AI Supported NDI Methods for Ceramic Components

ESA contract no. 4000141359/22/NL/RA/cb

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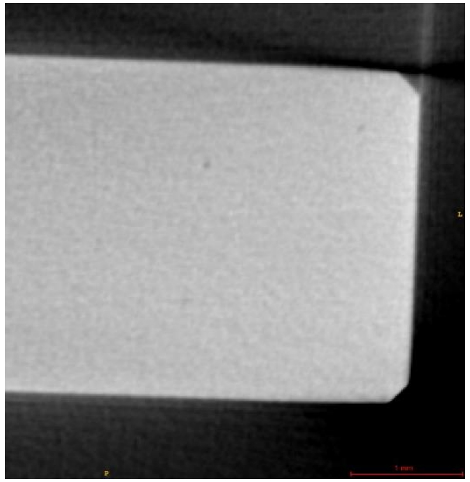
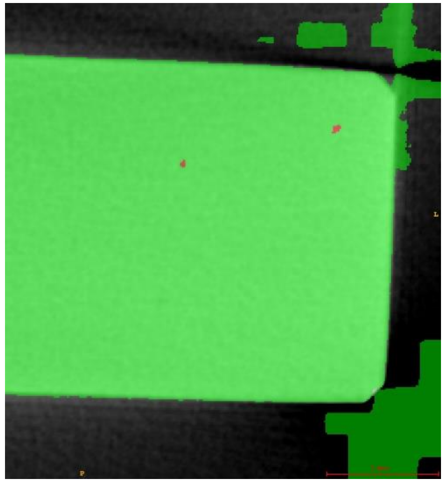
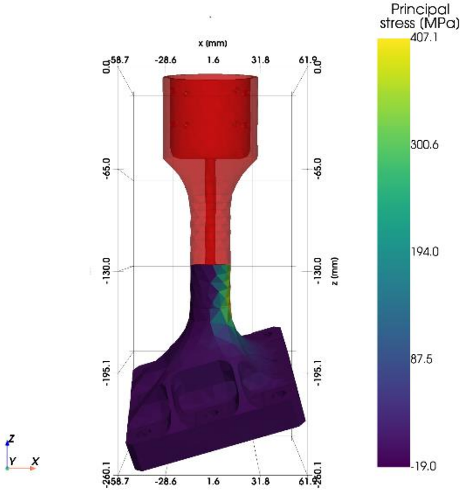
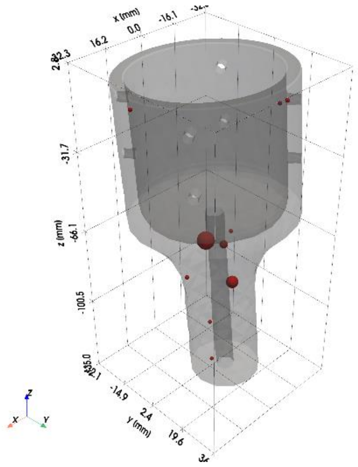
Final Review at ESTEC (Noordwijk), 11.07.2024







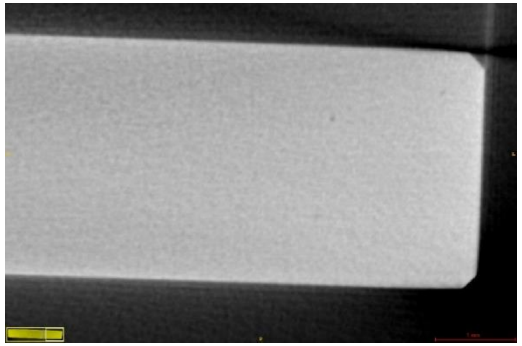


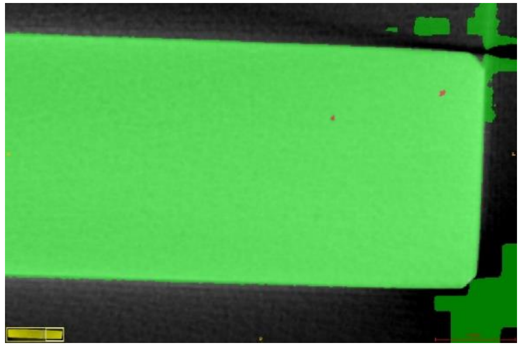
Project goal

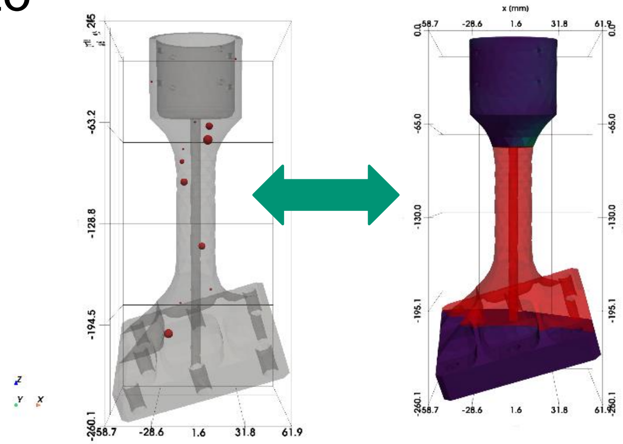
- Develop X-Ray Computed Tomography towards a reasonably fast and reliable non-destructive testing (NDT) technique by combining it with ...
  - appropriate artificial intelligence (AI) algorithms, and
  - Finite Element (FE) analyses of the stress fields under application conditions

- Develop an algorithm for automatized control of the CT inspection process including autonomous identification and scanning of the critical regions to be scanned with high CT resolution

- The technology to be developed shall be suitable for all space-relevant ceramic materials and transferable to material testing in general.







