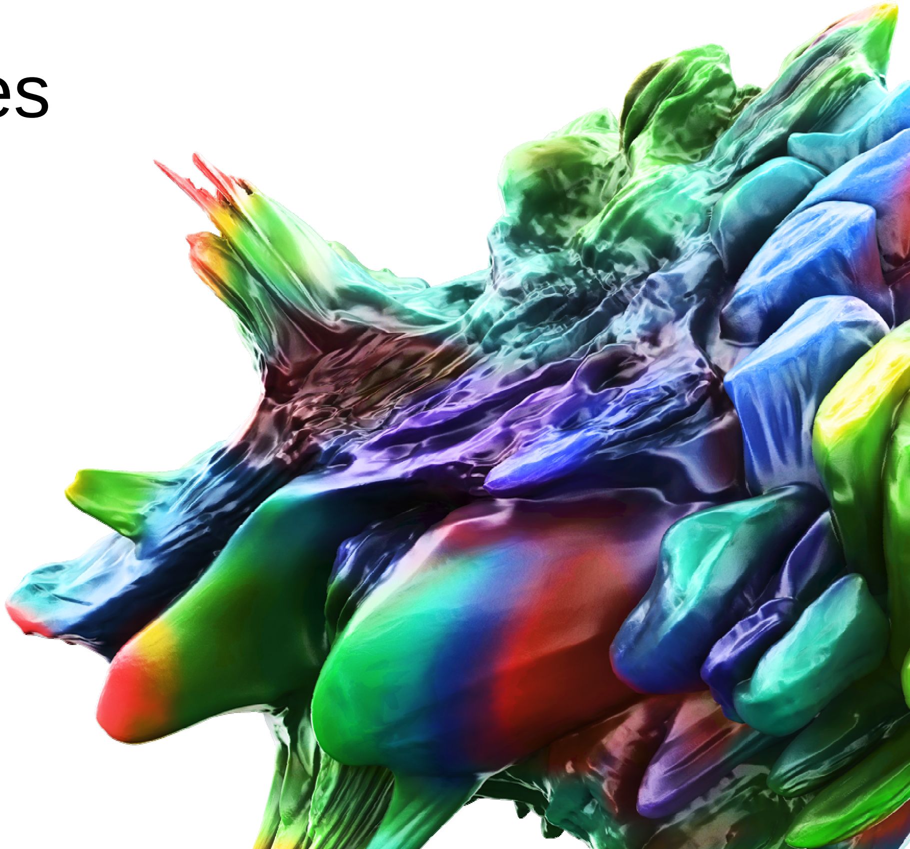


Overview

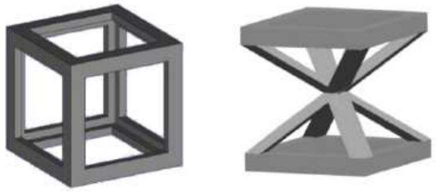
> **1. Porosity in 3D Printed Components**

2. Mechanical Simulation including Porosity
3. Industrial Computed Tomography (CT)
4. Mechanical Simulation Directly on CT Scans
5. Application Examples
6. Validation
7. Practical Use in 3D Printing
8. Summary

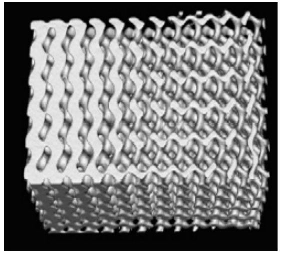
3D Printed Lattice Structures

Material

Periodic



Graded



Applications

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

Microstructure

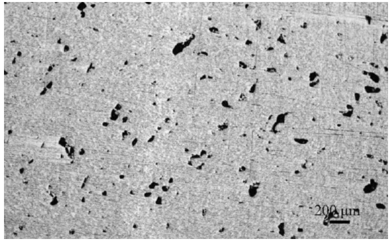
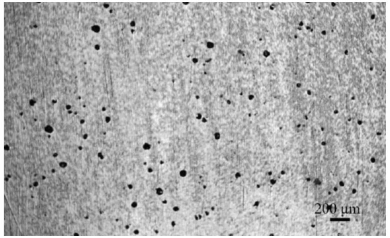
- Different unit cell geometries (e.g. cubic, diamond, dodecahedron, truncated cuboctahedron, gyroid)
- Pore sizes typically 500 – 1000 µm
- Strut sizes typically 100 – 500 µm

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

Porosity in 3D Printed Metal Components

Applications

- *Structural:* aircraft, aerospace, automotive components, medical implants, …

Material		Microstructure
Irre-gu-lar		▪ Porosity of ≈ 1 - 3 % resulting from incomplete melting ▪ Pores with irregular shapes and lengths of ≈ 25 - 250 µm
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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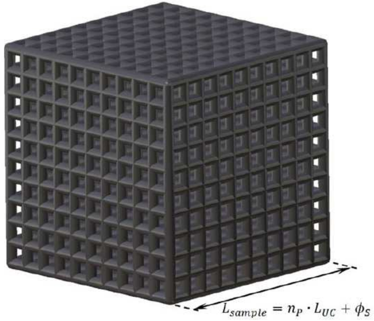
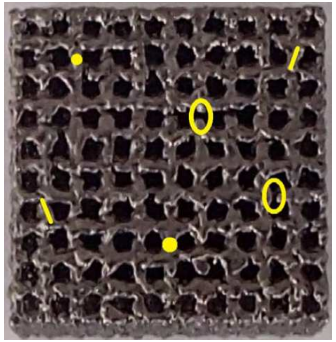
FEM Simulation of Lattice Structures

Possible in principle but significant manufacturing defects are hard to capture

- 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]



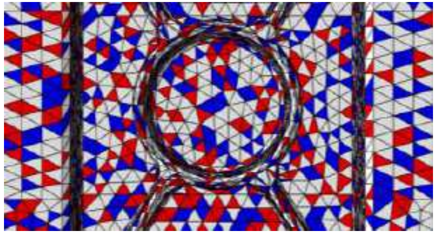


[1] D. Mahmoud, M. Elbestawi: Lattice Structures and Functionally Graded Materials: Applications in Additive Manufacturing of Orthopedic Implants: A Review. J. Manuf. Mater. Process. 2017, 1, 13; DOI: 10.3390/jmmp1020013
[2] F. Quevedo Gonzalez: Finite element modeling of manufacturing irregularities 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

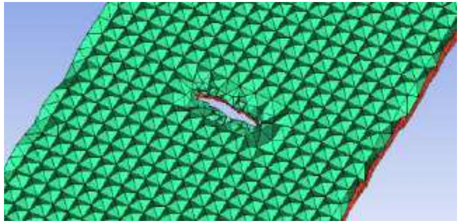
Various approaches (examples) – none of which exactly represents locations and shapes of all pores

Stochastic Distribution [1]



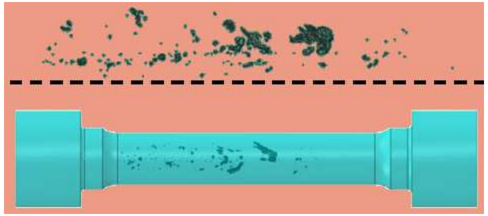
- Stochastic assignment of 3 aggregate porosity levels (e.g. 0 / 2 / 20%) and corresponding material parameters to the cells of an FEM model
- – Individual pores not captured at all

