Virtual Stress Tests Directly on CT Scans

K.-M. Nigge[1†], J. Fieres[1], P. Schumann[2], C. Reinhart[1]

[1]*Volume Graphics GmbH, Speyerer Straße 4-6, 69115 Heidelberg, Germany*

[2]*Concept Laser GmbH, An der Zeil 8, 96215 Lichtenfels, Germany*

[†]*E-mail: nigge@volumegraphics.com*

Abstract

A new structural mechanics simulation method is presented which allows to take the effects of defects such as porosity or geometry deviations in actual parts into account. Contrary to traditional FEM simulation, the new method does not require meshing, but works directly on computertomography (CT) scans. The results of the new method are in good agreement with both experimental results from tensile tests as well as with traditional FEM simulations for regular geometries. It is suggested to use the new method in quality assurance in order to obtain an explicit quantitative understanding of whether or not observed porosity or shape deviations in actual parts could have a significant detrimental effect on the mechanical durability of the components.

Keywords: computed tomography, CT, simulation, tensile strength, porosity, additive manufacturing

1 Motivation

The influence of material defects and geometry changes introduced by production processes such as die casting, injection molding or additive manufacturing on the mechanical properties of materials and components is traditionally considered through empirical safety factors applied to the results of FEM simulations and experimental tests of mechanical durability. If chosen too cautiously, however, such safety factors may hinder further advancements in lightweight construction. To overcome this limitation, a better understanding of the “effects of the defects” on the mechanical properties is required.

With the aid of X-ray computed tomography (CT), internal discontinuities and geometry deviations can be accurately detected and visualized. Their spatial distribution, size and shape parameters can be determined using suitable image processing and analysis software and then compared to corresponding specifications as set by the producer of the component. However, these specifications are typically based on historical experience. A more technical reasoning for these specifications would require knowledge about the extent to which the discontinuities and geometry deviations change the mechanical stresses inside the component compared to those that were simulated using CAD models and FEM software in the development process.

A new simulation method is presented which allows to simulate the internal stress distributions directly on CT data and may be used to predict the tensile strength and the location of crack initiation for real components with defects and deformations.

2 Simulation Method

As described in [1], conventional finite element methods require that the simulated domain is tiled into a mesh of small volume primitives before a simulation can be conducted. This meshing step is crucial for the success of the simulation and can be challenging for complex geometries [2, 3], or even practically impossible [4], since contrary objectives are to be met. First, the mesh must be fine enough to capture all relevant geometric details. Second, the number of mesh cells must not be too large in order to keep the computational effort at a practical level. Third, the mesh cells must conform to certain shape criteria in order to assure the numerical stability of the simulation [5].

Recently, mesh-less and immersed-boundary finite element methods have been used to overcome the meshing problem [5, 6]. Such methods do not require the generation of a boundary-conforming mesh and are suited for the simulation of arbitrarily complex domains as found in porous objects.

This approach is implemented in the structural mechanics simulation module of VGSTUDIO MAX by Volume Graphics [7] which is optimized for working with complex domains like porous materials. VGSTUDIO MAX does not require a polygon mesh at any point in the processing tool-chain. The reconstructed surface of the CT-scanned part is represented in an implicit manner directly sourcing the image data. The solver is based on an immersed boundary method and as such does not require a geometry-conforming mesh. It works directly on the implicitly represented surface.

3 Comparison with Experimental Results

A comparison between experimental results and simulation results of tensile tests was conducted for two types of additively manufactured AlSi10Mg components, namely a tension rod and a bionically optimized aeronautic structural bracket. In order to examine the effect of pores on their mechanical properties, porosity in different volume fractions, shapes and spatial distributions was intentionally introduced into the samples. Overall, 18 specimen of tension rods and 18 specimen of the aeronatic bracket were CT scanned and subject to experimental quasi-static tensile tests. A selection of the test specimen is shown in Figure 1. The details of the sample design and manufacturing process, the CT scanning and the tensile test procedure are described in [1].

Static structural mechanics simulations were performed based on the reconstructed surfaces from the CT scans. A linear-elastic isotropic material model was used with a Poisson's ratio of 0.3 which is a common choice for metals. The boundary conditions were set up as to mimic the physical tensile tests. All simulations were performed with a unit total applied force. The static structural mechanical simulations provide the local stress tensor at all points within the undeformed specimen, from which the local von Mises stress is calculated. The resulting simulated stress field does take into account the stress concentration effect of the pores in the probes.

