Accurate and efficient simulation of real pore geometries directly on CT images

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1. Background

In cast or additively manufactured components, a certain amount of unwanted porosity is typical to the manufacturing process and cannot be avoided altogether within economically feasible limits. Therefore, the assessment of the mechanical effects of porosity by finite-element analysis (FEA) has gained strong interest. With computed X-Ray tomography (CT) it is possible to capture the full three-dimensional geometry of real porosity in high resolution without destroying the component. Simulating such realistic geometries using classical finite elements analysis (FEA) is difficult. FEA requires the creation of a geometry-conforming mesh. For pores captured by CT, this constitutes a major challenge due to the often-complex structure. In fact, the meshing process is often the limiting factor in the simulation process, sometimes leaving it impractical.

Recently, immersed finite element methods, also known as embedded of fictitious domain methods, have been developed to overcome the meshing problem (see, e.g., [1]). Such methods do not require the generation of a boundary-conforming mesh and are thus well suited for simulating complex geometries. The simulated domain is embedded into an extended, much simpler, domain which can be discretized in a trivial way, e.g., with straight hexahedral elements. Using a custom integration scheme, the original object shape is still simulated accurately (see Fig. 1).

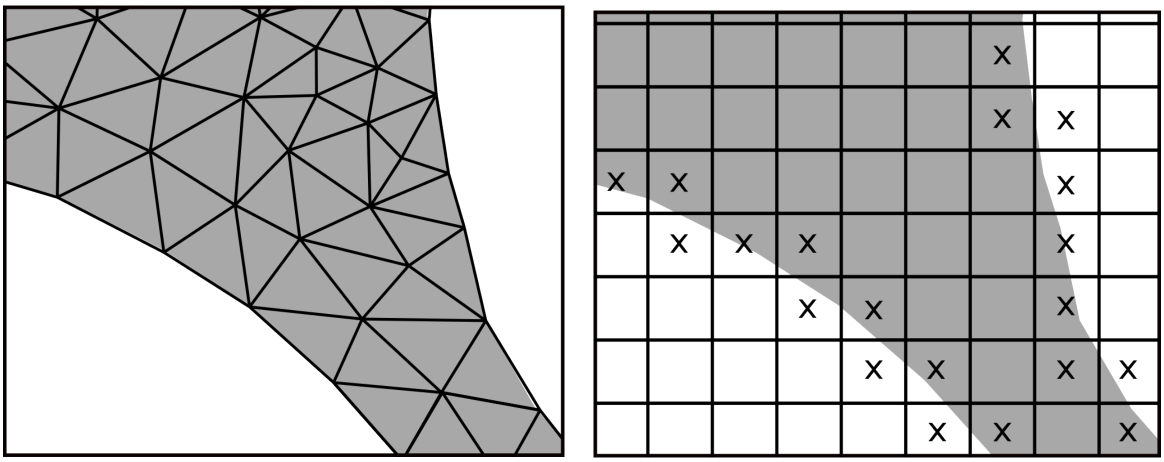

Fig. 1. Left: Classical FEA: The shaded area is a detail of a complex simulated object. The object is represented by a geometry-conforming mesh (black lines). Right: Immersed method. The simulation domain is extended beyond the object borders and discretized by a trivial quadrilateral mesh (black lines). The mesh cells cutting through the object boundary (marked with crosses) are treated in a special way to regard the exact object surface (no "Lego"-brick model!)

2. Methods

A high-performance immersed finite element code is available in the CT analysis software VGSTUDIO MAX software by Volume Graphics GmbH. The code processes directly raw CT image data, but it works evenly well with explicit models like surface meshes or CAD data.
In this study, we compare the immersed finite element code against an established classical FEA from ANSYS Inc.

A: Idealized pore geometry. Two cylindrical test specimens with 14 mm diameter is modelled using CAD software. In each, a single pore is placed in the centre of symmetry. In the first model, the pore is idealized by a sphere (diameter 3.0 mm), in the second by a lenticular biconvex shape (long/sort axis 3.0 mm/0.6 mm, fig.2). Both models are simulated in linear-elastic uniaxial stress by VGSTUDIO MAX and ANSYS Workbench.