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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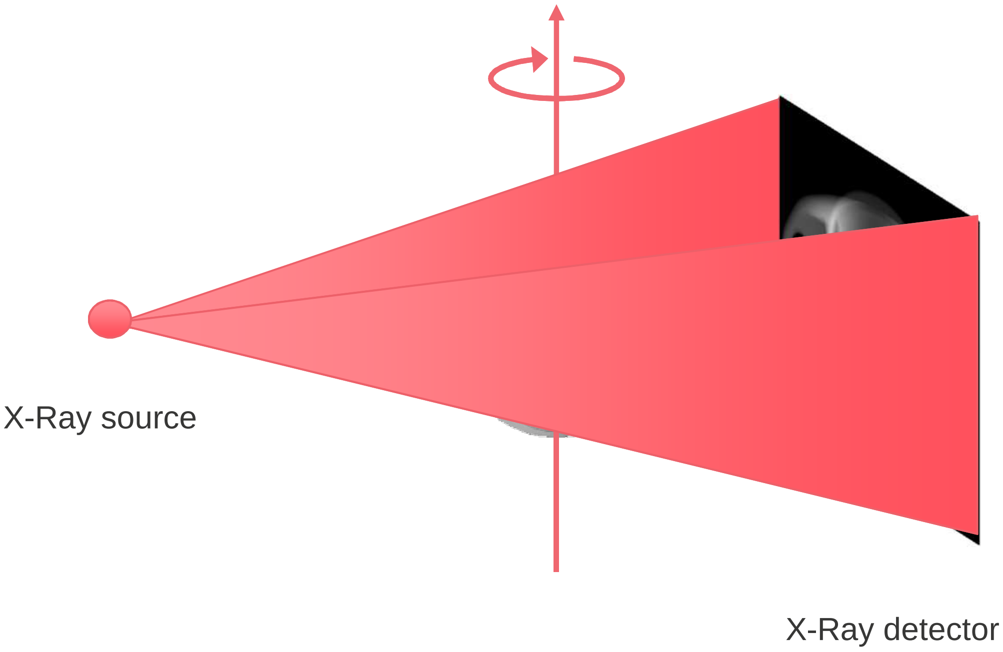
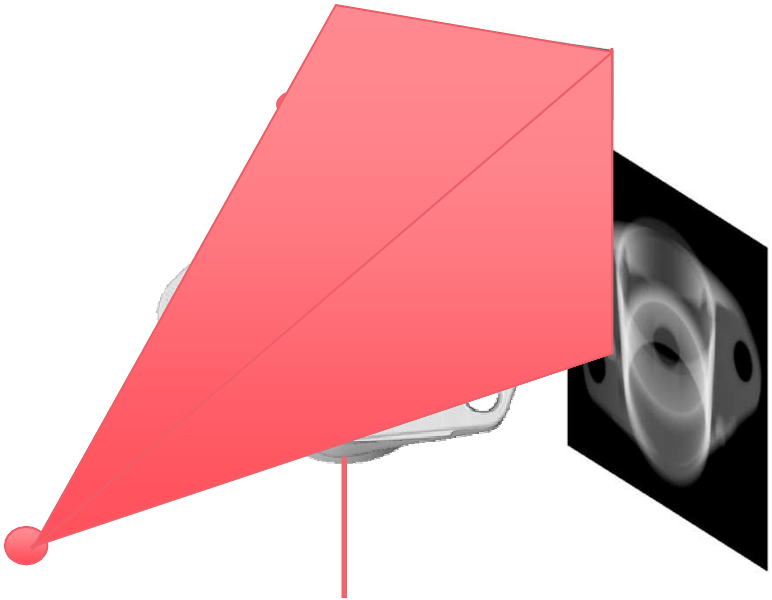
Industrial X-Ray Computed Tomography (CT)



Industrial X-Ray Computed Tomography (CT)



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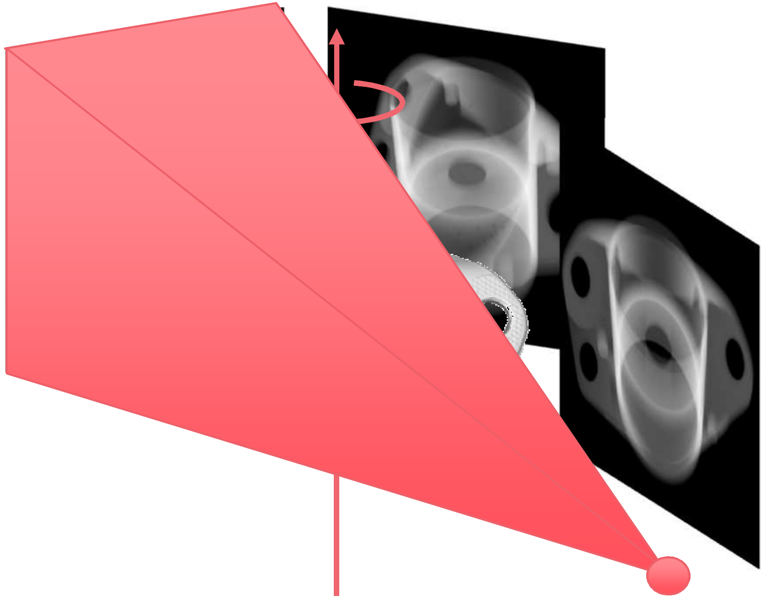

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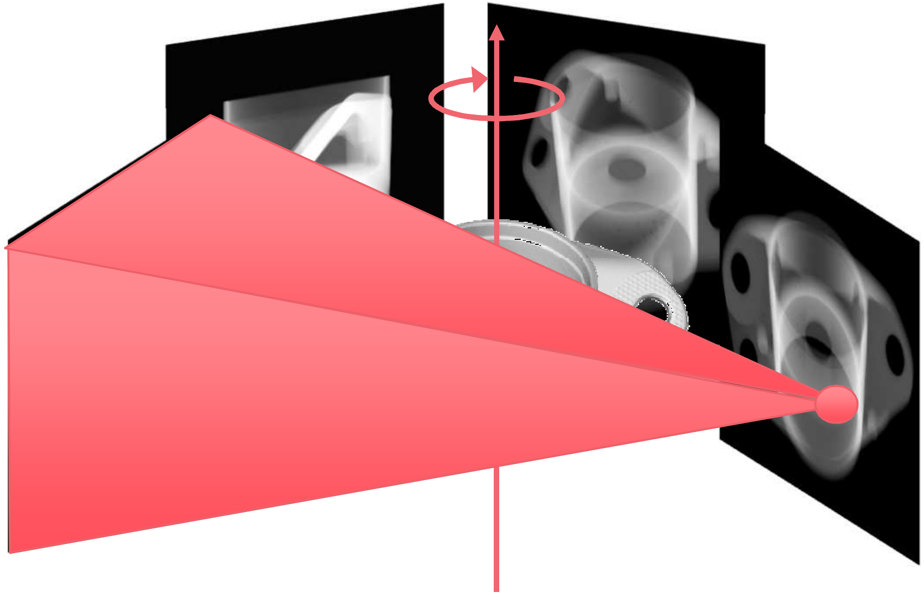

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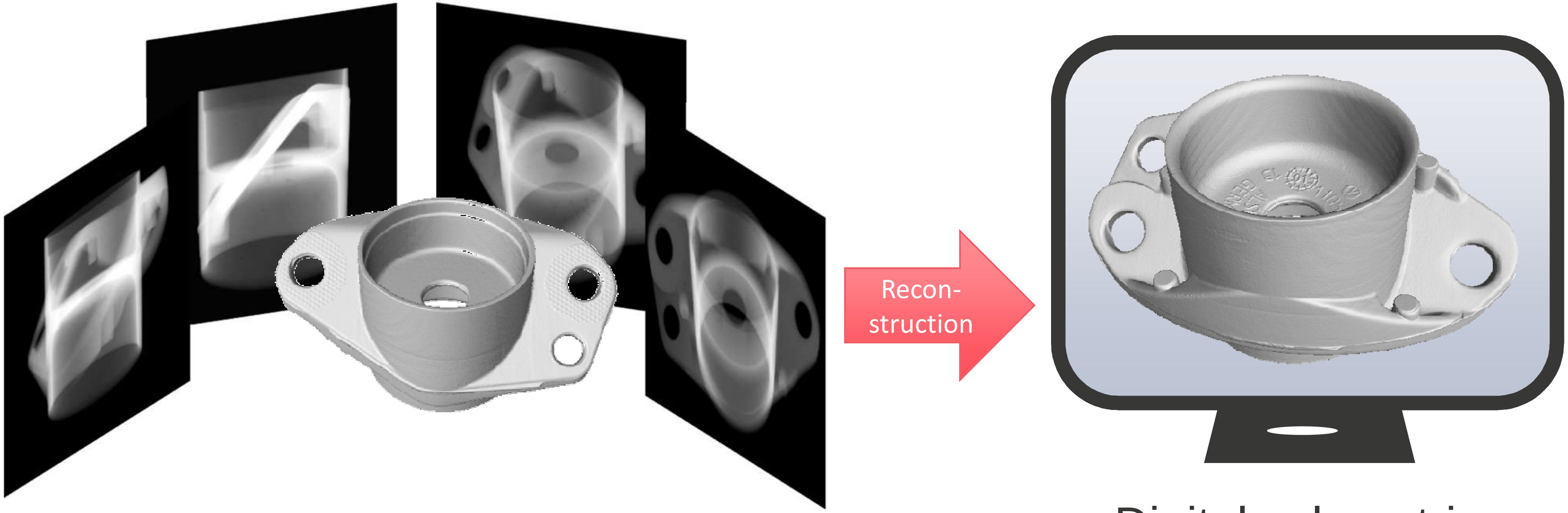
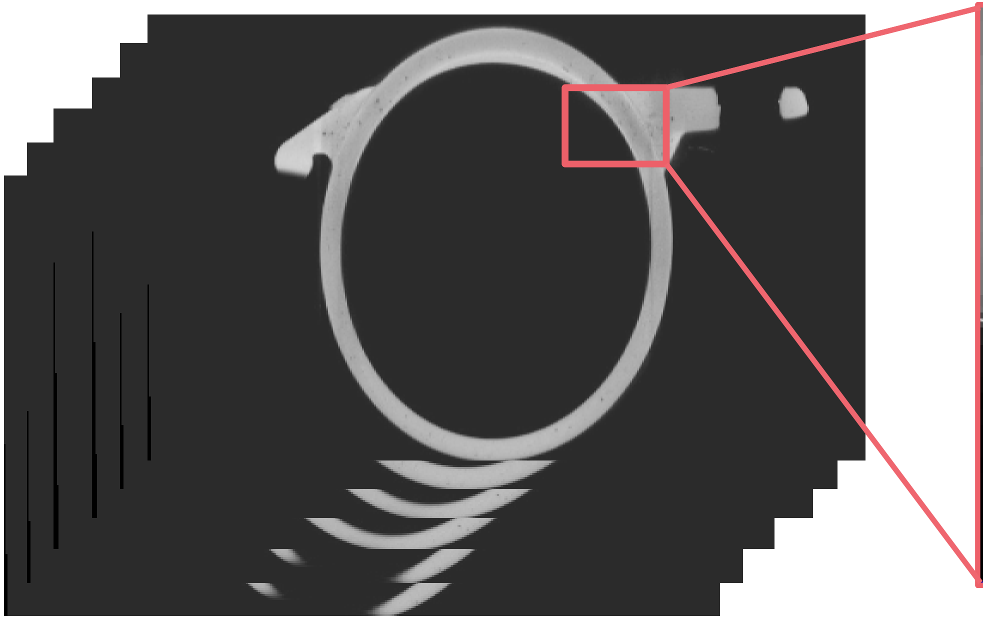
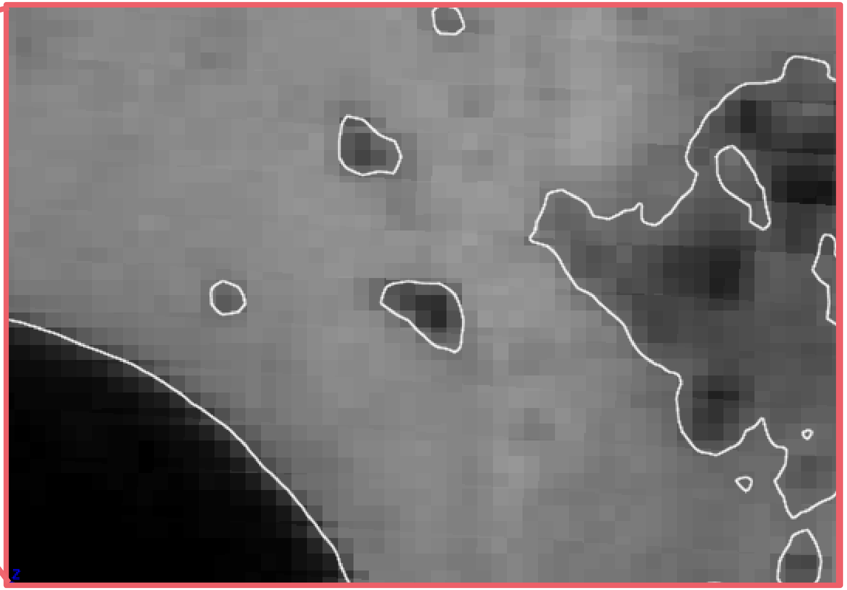