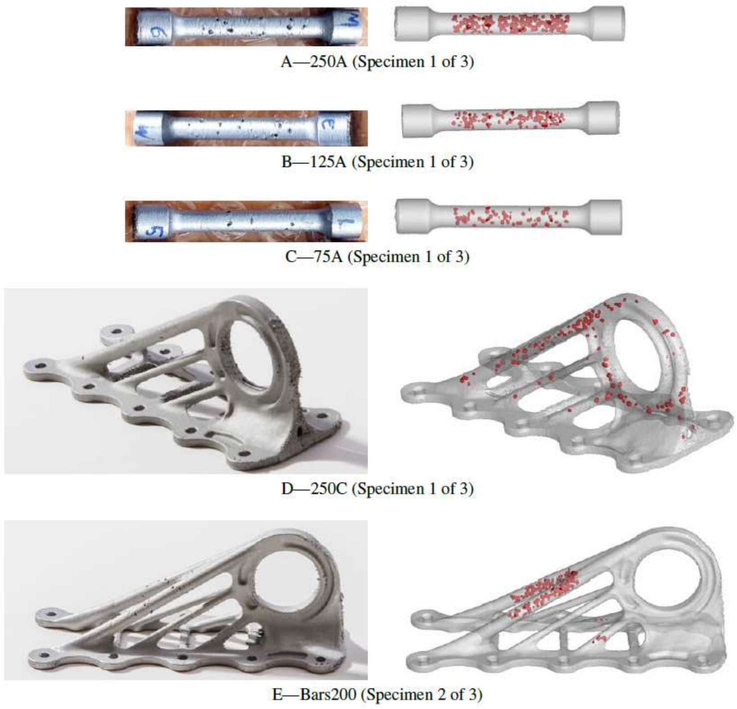

Figure 1: Five out of 36 test specimens. A–C: Tension rods, D–E: Aeronautic parts. For each specimen: Left—photograph, beforedestructive test. Right—CT image data of same specimen, outer surface transparent, porosity highlighted in red. [1]

Given that the von Mises stress is proportional to the applied force (which is assumed in the linear-response approximation of the material and for small enough deformations) the first crack of the probe can be expected to occur at the location where the von Mises stress at unit force takes on its global maximum, and the applied force F_{crack} necessary to initiate the first crack can be expected to be inversely proportional to the global maximum of the von Mises stress.

In practical simulations, we often find a few local stress maxima with stress values only slightly less than the global stress maximum. In the following we will denote local stress maxima by the more intuitive term hot-spots. The used software automatically detects all hot-spots and sorts them by their von Mises stress. We denote the von Mises stress at the first hot-spot by HS_1. It is equal to the global von Mises stress maximum. The subsequent hot-spots HS_2, HS_3 etc., are the next largest local maxima in descending order. Due to various uncertainties in modeling, imaging, surface reconstruction, and simulation, the first crack seen in the physical experiment does not always happen at HS_1, but it will happen at any of the first few hot-spots. To level out the uncertainties to some amount, we take the average of the N largest hot-spots

$$< HS >_N = \sum_{n=1}^{N} HS_n \quad (1) \quad [1]$$

and expect this to be inversely proportional to F_{crack}:

$$F_{crack} \sim \frac{1}{<HS>_N} \quad (2) \quad [1]$$

In this study, we chose N=3. This choice does not seem to be very critical. We tested N = 1 . . . 4, not changing the reported results qualitatively.

3.1 Tensile Strength

Figure 2 shows the comparison between F_{crack} as expected from the simulation results according to formula (2) and F_{crack} as measured in the experimental tensile tests.