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Summary of performed works

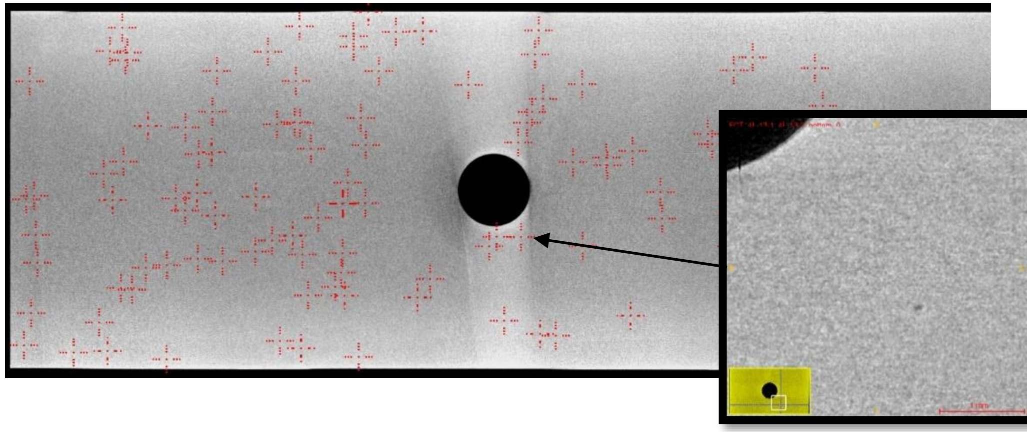
- Development of image segmentation for ceramic CT images (WP1 + WP2)
  - Preparation of training data set based on data from previous project
  - Training and validation of the model

- Selection of demonstrator part (WP3)
  - Lower-end fitting part provided by Thales
  - Execution of CT scans at multiple resolution scales
  - Finite element (FE) mechanical simulations of part under application conditions

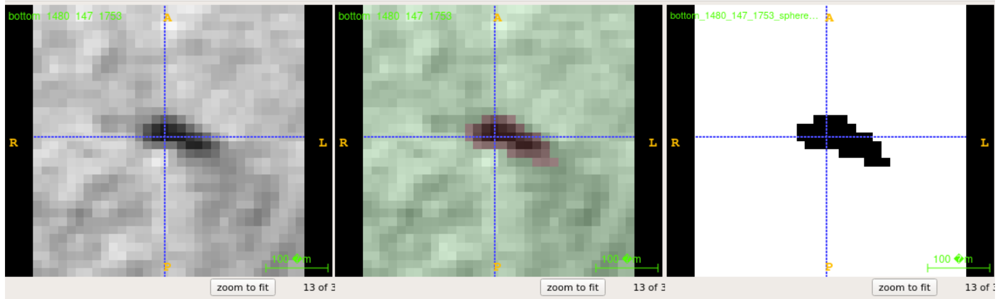
- Development of adaptive CT scanning strategy (WP3)
  - Algorithm for assessment of defects in combination with FE data
  - Iterative refinement of scanning resolutions at selected regions of interest

Revision: Image segmentation algorithm for ceramic CT images (WP1 + WP2)

- Preparation of training data set based on existing data from previous project
  - Utilization of CT scans of Si_3N_4 samples
  - Generation of training data from human-labeled defect locations



- Training and validation of the convolutional neural network for 3D segmentation of defects
  - Implementation based on (open source) nnUNet framework
  - Ability of the model to correctly label background, matrix and pores / regions of inhomogeneity
  - Evaluation using additional scans not used during training
  - Delivery of algorithm as Python package (TN3)



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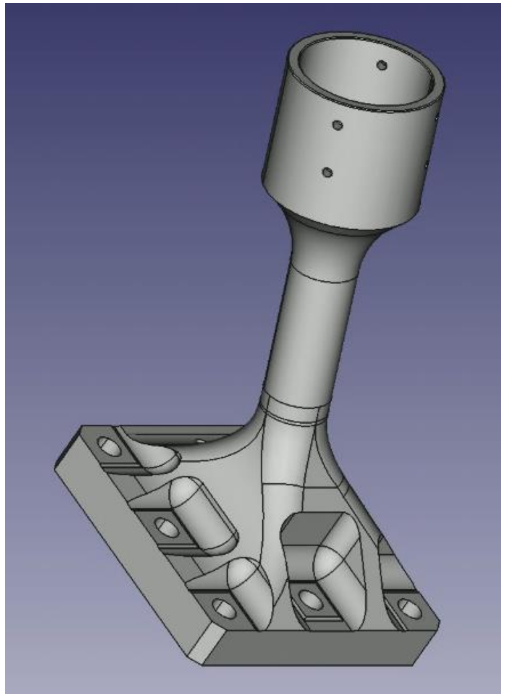
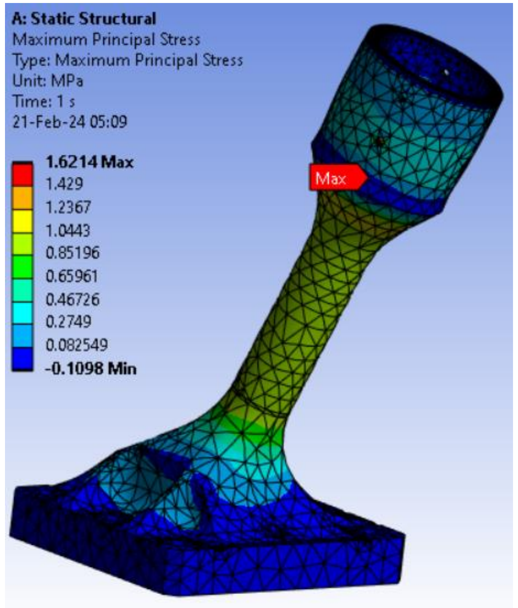
WP3: Selection of demonstrator part

