At-line X-ray computed tomography of serial parts optimized by numerical simulations

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Abstract. Within this work, optimisation advances of an at-line X-ray computed tomography (XCT) inspection system at Nemak Linz are presented. The ZEISS VoluMax 1500 G2 is operated together with an ABB loading robot for automated inspection of serial parts as wells as prototypes of aluminium casted cylinder heads produced for the automotive industry. Typical scanning times for these high absorbing specimens are ranging from 40 to 400 seconds.

The defect detection software provided by the manufacturer is used to automatically identify and classify defects of serial parts and decide between “okay” and “not okay” parts. The ZEISS Automated Defect Detection (ZADD) software consists of anomaly detection, defect classification and a segmentation based on deep learning that requires an initial teaching phase.

The detection seems robust, but the artificial manufacturing of parts with critical defect types and sizes at specific locations and their experimental verification is challenging and very time consuming. This work presents an exemplary verification for one selected specimen and for one particular defect type with different sizes. Besides real also simulated data with virtual defects are evaluated using the ZADD. Advantages of numerical simulation in combination with the presented defect detection are discussed in detail.

Introduction

In the automotive industry, the demand for 100 % part inspection by original equipment manufacturers, and the supply of parts with zero-defects, is increasing to minimize value loss to the industry. Nemak Linz – a supplier of casting parts – acquired an at-line X-ray computed tomography (XCT) inspection system from ZEISS in 2018 to fulfil these demands. At Nemak, XCT is used for two different scenarios. The first task targets for an automated serial inspection of cylinder heads with a part-to-part time of well below two minutes and the second task targets to robustly inspect prototypes in the development phase with scanning times of 7-8 minutes. Thus, the main differences of those two inspection tasks are throughput rates, achievable image quality, part handling, data evaluation and primary inspection goals. Table 1 shows a detailed comparison.
Table 1. Inspection tasks covered with the at-line inspection setup

<table>
<thead>
<tr>
<th>Inspection task</th>
<th>Typical scanning times in [min]</th>
<th>Typical throughput per hour</th>
<th>Part handling</th>
<th>Data evaluation</th>
<th>Inspection goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial inspection</td>
<td>1-2</td>
<td>30-60</td>
<td>Robot</td>
<td>Automatic</td>
<td>Defect detection and continuity of water jacket</td>
</tr>
<tr>
<td>Prototype inspection</td>
<td>7-8</td>
<td>7-8</td>
<td>Manual</td>
<td>Manual</td>
<td>Defect detection and dimensional metrology (check sand core shrinkage)</td>
</tr>
</tbody>
</table>

Although XCT data in the case of prototype inspection has to be inspected manually, the longer scanning times make this particular inspection task much more robust. Though, setting up a robust and reliable serial inspection based on limited data is difficult, especially if the ability to detect critical defects at critical positions has to be qualified. One way to achieve this is to produce physical parts with specific defect types and sizes at specific locations. This is in particular challenging as some defect scenarios only occur at specific casting situations or under critical casting parameters and may not be imitated artificially.

A more elegant way is to use a virtual engineering approach by using numerical simulations of the X-ray imaging process. This work shows the potential of numerical simulations to generate a virtual failure catalogue for a selected specimen, find the detection limits for different defect types, optimize XCT acquisitions and simplify the teaching process of the ZEISS Automated Defect Detection (ZADD) provided by the XCT manufacturer. Related work in the field of inline XCT inspection is presented in [1].

1. Methods

1.1 At-line X-ray computed tomography system

The scanning setup of the VoluMax 1500 at-line XCT is built around X-ray components that allow fast data acquisition. This is achieved by a Comet 225 kV dual-focus X-ray source with a maximum power of 1800 W and with a focal spot size of 0.4/1.0 mm combined with a Perkin Elmer XRD1620 flat panel detector with 33 ms minimal integration time, when operated in binning 2x2 mode. Continuous rotation of the rotary table ensures fast data acquisition. The X-ray source is equipped with a mechanical shutter for continuous failure-free operation and guaranteeing a long lifetime in 24/7 use.

The at-line system is supported by an automated part loading robot (see Fig. 1 right). Robot support is necessary to achieve constant and high throughput rates and to be able to handle several hundreds of pieces a day. Safety circuits of automation and XCT system are linked together, which means operation is only possible if both safety circuits are closed. The whole system is running within a robot cell with regulated access doors. The serial inspection process is shown in Fig. 2 in a simplified flowchart. Part handling and data acquisition steps are highlighted in blue. The data evaluation steps are highlighted in green and are described in detail in the following chapter. Note that, data acquisition and evaluation may run asynchronously.
1.2 Automated Defect Detection

The automated serial inspection is performed with the ZADD software that automatically segments and classifies defects. The configuration of this software for a specific evaluation task works in three levels.

In a first step, a so-called golden part is calculated based on XCT data of at least 10 “okay” parts that are within the specification. Therefore, the used scan parameters have to be constant and similar to the actual serial inspection parameters. This golden part serves as reference for all work pieces that are tested in the serial inspection process. Special local features (grey values, standard deviations etc.) of work piece and golden part are compared and analysed to detect deviations from nominal specimen properties.