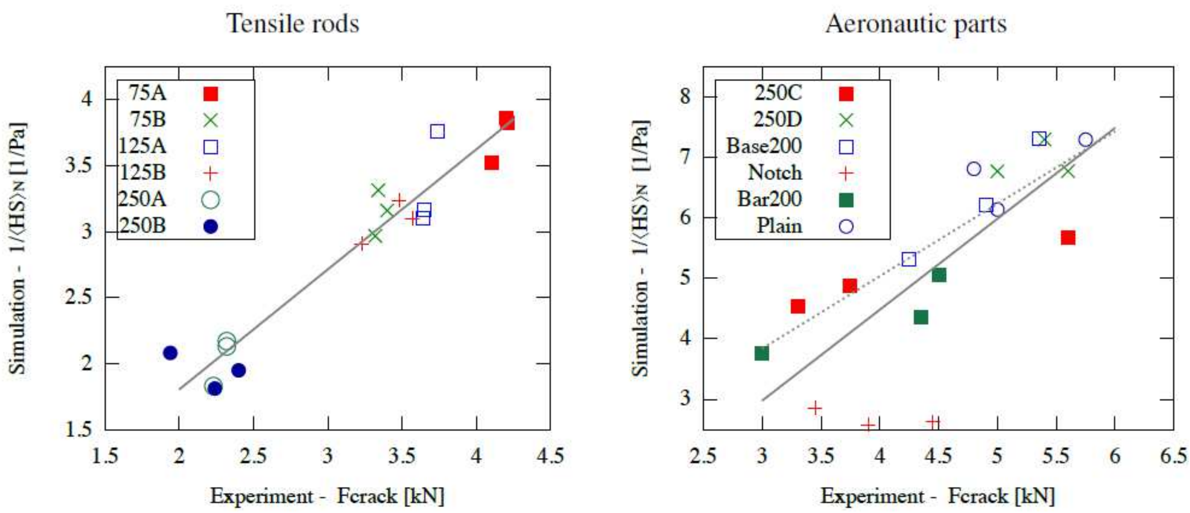

Figure 2: Measured force at first crack (F_{crack}) versus prediction from simulation ($1/<HS>_N$). Each data point represents one tested specimen. Left—tensile rods; right—aeronautic parts. The straight line is a least-squares fit to the data. Dotted line: least-squares fit without the Notch configuration [1]

Both experiment and simulation show that the mere number of pores in the specimen alone is not a good predictor for tensile strength, but tensile strength is significantly influenced by the spatial distribution and the shape of the pores. This suggests that conventional porosity specifications may introduce unnecessarily high safety margins.

The numeric cross-correlation between simulation results and experimental results is 0.96 for the tensile rods and 0.78 for the aeronautic parts. The numeric correlation between experiment and simulation raises from 0.78 to 0.86 when ignoring the Notch configuration which represents a different type of porosity (long thin groove as opposed to ellipsoid shaped pores in the other specimen). This may lead to a different stress-strain characteristics in the ductile range before cracking which is not considered in the linear elastic material model used in the simulations.