- Si_3N_4 lower-end fitting part of a satellite was provided by Thales Alenia Space (TAS)
  - 3D geometry file and report of mechanical simulations
  - → Used for 3D mechanical simulations at HTL
  - Physical component
  - → Used to demonstrate capabilities of the automated evaluation procedure

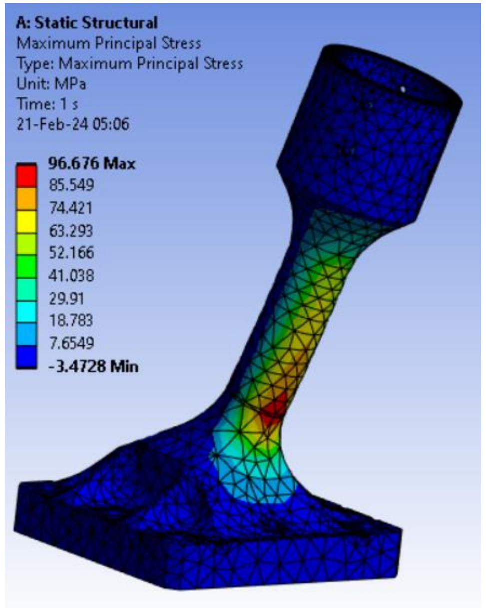


FE simulations of demonstrator part

- FE simulations of demonstrator part under operating conditions have been carried out (based on supplementary information provided by TAS)
- Boundary conditions:
  - Tensile:
    - Application of unit force of 1000 N along the central axis of the part
  - Bending:
    - Application of unit force of 1000 N orthogonal to central axis
- Resulting spatial distribution of stresses within the material serves as input for adaptive analysis