In a second configuration step regions of interest have to be defined based on the golden part to be able to tolerate slight casting variations (e.g. position tolerances of sand cores) or varying casting characteristics (e.g. core prints, foundry marks), which avoids pseudo detections. If the comparison of local feature values to the golden part indicates local deviations above a certain threshold, defects are segmented to determine defect properties e.g. size.

Subsequently, the determined defect properties are classified and compared with specified limit values that may differ in different evaluation regions (e.g. water jacket). Setting these local limits is the third configuration step of the inspection, which finally allows an automated decision between “okay” (OK) and “not okay” (NOK) part.
Typical macroscopic defects are shown in Figure 3 that can be found with the presented at-line inspection scenario.

Fig. 3. Typical defects that can be detected with an at-line system used for serial inspection: (a) flash, (b) core failure, (c) broken sand core, (d) core inclusion, (e) porosity or shrinkage holes, (f) crack, (g) void or air bubble and (h) higher-dense inclusion

In the case of a NOK part, a post-decision process is initiated, where the XCT results of this NOK part are presented to the XCT operator in form of a ZEISS PiWeb-report. Defects are shown from different directions and their position is visualised in a semi-transparent 3D rendering of the CAD. This visualisation enables the XCT operator to decide if the part is indeed NOK. If a defect is tolerable the XCT operator can declare a part as OK.

2. Experimental

2.1 Test specimen for serial inspection

The investigated cylinder head and cylinder heads in general are produced by the world leading dynamic casting process called Rotacast® process at Nemak. Rotacast® is a Nemak owned special permanent mould casting process for producing high quality parts. By a 180° rotation the mould is smoothly filled without turbulence creating an ideal temperature gradient that compensates the melt contraction and hence significantly reduces micro-porosity formation.

Systematic investigations within this work are done for a casted aluminium cylinder head with artificially prepared sand cores by sawing notches into the water jacket at selected positions. The notches result in wall-like aluminium structures in the casting that have a thickness of 1.2-1.35 mm and taper the water jacket. Sand core manipulations were made to achieve the following discontinuities in the water jacket:

- Position 1: partly closure of 75% at a single position
- Position 2: partly closure of 25% at a single position
- Position 3: partly closure of 25% at two positions in opposite direction
- Position 4: partly closure of 50% at two positions in opposite direction

Fig. 4 shows a 3D visualisation of the four water jackets and the corresponding manipulated sand cores used to cast the specimen.

The investigated cylinder head has a bounding box of roughly (200 mm x 130 mm x 400 mm) and is scanned by a stack of two cone-beam XCT scans with a voxel size of 313 µm. The X-
ray tube parameters for the serial inspection of this part are set to values slightly below the maximal voltage and current values to assure a safe 24/7 usage (reference to chapter 1.1) for the 1.0 mm big focal spot. Additionally, prefiltering of the spectrum with 1 mm of copper leads to a detectable dynamic range of intensities and avoids beam extinction. Since the ZADD is robust against artefacts caused by beam hardening and scattered radiation, no special emphasis is necessary to reduce those artefacts. The detector is operated in 2x2 binning mode with 33 ms integration time. Using the minimal integration time ensures minimal motion blur caused by the continuous rotation of the cylinder head during the acquisition.

Fig. 4. The top image shows the corresponding CAD file from the water jacket and the images at the bottom different preparation scenarios of the water jacket sand core

2.2 Simulation study

Preliminary to the presented investigations, SimCT [2] has been extended to support the ZEISS VoluMax G2 XCT device. The tool models the complete acquisition chain from the generation of X-rays and the interactions of X-rays with matter to the detection of X-rays in a detector, while considering most relevant physical effects. Several experiments were made at Nemak Linz to model image noise, the energy dependent detector efficiency, scatter related effects as well as image blur by modulation transfer functions. This step is a prerequisite to simulate and create virtual datasets close to reality.

Within this work SimCT is used to investigate the number of acquired projection images and the effect on image quality. The final goal is to find a trade-off for the scanning time and the expected through put of the serial inspection. The simulation-based approach overcomes the issue of manufacturing parts with defined defect scenarios, which is very challenging. The second investigation is a conceptual test, where SimCT is used to train and initialise the anomaly detection of the ZADD with a virtual golden part. For that purpose, 10 repeated numerical simulations are performed as realistic as possible of a defect-free and thus OK part. Not yet considered are uncertainties of the specimen placement by the robot and manufacturing tolerances [3]. Preliminary analyses have shown a high reproducibility of the specimen placement.
2.2.1 Virtual test specimen

A virtual replicate of the physically existing casting part described in section 2.1 is created with and without the discontinuities. The virtual replicate consists of a surface representation (triangulated meshes) and the aluminium alloy (mass weighted elements plus density), that is assumed to be homogeneously distributed within the closed surface. Additionally, one virtual test specimen is created where the water jacket is tapered by walls with a thickness of only 0.62 mm. This thickness is represented by approximately two voxels in the acquired XCT data.