Digital volumetric representation of scanned part

Segmentation of All (Internal and External) Surfaces

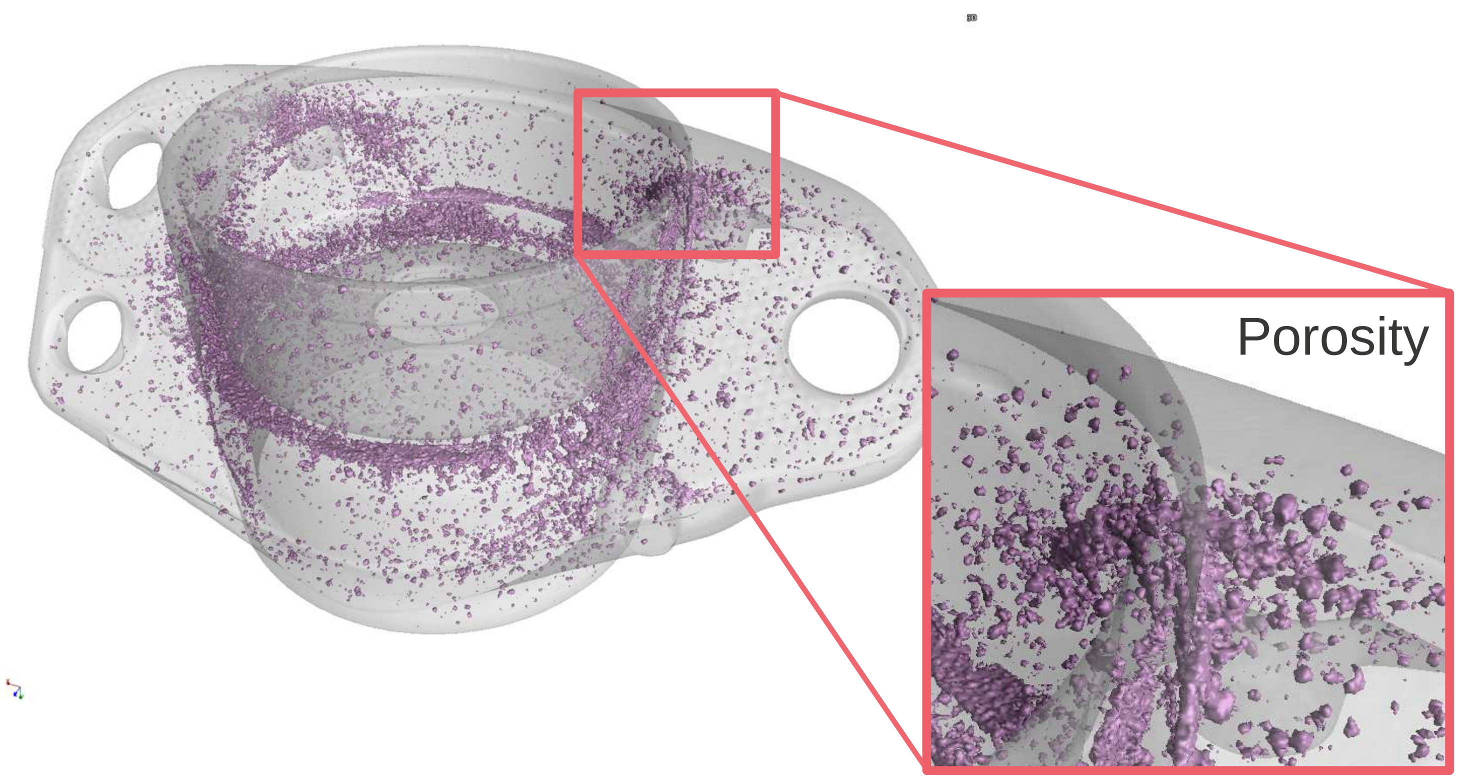


CT image data



Determined surface

Accurate Representation of Complex Geometry



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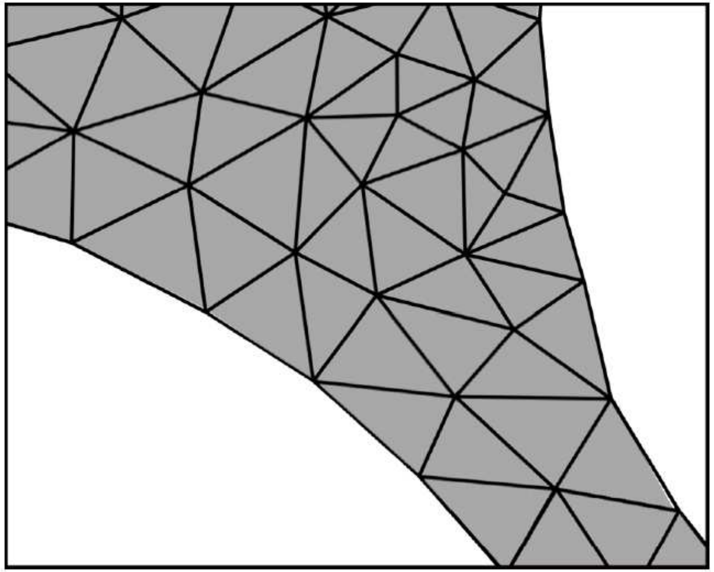
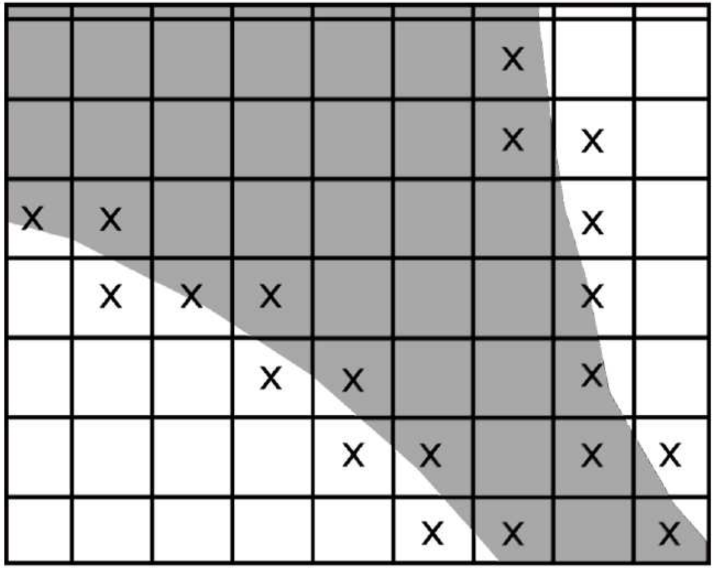
Immersed Boundary Method