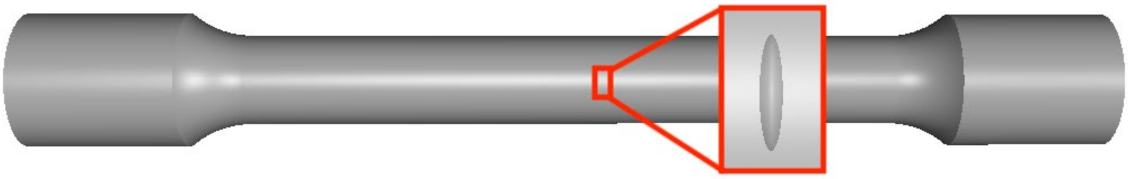

Fig. 2: CAD model of the test specimen. A pore is inserted at the centre of symmetry (elliptical version shown here).

B: Realistic pore geometry. Two physical test specimens are manufactured according to the idealized models using additive manufacturing by EOSINT M 270 for printing with powders of AlSi10Mg. The specimens were built with the main axis parallel to the growth direction Z. The geometry of the specimens and the shape of the designed defects are relatively simple, as compared to usually more complex ones in the field of AM. This approach was chosen in order to setup the method and to attain a first proof of concept, to be further validated by using more complex shapes. Due to typical process limitations, the ideal pores translate to a fractal-like shape in the physical world (see Fig. 3). CT Images are acquired with a voxel resolution of 63 um. The images are segmented using the surface determination algorithm of VGSTUDIO MAX. For proceeding with the ANSYS software, the surface data is exported as an STL file and a volume mesh is generated using ANSYS Workbench. The simulation code of VGSTUDIO MAX works directly on the internal surface representation and does not require a separate meshing step. For both simulations 15 kN load were used.

Both the idealized models and the CT data is taken from a previous study of pore effects (see [2]).

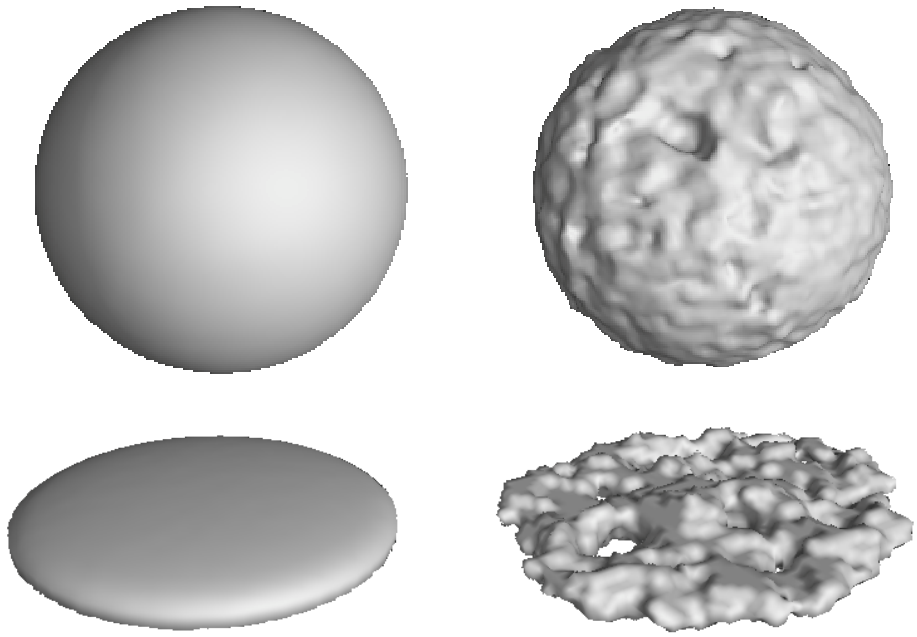

Fig. 3: 3D renderings of the studied pores, shown as solid bodies for better visualization. Top: Spherical pore (d=3mm), bottom: elliptical pore (3mm/0.6mm). Left: Idealized pore shape. Right: Real pores in additively manufactured parts. Surface segmented from CT images