3. Results and discussion

3.1 Comparison of real and virtual XCT images

Fig. 5 shows a comparison of XCT images acquired by real and virtual XCT scans at Position 1 where the artificial defect (red arrow) tapers the water jacket. Visually the images show a good agreement in terms of artefact appearances, but simulated images are slightly more prone to noise at locations with high attenuation of X-rays.

![Fig. 5. Slice images of (left) real scan data with artificial defect marked red and (right) simulated replicate of the real scan.](image)

3.2 Simulation-based investigation regarding number of projections and scanning time

Fig. 6-8 show results of a systematic simulation-based investigation of the needed number of projections, whereat the scan time increases proportionally with the number of projections. Fig. 6 gives insight into the detectability of the artificial structure at Position 1 described in section 2.1. The contrast-to-noise ratio between air and aluminium flash, representing a discontinuity within the water jacket, increases with the number of projections. Nevertheless, 242 projections would be already enough to detect the flash within the water jacket. Less than 242 projections and even faster scans are not possible, since another limiting factor besides the minimal integration time is the maximal rotation speed of the rotary table. Results and trends are equal for even smaller structures in Fig.7, where the tapering wall is only two voxels in thickness.

With the current state of used source and detector models, simulated data is slightly more prone to noise, this means in real scans the detectability of the shown flashes would be slightly better.

On the contrary, Fig 8 shows a region of interest located close to the maximal radius of the permissible reconstruction volume. The slice image comparison depicts that aliasing effects
at this location are quite strong for thin structures reconstructed with only 242 projections and at least 400 projections should be and are used for the real serial inspection of this cylinder head at Nemak Linz.

**Fig. 6.** Slice images at a water jacket position generated by simulation with varying number of projections. The thickness of the flash corresponds to the real artificial feature. The number of projections is proportional to the scan time.

**Fig. 7.** Slice images at a water jacket position generated by simulation with varying number of projections. The thickness of the flash is two voxels.

**Fig. 8.** Simulated slice images at thin walls that are prone to sampling artefacts with varying number of projections. The structure seems blurred due to aliasing.

### 3.3 Automated defect detection supported by numerical simulations

Fig. 9 shows three different ways of using the ZADD software at the defect of Position 2. The first row shows slice images of the mean golden part representation and the second row the XCT-data that should be analysed. The last row shows the segmented data, where the green and blue contours indicate the examination areas for the raw material respectively water jacket. The yellow line indicates areas with detected deviations and the light-red area the actual segmentation of the defect.

The left column shows the first standard way of using the ZADD, were 10 (typically up to 50) real scans of OK parts are used to generate the golden part. A real scan is tested against
this golden part and the artificial defects are found. The middle column is a test run, where a virtual part is tested against a virtual golden part and the column on the right shows the inspection of real data against a virtual golden part. Although, there are still slight differences between real and simulated data, it seems to be possible to perform the initial training of the anomaly detection with simulated data.

![Images showing mean golden part of real scans, mean golden part of virtual data, mean golden part of virtual data, real scan, virtual data, real scan, automatic detection result, automatic detection result, and automatic detection result.]

**Fig. 9.** The left column shows the scenario of a defect detection scenario with real golden part and real scans, the middle column shows a pure virtual detection scenario and the right column a combination of a real scan tested against a virtual golden part.

In practice, after the first inspections of real parts are done, every time an OK part is identified, it can be appended to the stack of scans that is used to calculate the golden part. This means the golden part could be iteratively updated and consider more and more effects, which gradually improves the robustness over time. Optionally, virtual datasets could be completely replaced by real scans, when enough scans of manufactured OK parts are available.

In other words, the virtual datasets could be used to identify OK parts, in the setup phase of a serial inspection process, which can be one of the most challenging and time-consuming steps with the described approach.

### 4. Conclusion

At-line XCT has the potential to replace standard methods such as flow tests, light through methods or endoscopy to check the continuity of water jackets in cylinder heads. The presented XCT inspection scenario is fully automated, except in the case of a NOK part, where a decision of the operator is needed, can handle highly complex inner structures of cylinder heads and avoids manual and user dependent inspections.

This paper showed the successful implementation of fast serial inspection with XCT at Nemak Linz for one exemplary cylinder head. Additionally, the inspection was successfully
supported by numerical simulation to optimise scan parameters and on the other hand, initial tests have shown that SimCT can support XCT-operators during the teaching phase of the used ZADD software. Both a-priori studies and the teaching of the defect detection software can be performed even before an actual part has been casted.

Further, numerical simulations give insight into the detection limits of XCT inspections, since any kind of defect (size, shape and material) can be virtually positioned at any location in the specimen. Within this work one possible defect type has been physically created in a cylinder head and real XCT scans have been compared to virtual ones, which further increases the acceptance of numerical simulations. Nevertheless, additional efforts will be made to reduce existing deviations between numerical simulations and real XCT scans.

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**References**