Classical FEM



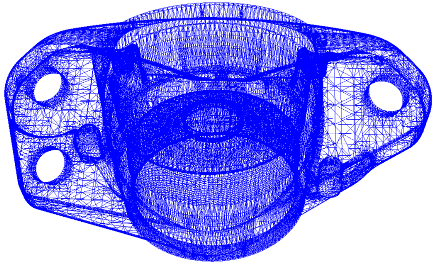
Immersed Boundary



Immersed-boundary FEM in VGSTUDIO MAX

VOLUME GRAPHICS

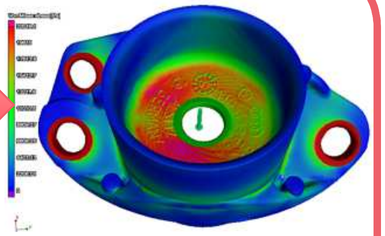
CT Scan



3D surface models (CAD, STL)

Surface segmentation

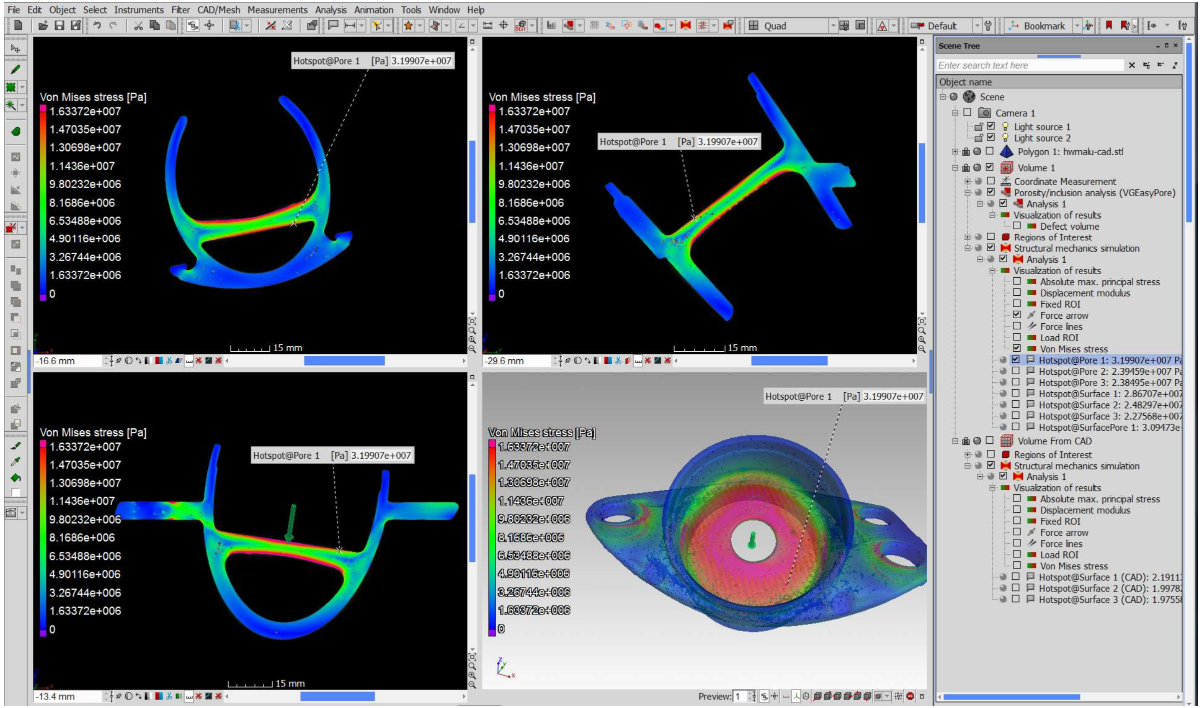
Immersed boundary solver



VOLUME GRAPHICS VGSTUDIO MAX

Immersed-boundary FEM in VGSTUDIO MAX

VOLUME GRAPHICS



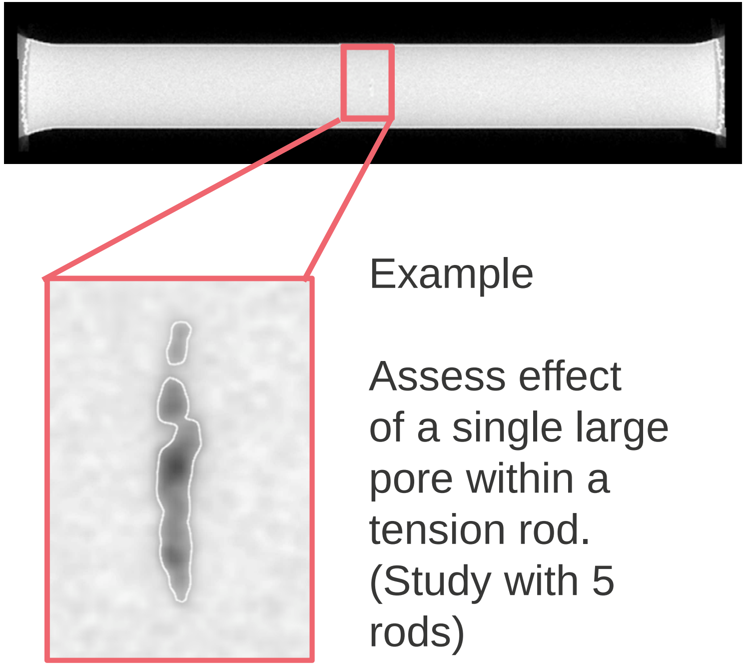
Structural mechanics

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

No meshing required!

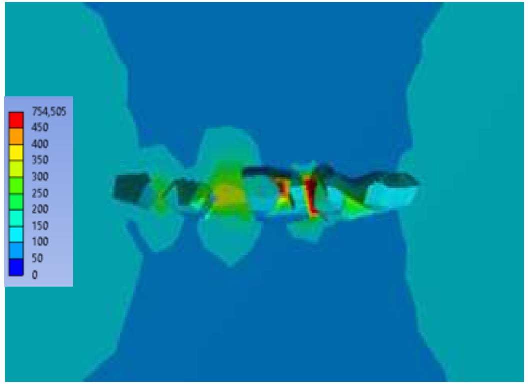
Example: Tension Rod with just 1 Pore

Comparison between classical FEM and immersed boundary FEM



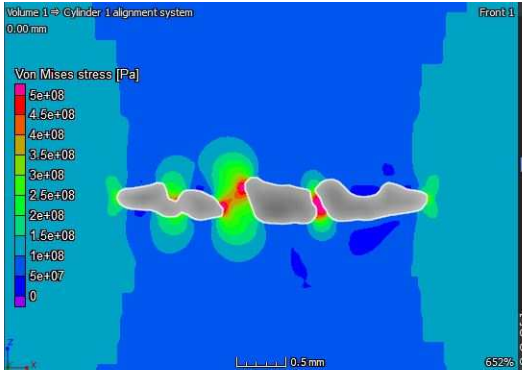
Example

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



<u>ANSYS</u>

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



<u>VGSTUDIO MAX</u>

- Solve (13 min)

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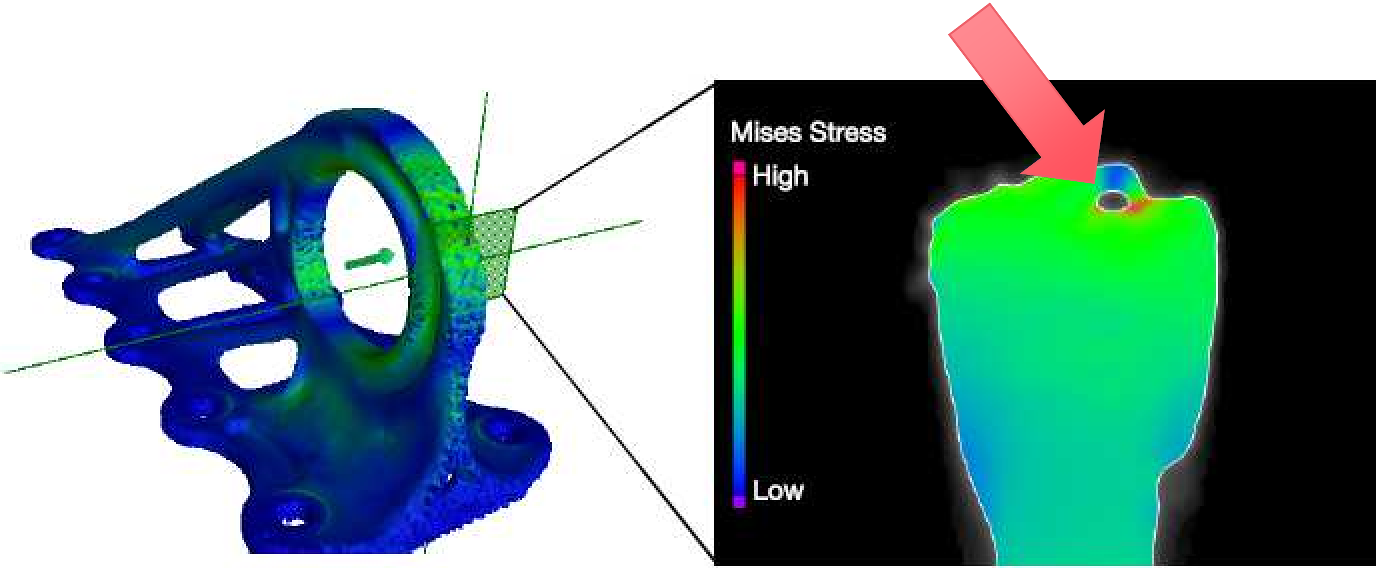
Example: 3D Printed Component with Pores (1)