Tensile load

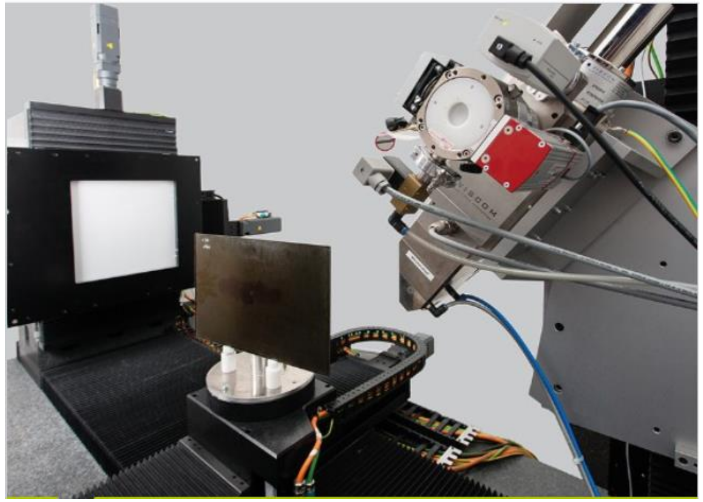


Bending load

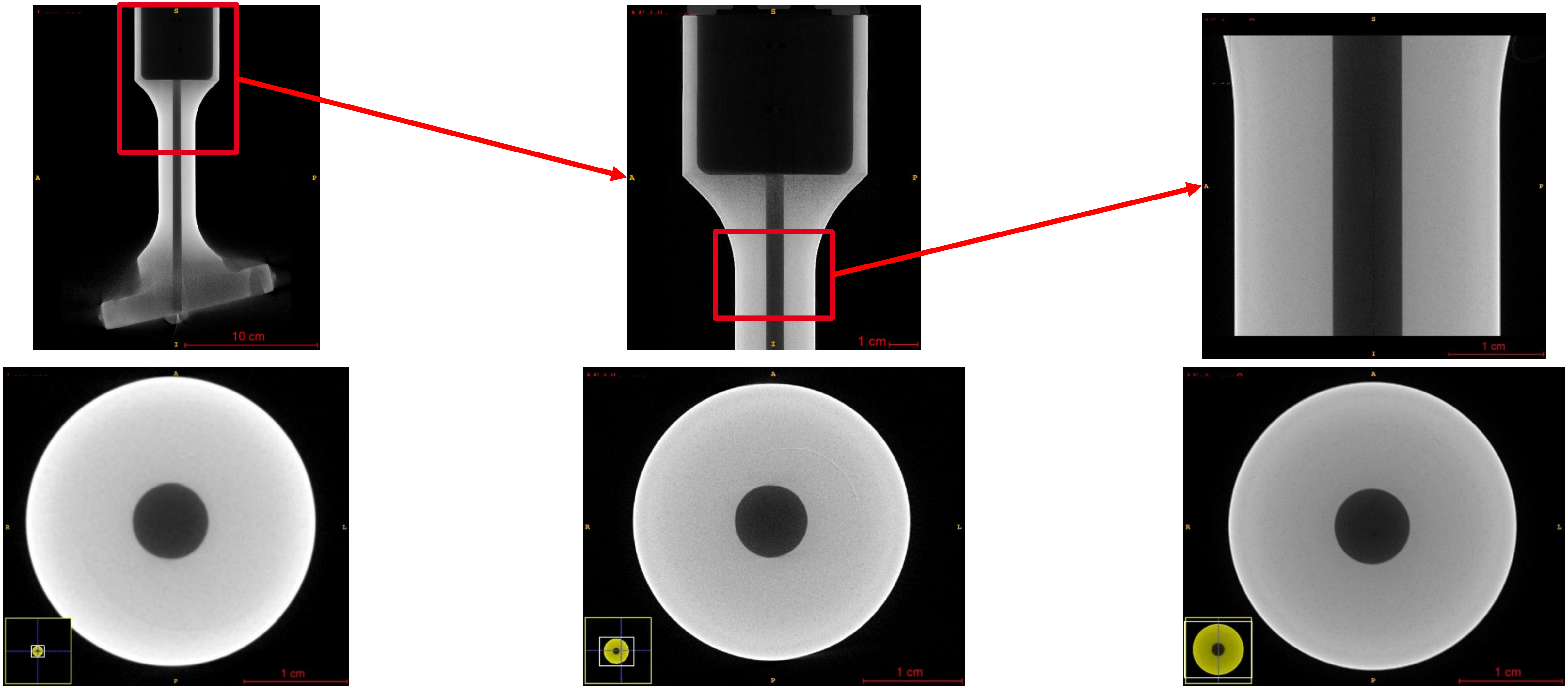
CT scans of demonstrator part

Scan ID	Scan type	Resolution	Voxels	Scan volume [cm³]
0	Full part, low-res	0.08687 mm = 87 µm	1999x1999x3016	7900
1	Upper section, mid-res	0.03682 mm = 37 microns	1999x1999x 3261	650
2	Upper section, high-res	0.01815 = 18 microns	1999x1999x1747	41
3	Upper section, very high-res	0.01022 mm = 10 microns	3890x3890x1492	24

- CT scans of demonstrator part at different resolution scales have been carried out
- Variation of resolution between 87 and 10 microns
- Scanning time for scans 0 – 2: approx. 90 minutes each
- Scanning time for scan 3: approx. 180 minutes
- Scanning of full part at highest resolution scale would take several days worth of scanning time
→ not feasible



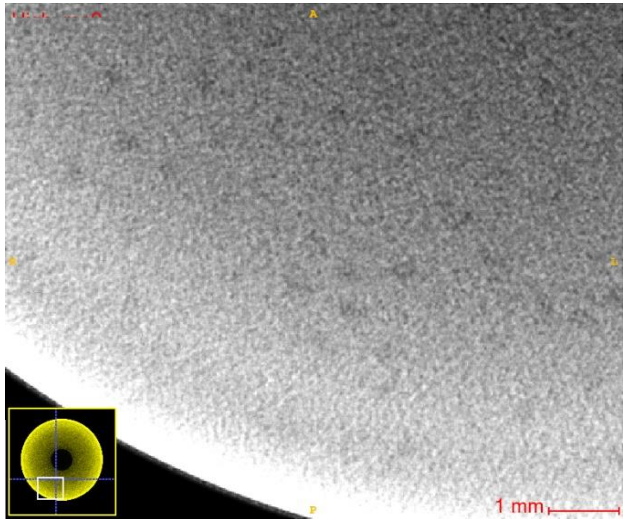
Previews of CT scans of demonstrator part

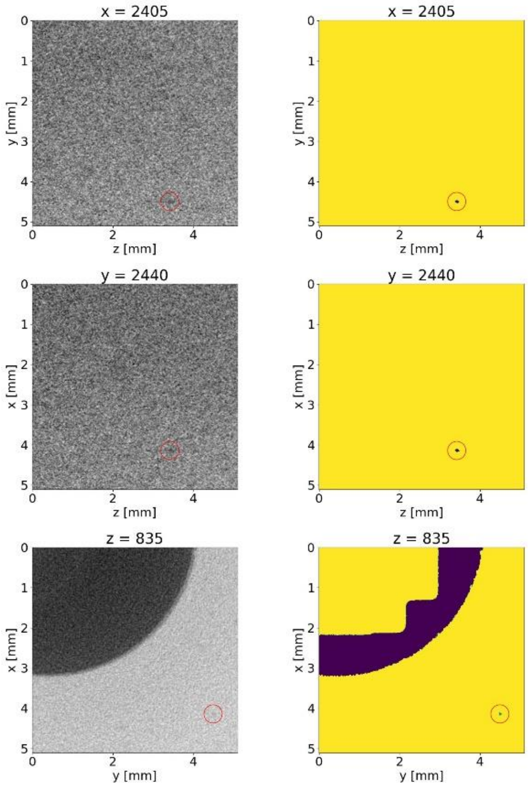


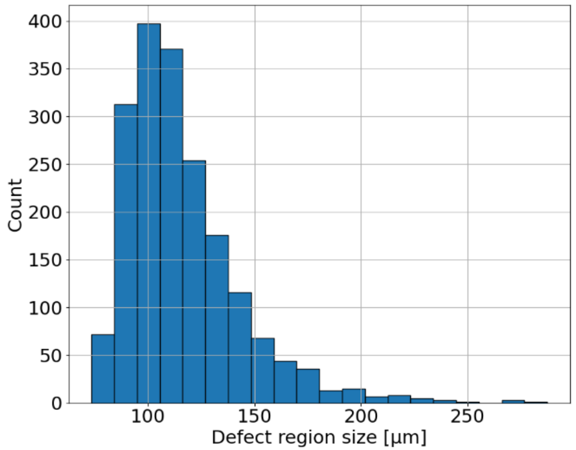
87 microns | 37 microns | 18 microns

Defect analysis based on CT data

- Close-up reveals large number of inhomogeneities within the material (visible only at highest resolution scale)
- Defect segmentation algorithm was applied to the scanned image
- The algorithm was able to identify a number of pores in the image (including information about location, size, and shape)