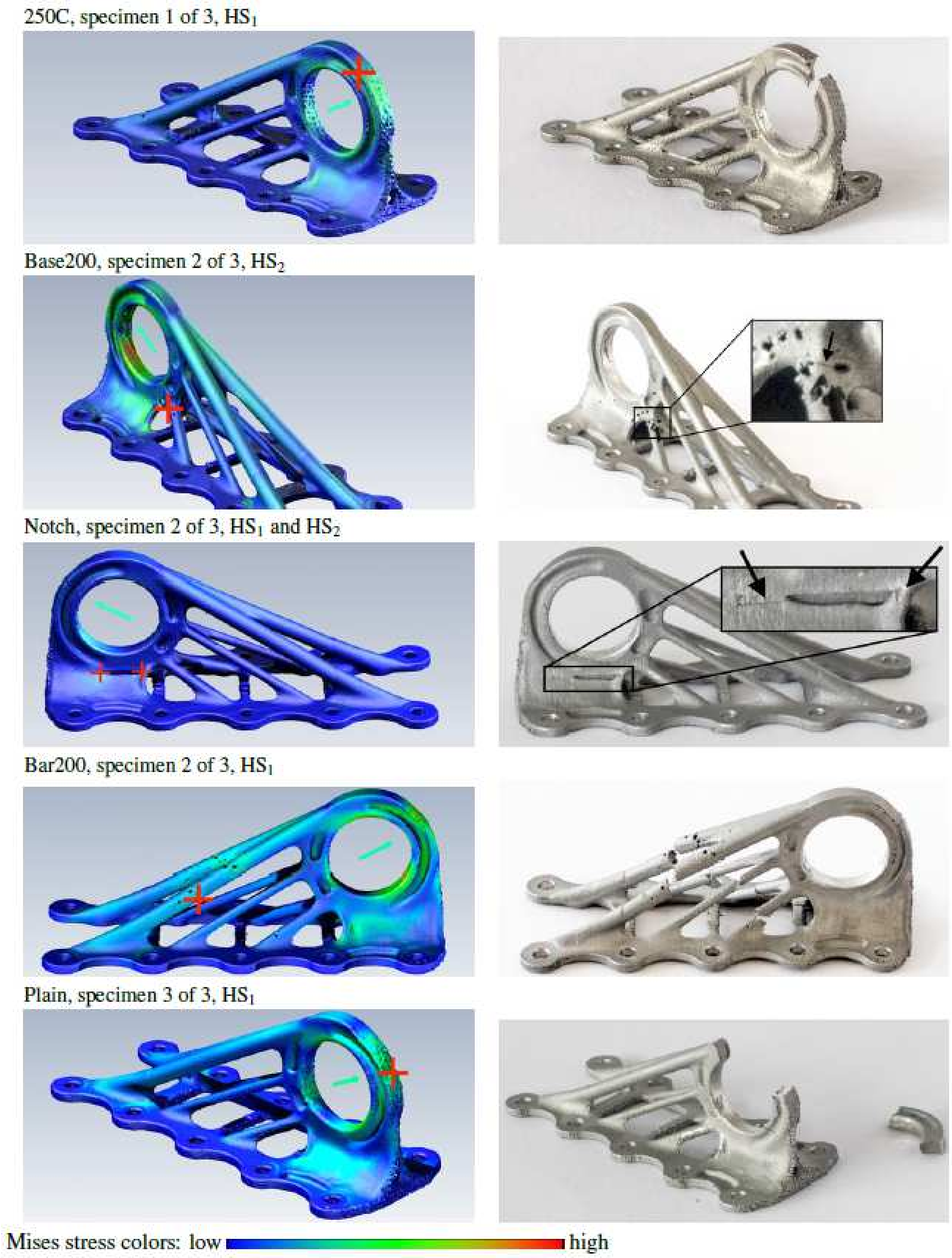

Figure 3: Predicted versus real locations of fracture for five examples. Left column—Digital reconstruction from CT-scan of intact part. Simulated von Mises stress shown as color overlay. Predicted fracture location indicated by red cross. Rows 1, 4, and 5: cross=global von Mises maximum (HS1); row 2: cross=second-largest local von Mises maximum (HS2); row 3: crosses=global and second-largest von Mises maxima (HS1, HS2). Right column—photographs of the parts after tensile tests. [1]

3.2 Crack Location

For 12 out of 18 specimens, a crack did actually occur at the first or second most-likely crack location as predicted by the simulation. For 3 specimens, cracks did occur within the top-ten most-likely predicted locations. Only for the remaining 3 specimens (incidentally, all 250D specimens), there was no coincidence between any predicted and real crack location. Figure 3 shows the simulated versus predicted crack locations for five selected specimen.

4 Comparison with FEM Simulation

In [8], the results of the structural mechanics simulation in VGSTUDIO MAX were compared with those of a classical FEM simulation for a solid cube and a cubic lattice made from Ti6Al4V. In this case, the VGSTUDIO MAX simulation was carried out on an .stl mesh of the structures, and Autodesk Fusion 360 with a Nastran solver was used for the FEM simulation. For the solid cube, the maximum displacement and the effective Young’s modulus calculated with the VGSTUDIO MAX simulation differed by only +0,7% from the results of the Nastran solver. In the case of the lattice structure, the maximum local von Mises stress and the effective Young’s modulus are 2,5% higher than those obtained with the FEM solver. Given the inevitable variance of the setup of any simulation model and its influence on the results, this indicates a good agreement between the results of the VGSTUDIO MAX simulation and those of a classical FEM solver.

5 Practical Use in Quality Assurance

The task in quality assurance of manufactured components is to determine whether the observed defects such as porosity determined from CT scans can still be accepted or not. This is traditionally done by defining maximum acceptable levels of porosity in terms of aggregate porosity, maximum size and shape of pores and combinations thereof. These tolerancing criteria are typically based on experience and are heuristic in character. They do not explicitly quantify changes in the internal stress distribution caused by the defects compared to the CAD based FEM simulations of the idealized component which are used in the development and construction phase to assess the mechanical durability of the component.

Given the good agreement of the structural mechanics simulation of VGSTUDIO MAX as described above with both experimental results and traditional FEM simulations, the following procedure for quality assurance may be suggested: for manufactured components which have been CT scanned, a simulation of the internal stress distribution for the typical load case(s) is carried out using both the CT scan which represents the actual state of the component including defects and geometry deviations and a CAD model or surface mesh representing the ideal component as used in the design, construction and

FEM based durability simulation of the component. Tolerancing criteria can then be explicitly based on the extent to which the internal local stresses in the actual component exceed those in the ideal component and how this exceedance relates to the critical locations identified and the safety margins applied in the durability design of the component. An example for such a comparison is shown in Figure 4.