Stress concentration caused by a pore

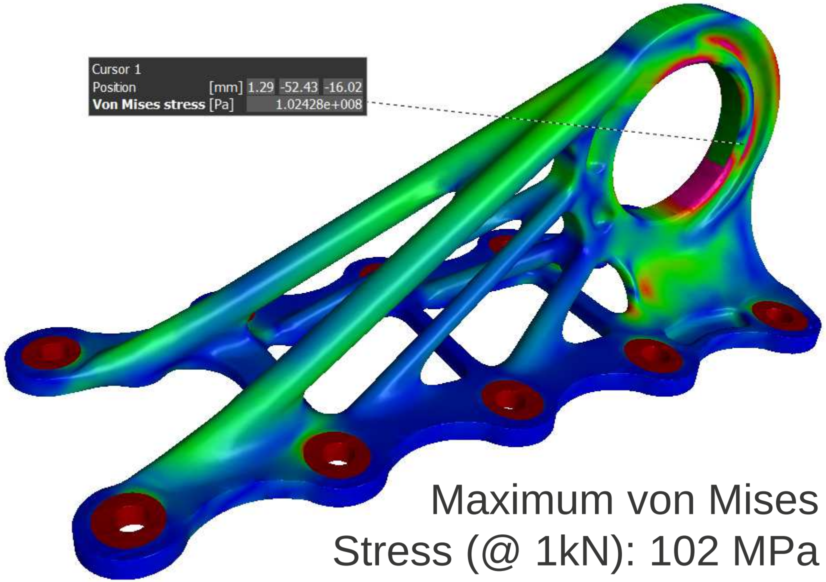
Pore causing hotspot



Example: 3D Printed Component with Pores (2)

Stress Distribution on Ideal vs. Real Component

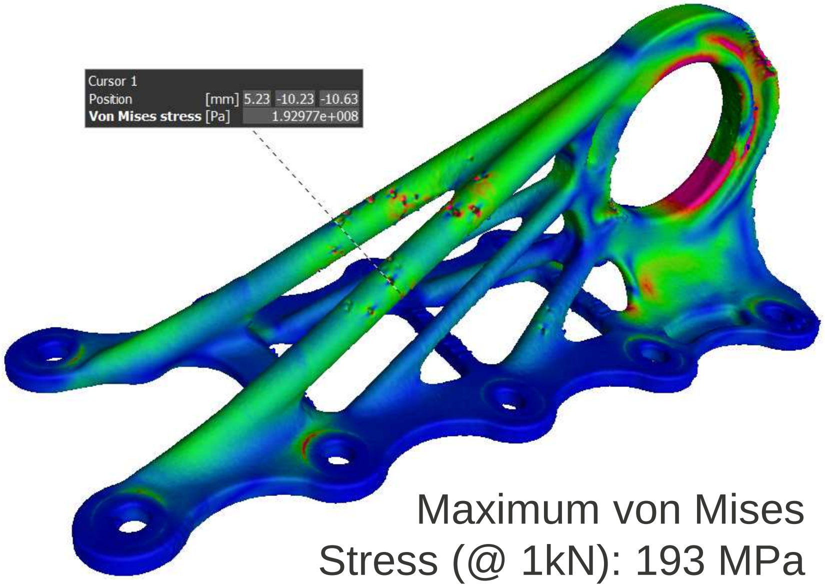
CAD



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

CT Scan

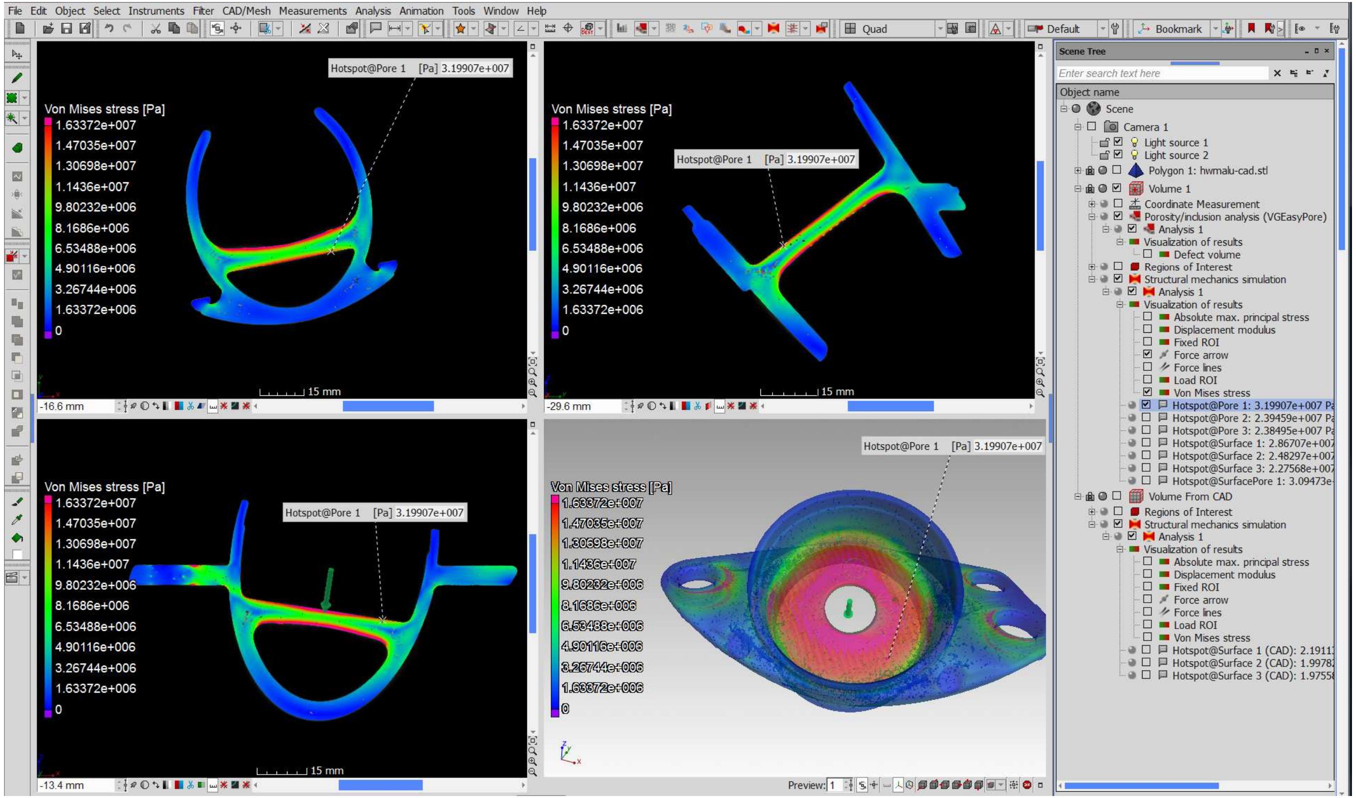
(or result of process simulation)