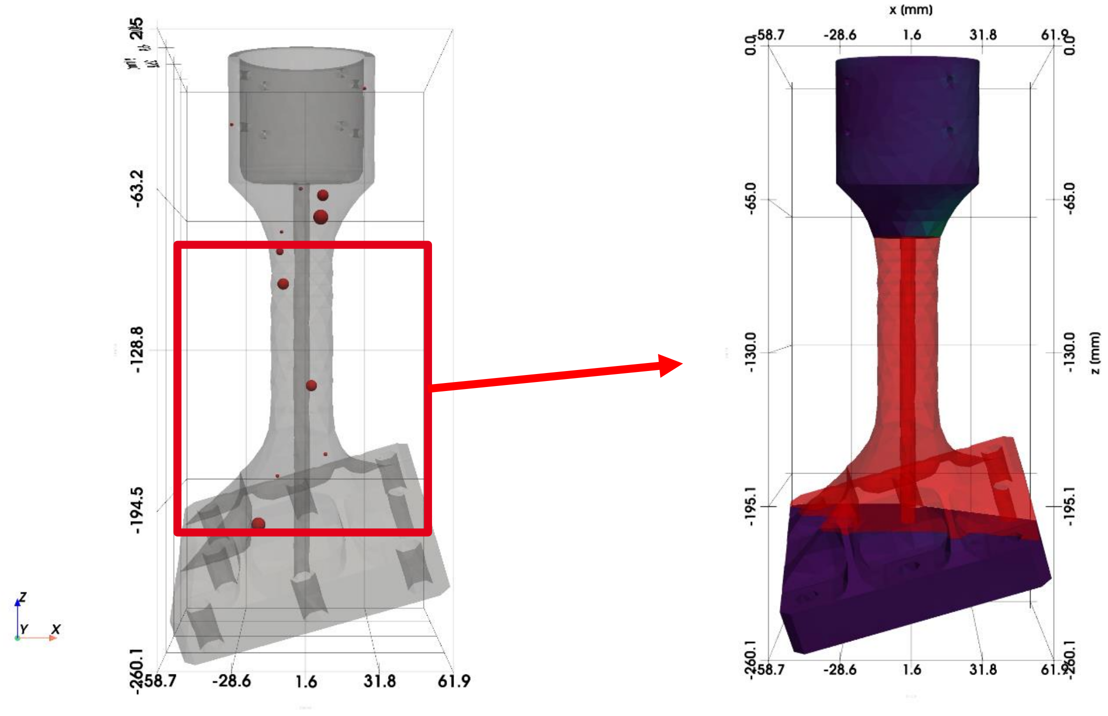


Adaptive CT scanning procedure

- Aim: develop a methodology for optimized scanning of complex ceramic parts

- Idea:
  - Start with coarse scan of the part
  - Combine information from FE analysis and defect locations at low-resolution
  - Refine scanning resolution in selected regions-of-interest (ROI) based on local critical defect size

  → Could permit the presence of defects in regions of the part where low stresses are expected



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Defect assessment routine

- Inputs:
  - K_{IC}: fracture toughness of material
  - σ_f: tensile strength of material
  - $\sigma_{FE}, \sigma_{FE}^{max}$: FE local stress distribution, maximum local stress from FE
  - f: safety factor (≥ 1)

1. **Calculate the global critical crack length of the material according to $a_{glob} = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_f}\right)^2$.**
2. **Run segmentation algorithm for initial scan and mark all defects detected by the segmentation algorithm as *possibly critical*.**
3. **For each defect voxel region, perform the following steps:**
   a. **Determine equivalent defect size a.**
   b. **If $a < a_{glob}$, mark the defect as *not critical*.**
   c. **Otherwise, compute the local stress σ_{loc} at the defect using the finite element simulation result σ_{FE} of the part under application load.**
   d. **Compute a local critical crack length by $a_{loc} = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_{loc}\, f}\right)^2$.**
   e. **If $a < a_{loc}$, mark the defect as *not critical*.**
4. **Mark all remaining defects as *critical* → re-investigate at higher resolution scale.**