3. Results

Numeric accuracy. We plot line profiles of the Von Mises stress in the proximity of the pore, both parallel and perpendicular to the load axis. We see that for the idealized structures both solvers predict effectively the same stress distribution (Fig. 4, top row). For the simulations based on CT images, differences are present (Fig. 4, bottom row). For the elliptical pore, the predicted stress concentration in the perpendicular profile is much lower for the classical FEA solver. For both pores, the stress variations in the parallel profiles are more pronounced in the immersed method. In Fig. 5, we show a visualization of the Mises stress in a 2D section through the elliptical pore. Apparently, the level-of-detail of the immersed method is much greater. This explains the differences we see in the stress profiles. With the immersed method, the spatial accuracy of the solution is only limited by the resolution of the CT images whereas in the classical method accuracy is lost in the additional discretization step of volume meshing. We assume that, for the real geometries, the immersed method is better suited to reveal the true stress distributions.

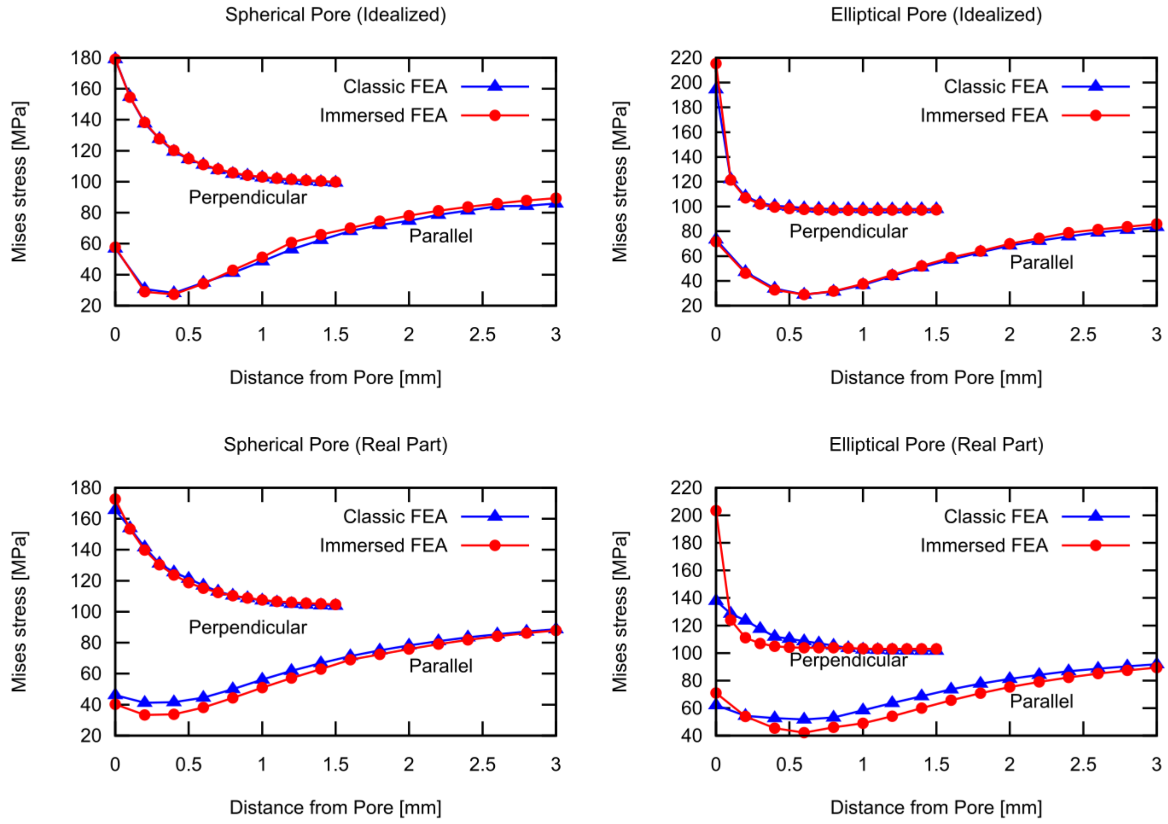

Fig. 4: Top row: For idealized geometries the computed stresses are effectively identical between the classic FEA and the immersed solver. Bottom row: For simulation on CT images of real parts, the immersed method takes more geometric details in to account and thus yields more accurate results.