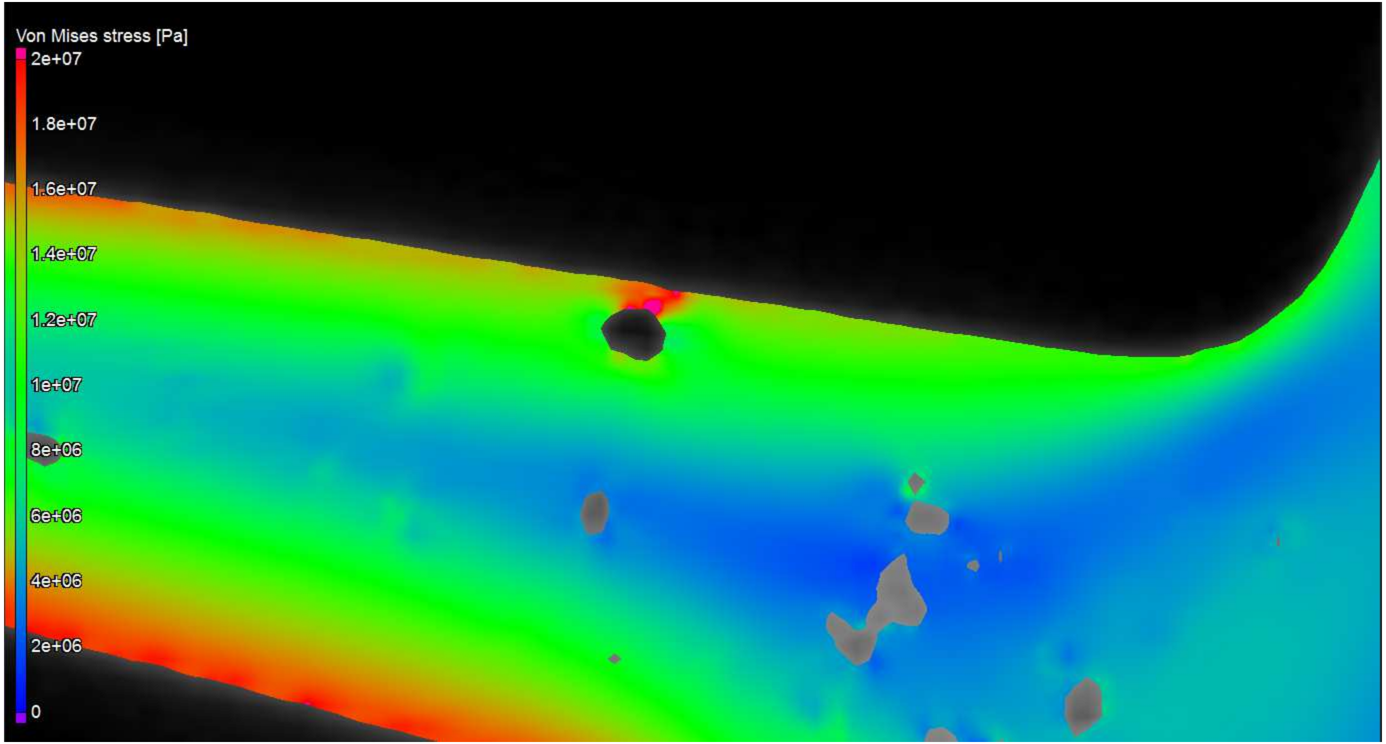
Maximum von Mises
Stress (@ 1kN): 193 MPa
(+ 89%)

Example: Cast Al Part with Porosity (1)

Structural Mechanics Simulation taking the porosity and shape deviations into account



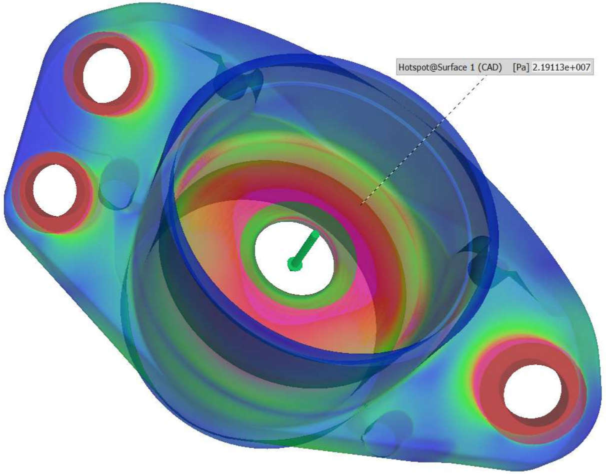
Stress Concentration Around Pores



Example: Cast Al Part with Porosity (2)

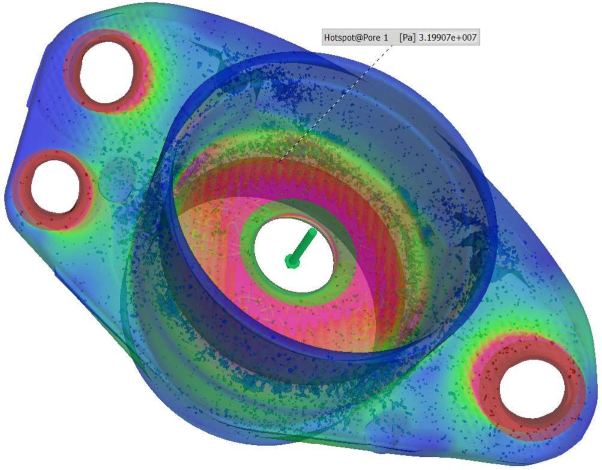
Stress Distribution on Ideal vs. Real Component

CAD



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

CT Scan

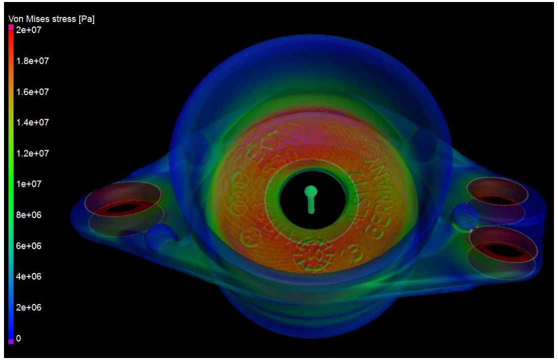


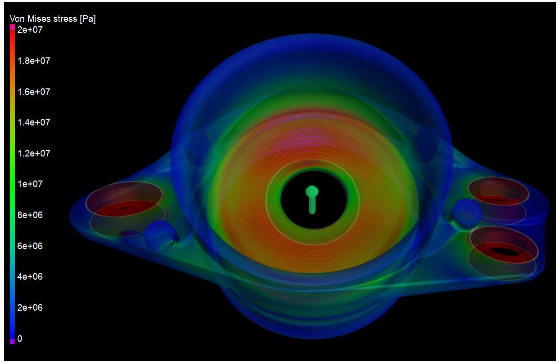
Maximum von Mises
Stress (@ 1kN): 32 MPa
(+ 45%)

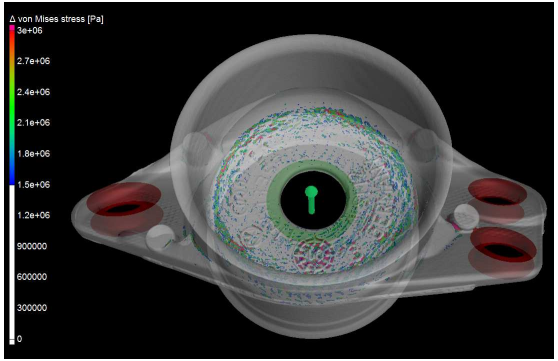
Comparison with Reference Simulation

> Calculate and visualize differences in results to a reference simulation

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







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Validation Experiments: Test Specimen

A—250A (specimen 1 of 3)

B—125A (specimen 1 of 3)

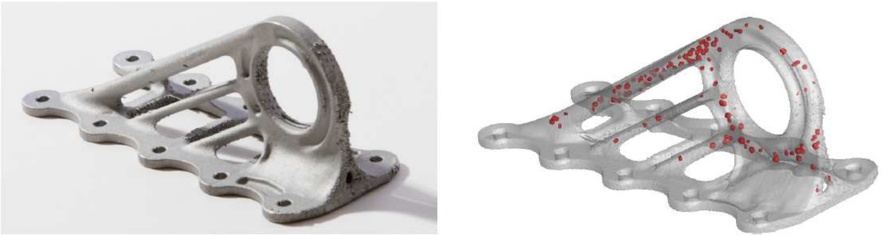
C—75A (specimen 1 of 3)

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)

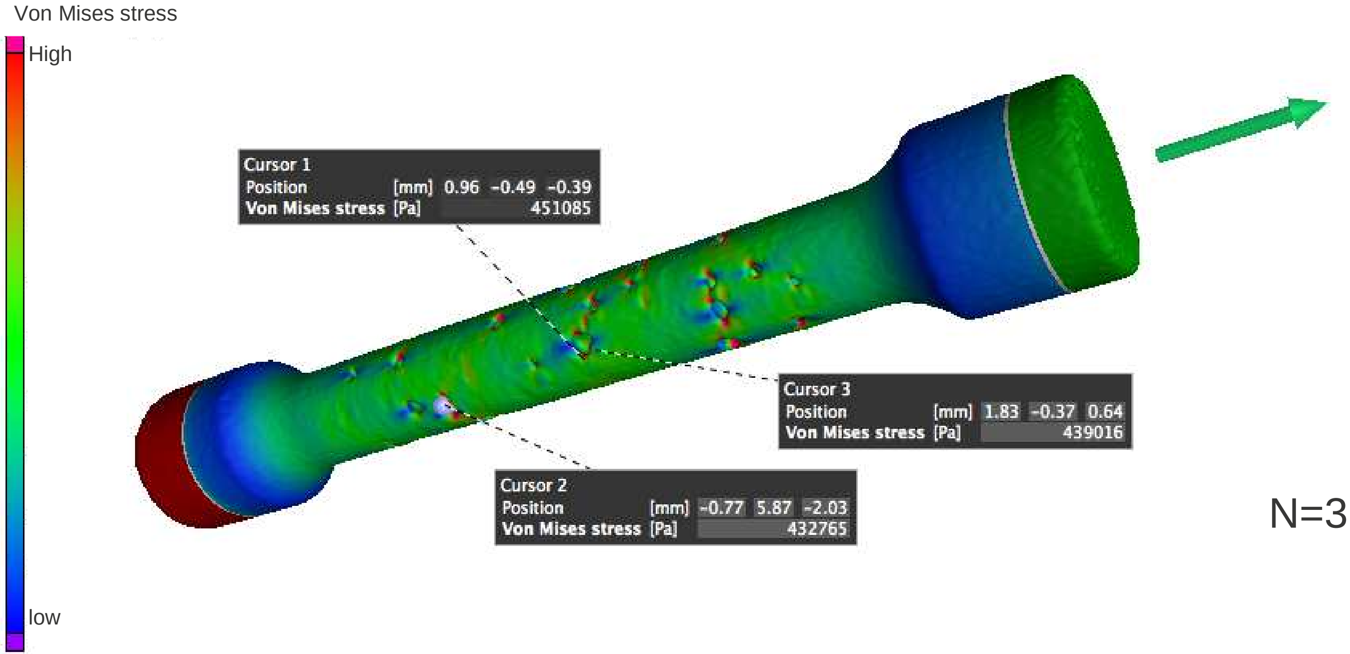
Validation Details

Find largest N local maxima of von Mises stress: σ_1 (=σ_{max}), σ_2, … , σ_N

Predictions:

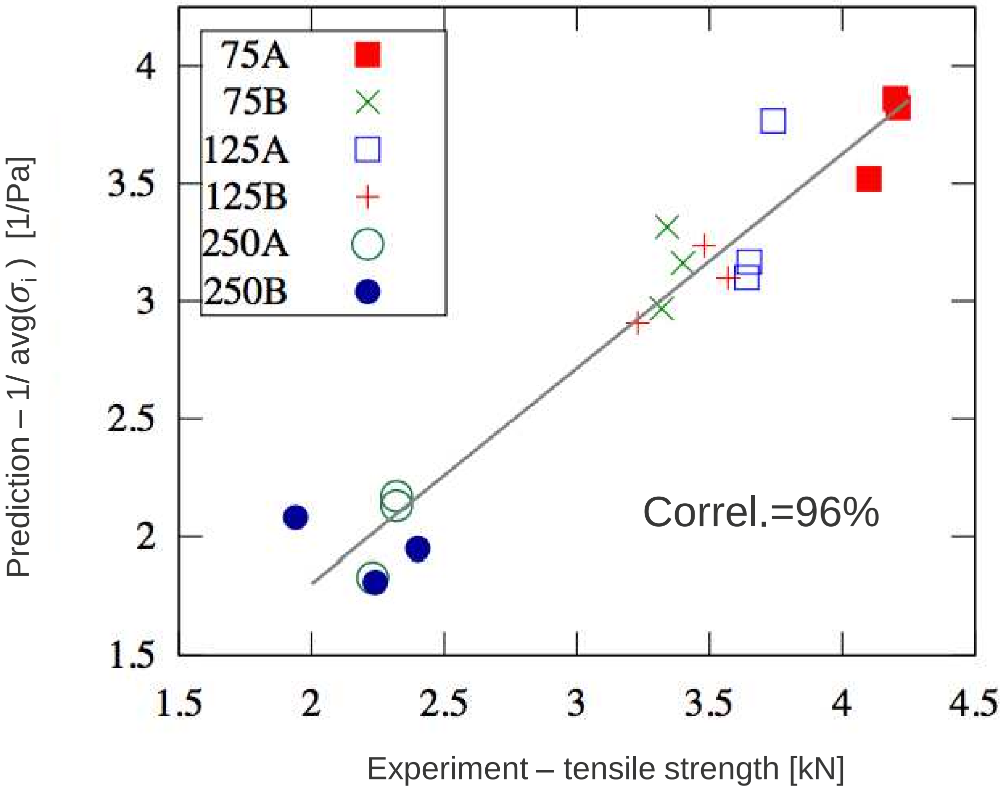
> First crack occurs at either one of these positions

> Ultimate strength ∝ 1 / ($\Sigma \sigma_i$ / N)

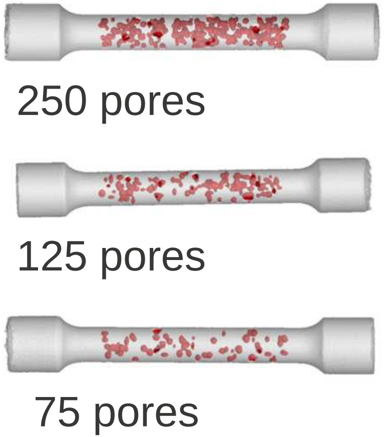


N=3 in this study

Results: Prediction of Tensile strength

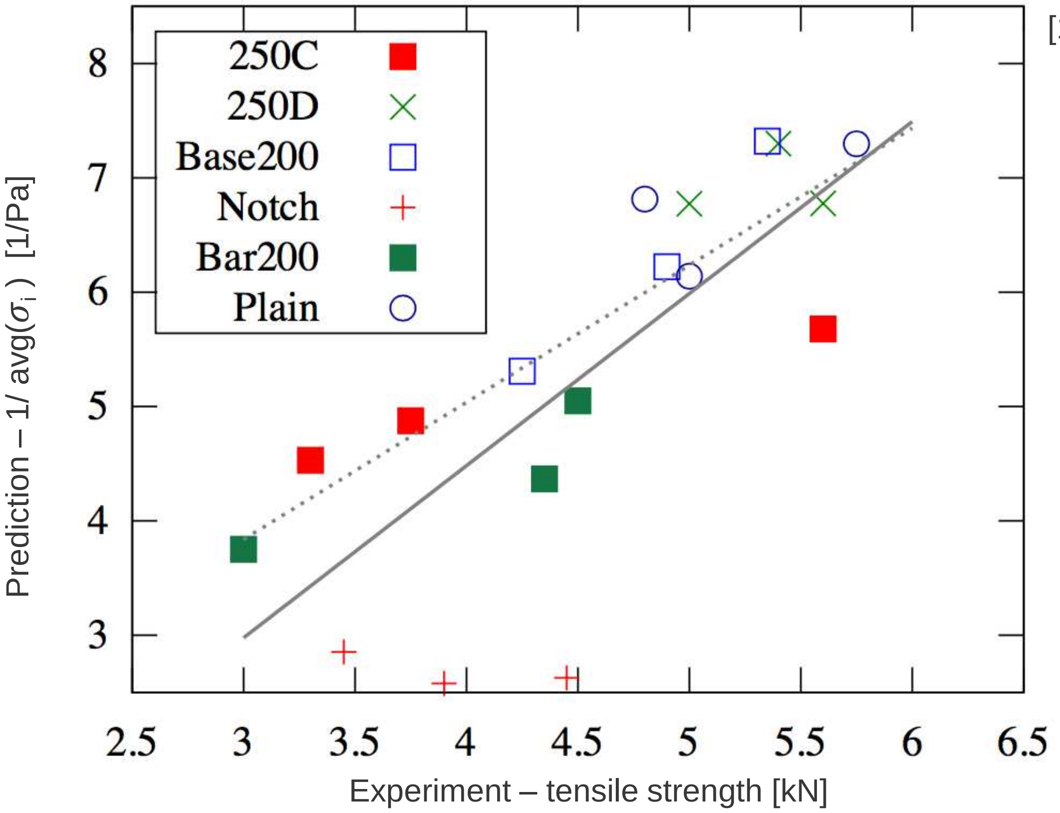


[1]



[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]

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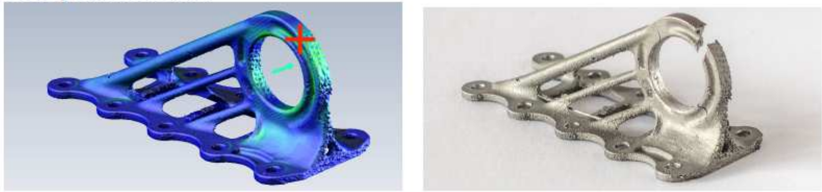
Results: Crack Locations

250C, specimen 1 of 3, HS_1

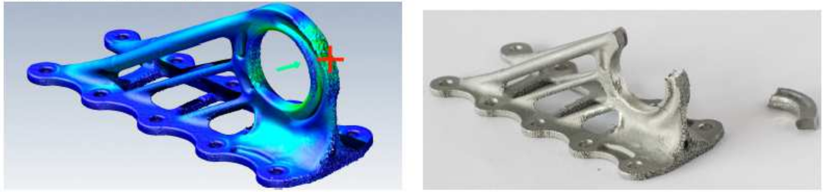


Base200, specimen 2 of 3, HS_2

Notch, specimen 2 of 3, HS_1 and HS_2

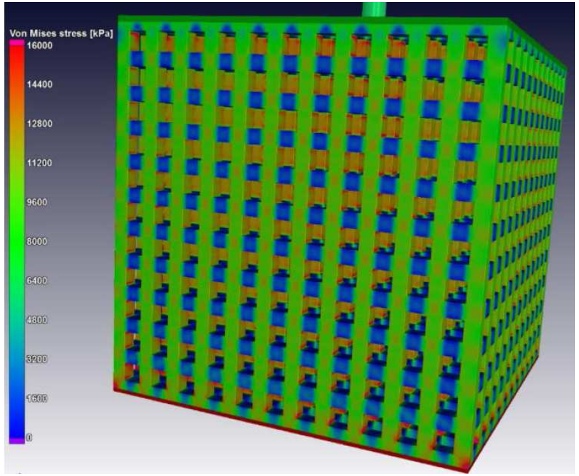
Bar200, specimen 2 of 3, HS_1

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., Lattice structure simulations: comparison of finite element and voxel-based static loading simulations. South African Journal of Industrial Engineering, submitted for publication, 2017.