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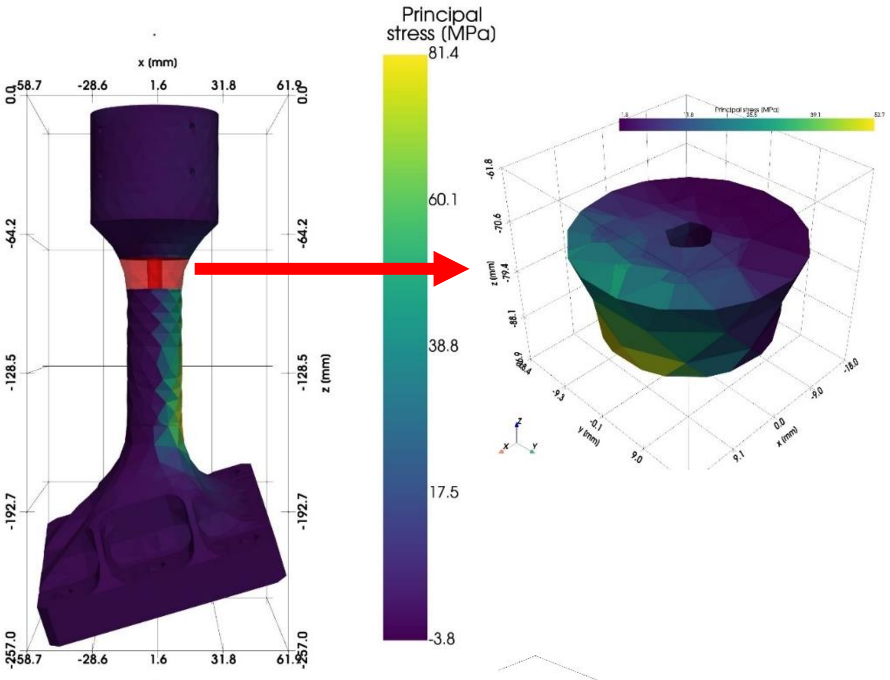
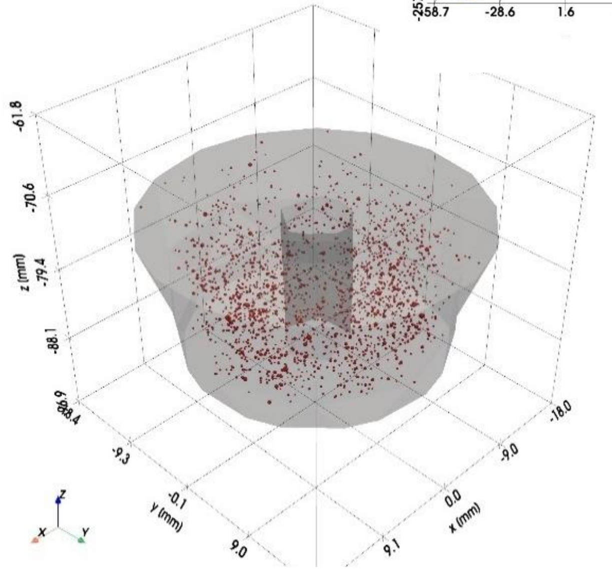
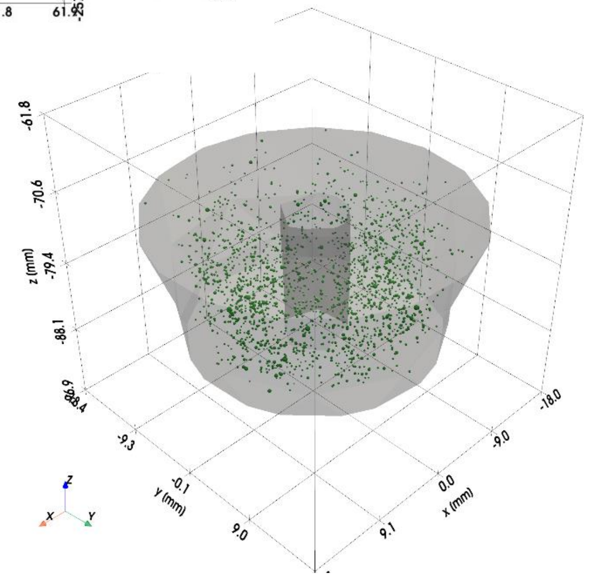
Demonstration of defect assessment routine

- Defect assessment is demonstrated for highest-resolution CT scan (10 microns) of upper section of the demonstrator part
- Image segmentation algorithm successfully identifies regions of inhomogeneities
- Mapping of FE stresses from bending test to defect locations and assessment using Griffith's criterion
- With the given material parameters, external load and safety factor of $f = 1$ all defects are assessed as uncritical





Defects identified by segmentation algorithm



Evaluated defects (green = uncritical)

Algorithm for adaptive scanning procedure

- Inputs:
  - K_{IC}: fracture toughness of material
  - σ_f: tensile strength of material
  - $\sigma_{FE}, \sigma_{FE}^{max}$: FE local stress distribution, maximum local stress from FE
  - f: safety factor (> 1)

1. Determine resolution for initial scan W_0 based on critical defect size from Griffith's criterion:

$$r_0 = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_{FE}^{max} f}\right)^2$$

2. Perform image segmentation and evaluate defects using defect assessment routine (see previous slide).
3. If any *critical* defects remain, set next resolution $r_i = \frac{r_{i-1}}{2}$
4. Generate scanner configuration files for taking new images W_i^j covering the locations of all critical defects
5. Resume adaptive algorithm at 2.
6. Terminate algorithm if:
   - No *critical* defects remain or
   - any defects have been confirmed as *critical* at two subsequent iterations or
   - minimum resolution $r_n < \boldsymbol{a_{glob}}$ (global critical defect size) has been reached.

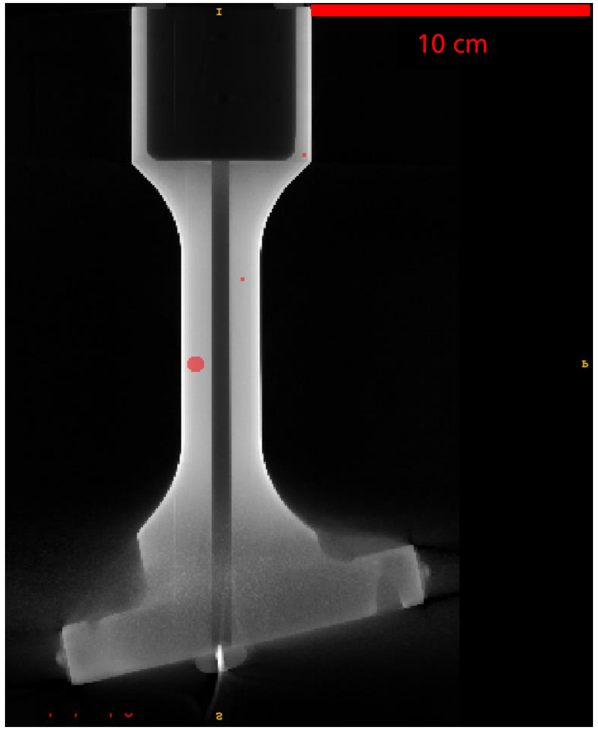
Demonstration of adaptive algorithm

- Working principle of the adaptive algorithm is demonstrated using hypothetical pore locations