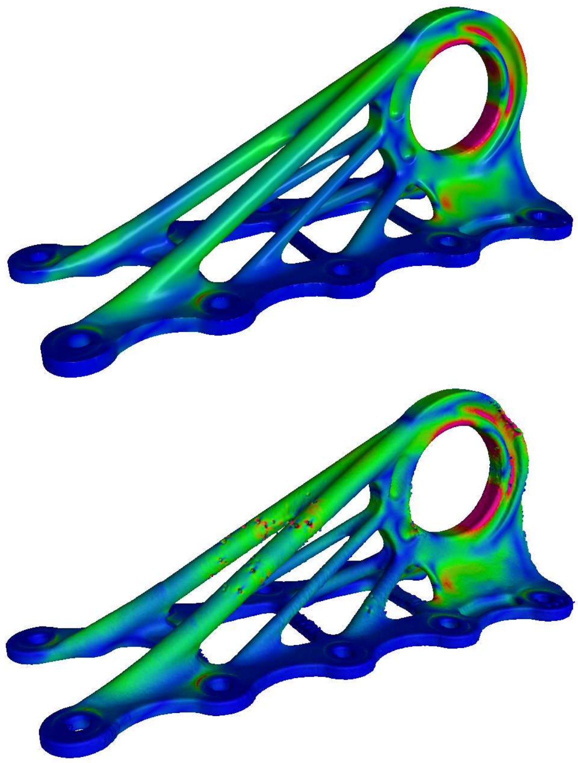

Figure 4: Comparison of the local von Mises stress distribution in an ideal component described by an .stl surface mesh (top) and an actual produced component with defects represented by its CT scan (bottom)

In this example, the porosity in the actual part leads to hot spots of higher local stress compared to the ideal component. The maximum internal stress observed anywhere in the specimen increases by more than 80 % and is found at a hot spot with a small volume in the zone of high porosity.

6 Summary and Conclusion

The new structural simulation method presented in this paper is capable of taking the effects of material defects like porosity and geometry deviations as determined from CT scans of manufactured components into account in the calculation of the internal stress distributions under a given external load. Its results are in good agreement with both experimental tensile tests as well as traditional FEM simulations. This suggests that it may be used in quality assurance to obtain an explicit quantitative understanding of whether or not observed porosity, defects or geometry deviations in actual parts could have a significant detrimental effect on the mechanical durability of the component.

Acknowledgements

This paper is an extended version of [1]. We thank Airbus Emerging Technologies & Concepts for the permission to use the bionically optimized bracket model. We thank diondo X-ray Systems and Services, Hattingen, Germany, for performing the CT scanning.

References

[1] J. Fieres, P. Schumann, C. Reinhart, "Predicting failure in additively manufactured parts using X-ray computed tomography and simulation", *Procedia Engineering*, (accepted for the proceedings of the conference Fatigue Design in Senlis, France, 29-30 November 2017), 2017.

[2] Q. Wan, H. Zhao, and C. Zou, Effect of micro-porosities on fatigue behavior in aluminum die castings by 3D X-ray tomography inspection, *ISIJ international* vol. 54, no. 3, pp. 511–515, 2014.

[3] E. Maire, A. Fazekas, L. Salvo, R. Dendievel, S. Youssef, P. Cloetens, J.M. Letang, X-ray tomography applied to the characterization of cellular materials. Related finite element modeling problems, *Composites sci. and technology* vol. 63, no. 16, pp. 2431–2443, 2003.

[4] V.P. Nguyen, T. Rabczuk, S. Bordas, M. Duflot, Meshless methods: a review and computer implementation aspects, *Mathematics and computers in simulation*, vol. 79, no. 3, pp. 763-813, 2008.

[5] J.R. Shewchuk, What Is a Good Linear Finite Element? *Interpolation, Conditioning, Anisotropy, and Quality Measures*, University of California at Berkeley 73, Preprint, 2002.

[6] D. Schillinger, M. Ruess, The Finite Cell Method: A Review in the Context of Higher-Order Structural Analysis of CAD and Image-Based Geometric Models, *Arch. Comp. Meth. Engin.* vol. 22, no. 3, pp. 391–455, 2015.

[7] Volume Graphics GmbH, Heidelberg, Germany, https://www.volumegraphics.com (loaded 17 May 2017), 2017.

[8] 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.