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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

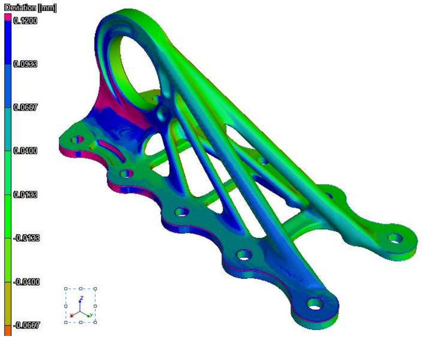
(1) Simulate stress distribution $\sigma_{CAD}(\underline{x})$ for CAD model

(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)

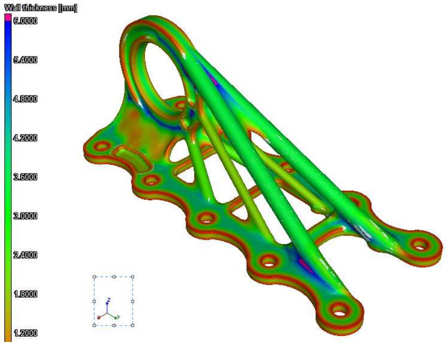
$$\max \sigma_{CT}(\underline{x}) <\approx \max \sigma_{CAD}(\underline{x}) \ !$$

* Focusing on potentially critical regions of interest if necessary

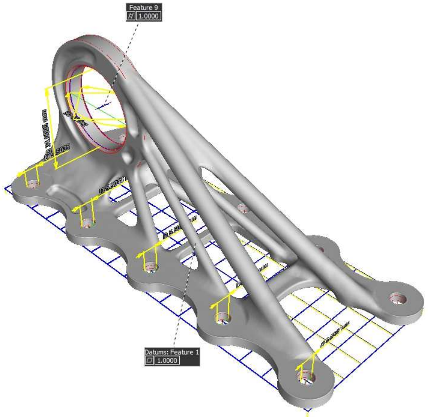
CT for Quality Assurance in 3D Printing



Nominal/Actual Comparison

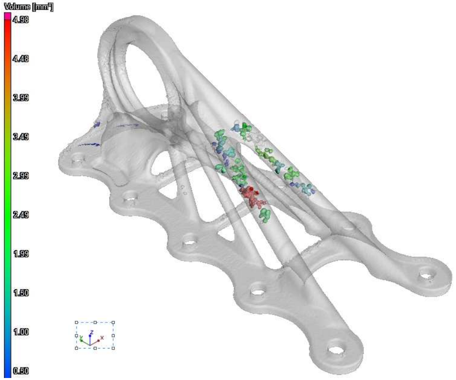


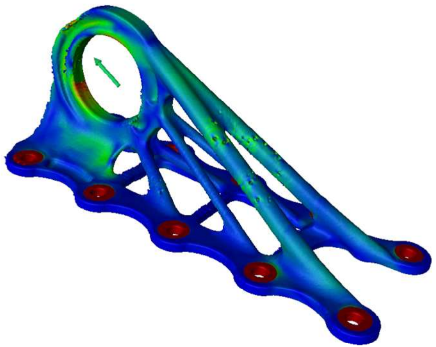
Wall Thickness Analysis



Coordinate Measurement

Porosity Analysis

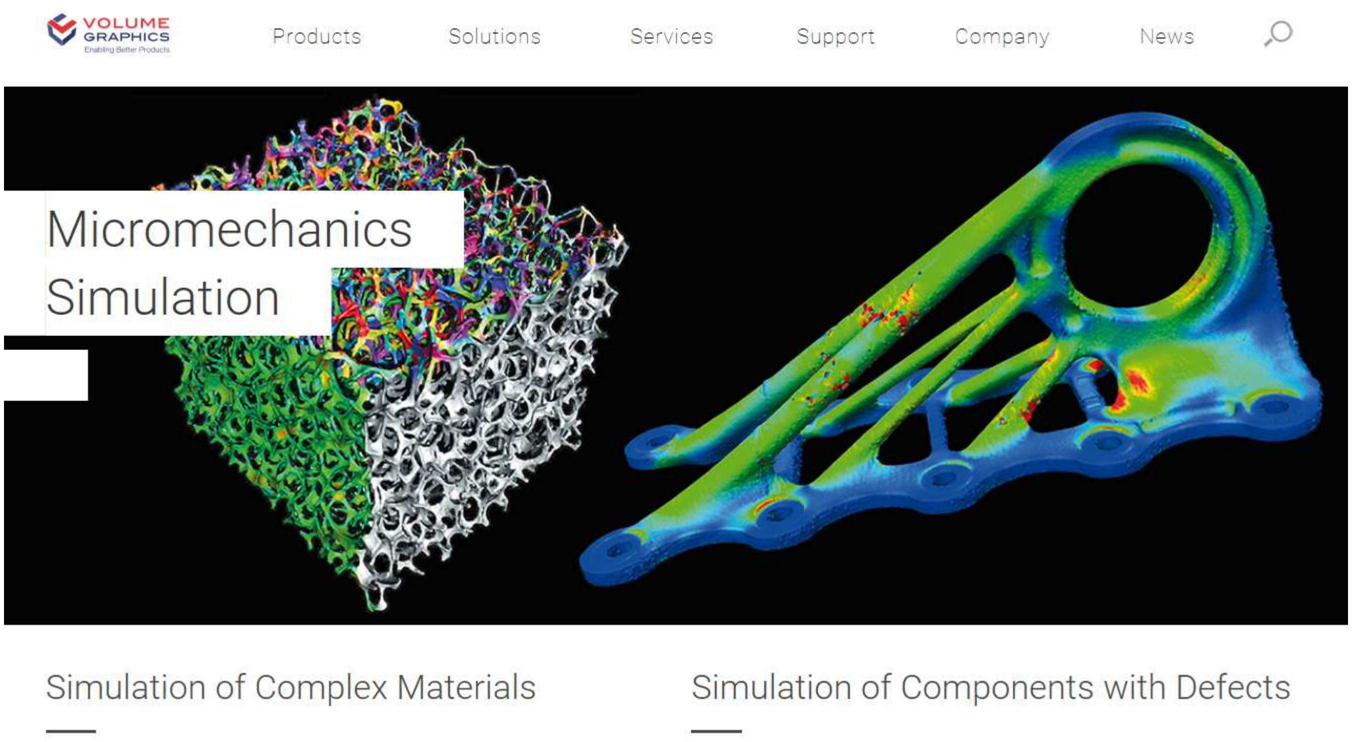




Mechanical Simulation

Overview

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

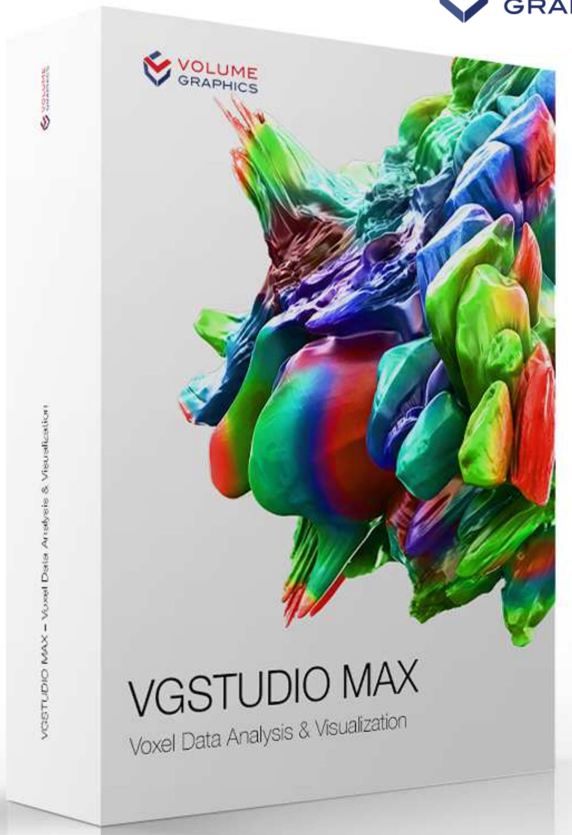
- All microstructural details are captured by a subvoxel-precise material segmentation
- Simulated stresses can be directly related to the underlying material microstructure (e.g. size, location and shape of pores or thicknesses of struts in open-cell foams)

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

Volume Graphics

- Developer of leading software for the analysis and visualization of industrial CT data
- For quality control, metrology, damage analysis, and product development
- Used by more than 70% of the “Fortune Global 500” companies in the automotive and electronics industries*
- Founded in 1997 in Heidelberg
- Support and VG Academy



*As of 2016

Thank You !

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