Performance. We report the calculation efforts in Table 1. The total computing time is much shorter with the immersed finite element solver. In the classical FEA approach, most of the effort goes into the meshing procedure. The advantage of the immersed method in terms of performance is apparent.

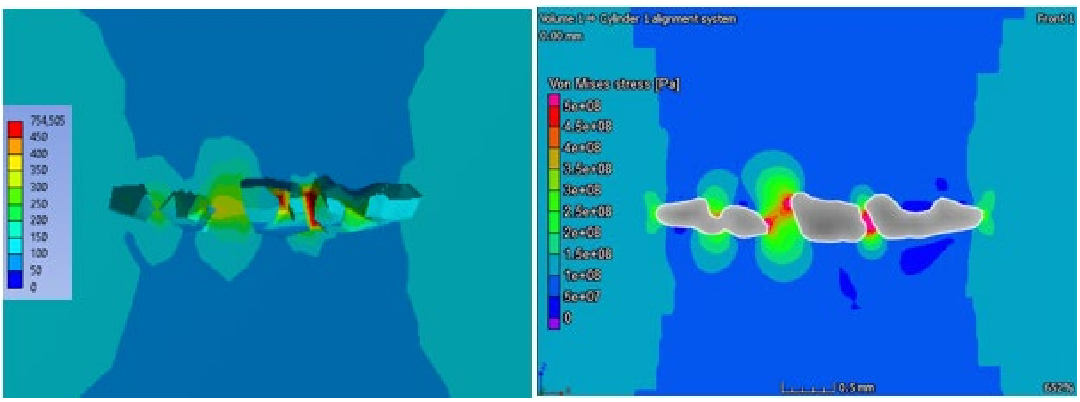

Fig. 5: Mises stress on a 2D section through the elliptical pore. Left: Classical FEA, Right: Immersed method.

	ANSYS Workbench			VGSTUDIO MAX
	Meshing [min]	Solving [min]	**Total [min]**	**Total [min]**
Ideal sphere	4	5	**9**	**3**
Ideal ellipse	4	5	**9**	**3**
Real sphere	30	5	**35**	**10**
Real ellipse	30	5	**35**	**10**

Table 1: Computation time spent for simulating the ideal and real geometries.

4. Conclusions

An immersed finite element solver can achieve accurate results on idealized data, especially regarding the precision around the defect boundary. Furthermore, when simulating on CT image data, the immersed method can play its major advantages: a) A much finer level-of-detail since no accuracy is lost in the meshing step, and b) less total computer time spent, since the meshing procedure is saved, which otherwise dominates the total simulation effort.

This study was conducted on a single pore only. However, in real components we find typically many (hundreds or sometimes thousands) of individual pores. We note that, for the immersed finite element solver, the computational effort does not increase with the number of simulated pores in the part. With classical FEA, however, the meshing effort will strongly increase if more pores are to be simulated.

We conclude that the immersed method is an accurate and efficient method for the simulation of mechanical effects of porosity in real parts. Components with more complex geometry, more real defect and with different materials could be basis for future development, comparing with experimental data and adding non-linear field behaviour.

References

[1] Schillinger, D., Ruess, M. (2015). 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., 22(3), pp. 391–455.

[2] F.Esposito, A.Gatto, E. Bassoli, L.Denti, ‘A Study on the Use of XCT and FEA to Predict the Elastic Behavior of Additively Manufactured Parts of Cylindrical Geometry’, Journal of Nondestructive Evaluation (2018) 37:72, https://doi.org/10.1007/s10921-018-0525-x