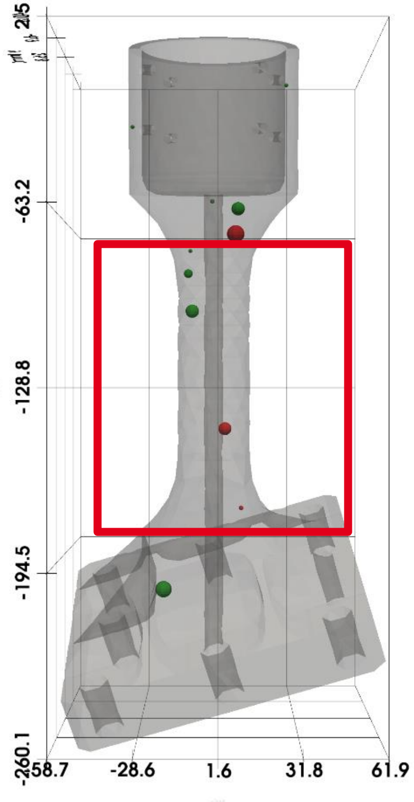
- Initial scan of full part at resolution of 695 microns
- Application of defect segmentation algorithm to identify defect locations
- Evaluation of detected defects using assessment procedure

- Generation of scanner configuration for higher-resolution scans parts of the image with critical defects
- Re-scanning of selected part → scan images W_1^1, W_1^2, W_1^3

Initial scan W_0



Defect assessment for W_0



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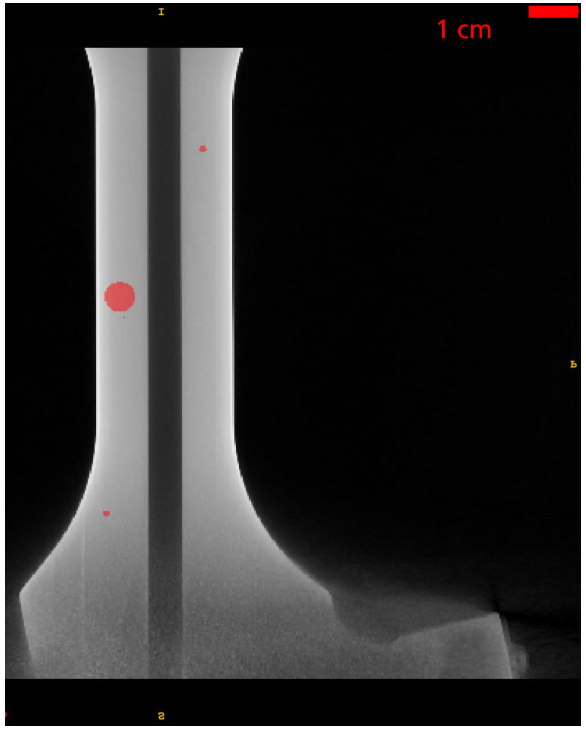
Demonstration of adaptive algorithm

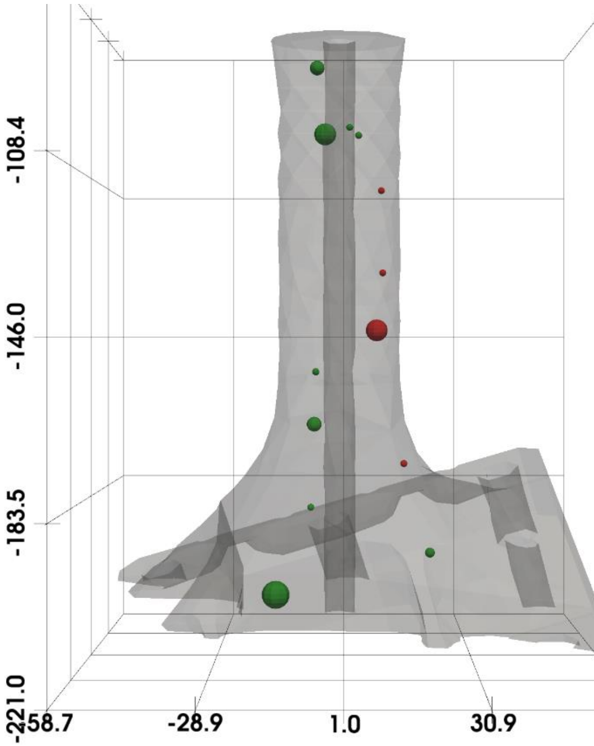
- Second scan of central region of the part at halfed resolution of 347 microns
- Application of defect segmentation algorithm to identify defect locations
- Evaluation of detected defects using assessment procedure

- In this case, the algorithm would terminate, because a a defect is marked as critical at two subsequent iterations

Second scan W_1^1



Defect assessment for W_1^1



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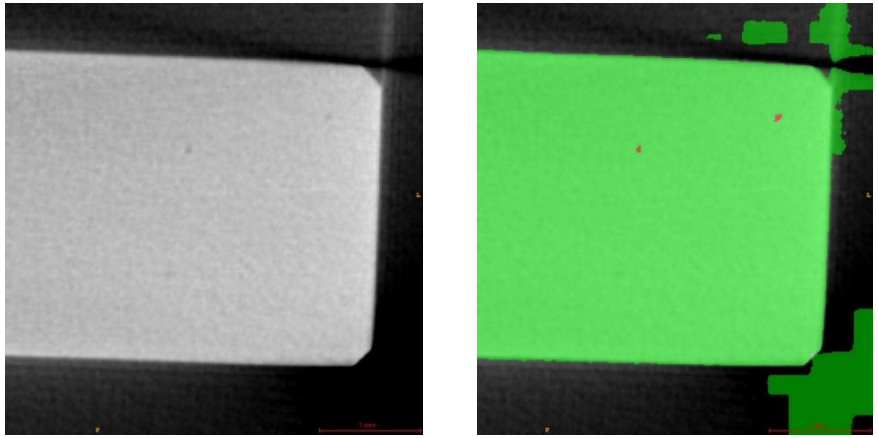
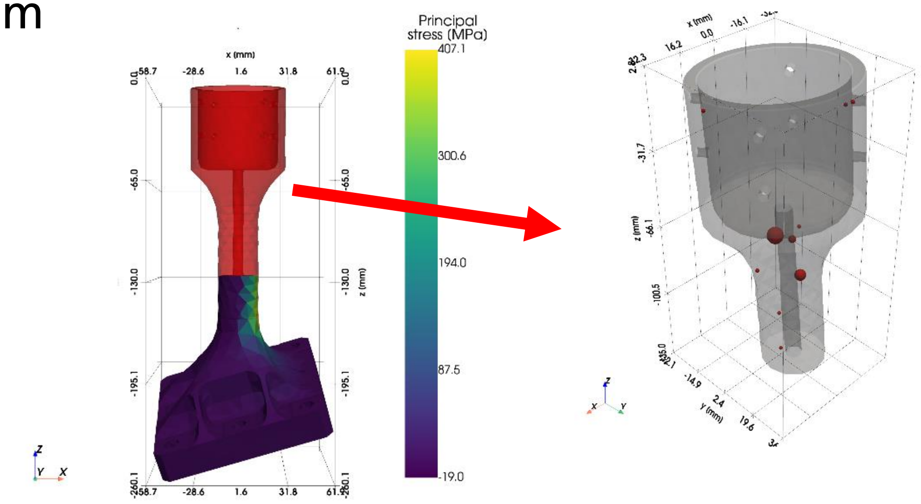
Summary and conclusion



- An AI based method for defect detection and segmentation in CT images of ceramic components has been developed



- Information about detected defects is combined with data from FE analysis to enable assessment of defect under application conditions
- Defect assessment procedure is applied in adaptive fashion to enable iterative refinement of CT scanning resolution and reduce total scanning time
- Developed methodologies are demonstrated using a real Si_3N_4 ceramic part

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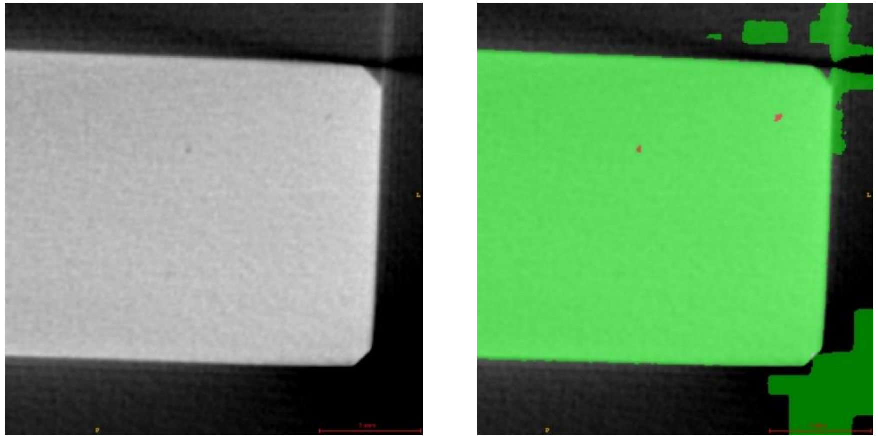
Summary and conclusion



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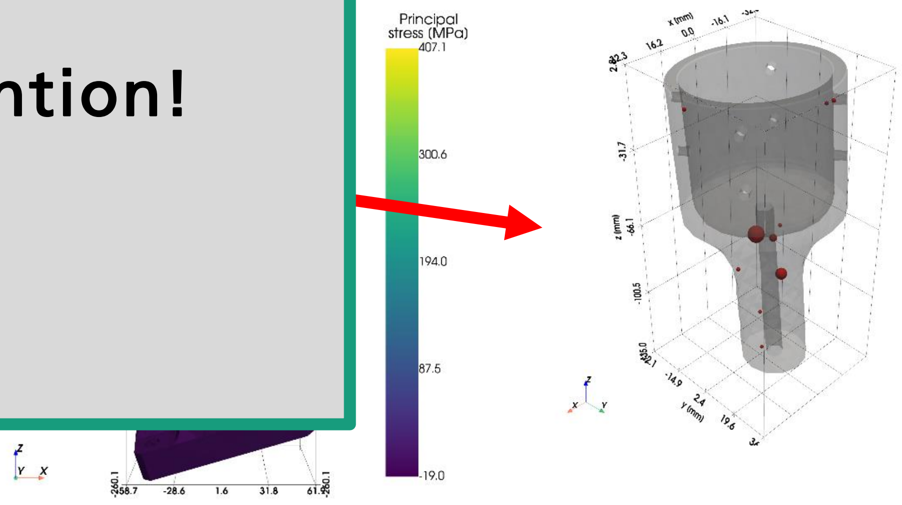
Thank you for your attention!

Any questions?



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