Scanning strategies for composite overwrapped high pressure vessels for hydrogen

Philipp Jatzlau1, Kayo von Eisenhart-Rothe1, Ralf Schäuble2, Christoph Sauerwein1

1RayScan Technologies GmbH, Klingleweg 8, 88709 Meersburg, Germany, e-mail: p.jatzlau@rayscan.eu
2Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen (IMWS), Walter-Hülse-Straße 1, 06120 Halle (Saale), Germany

Abstract
Against the background of climate change, hydrogen from renewable energy sources is considered one of the keys to reducing greenhouse gas emissions. A crucial challenge in the use of hydrogen as an energy carrier is its transport and storage, which for efficiency reasons should be carried out at the highest possible pressure. Due to its specific strength, CFRP is an ideal material for pressure vessels that have to withstand high loads at up to 1000 bar and still be easy to handle due to being relatively lightweight. To this end, the German Federal Ministry of Education and Research is funding the development of innovative concepts for the design, manufacture and analysis of the vessels in the H2-HD project (FKZ: 03ZZ0743B). In addition to manufacturing processes, microstructure analysis and FE modelling, the development of a fast, efficient scan concept using 3D X-ray CT is a central element of the project. One aspect is the characterization of local properties resulting from the filament winding process, such as fiber angle deviations, pores, etc. after different stages of manufacturing and testing. Furthermore, critical vessel regions and typical defect patterns are specifically investigated with different scanning methods and suitable scanning strategies are derived from this. The final result is a detailed concept for a CT system for 100% quality monitoring of CFRP high pressure vessels.

Keywords: Hydrogen, CFRP, filament winding, pressure vessels, 3D-CT

1 Introduction
Today, international policymakers consider the usage of hydrogen as energy carrier one essential element on the way to a carbon-neutral future of mobility, industry and energy sectors [1]. In this context, the storage of hydrogen is a crucial component of the new infrastructure to be created. Within the mobility sector, the focus of aerospace companies is on the use of liquid hydrogen due to its higher energy density, although storage is more complex due to the low temperatures required [2]. Other mobility branches and industries consider the use of compressed gaseous storage of hydrogen, for example in the sector of heavy-duty trucks [3]. The analyses presented in this paper focus on the latter, more precisely on the development of high performance lightweight transport tanks for a reliable and safe storage of the gaseous hydrogen at pressures of up to 1000 bar. In order to keep the transportation weight as low as possible, carbon fiber reinforced polymers (CFRP) are used as load-carrying material, overwrapping a gas-tight polymer liner (Type IV pressure vessel). In this configuration, metal boss parts are required to attach valves or other fittings. For process and material evaluation, X-ray CT plays a key role in development and design of the vessels. However, the nature of the object poses multiple challenges to the thorough examination by CT. There are three major obstacles to overcome: Firstly, size, shape and surface of the vessel make it difficult to handle using a conventional 3D-CT system. Secondly, the mix of materials and their thicknesses lead to artifacts and potential overexposure, especially where CFRP and metal meet and wall thicknesses are high. Lastly, due to the long and slender shape the commonly used one-sided clamping potentially leads to vibration of the object when rotated on the turntable. The resulting motion blur significantly reduces image quality if no further post-processing correction algorithms are applied.

In the literature, there are only a few examples of investigations of CFRP high pressure vessels carried out with X-ray CT. One case is the study of liner deformation after emptying the vessel or after the vessel was subjected to an external impact [4]. Other investigations include the post-impact analysis of the composite material [5]. There are no publications known to the authors that specifically address the issues and factors influencing scan quality and their optimization with regard to this type of test object. For this reason, in this paper we present a systematic approach to X-ray 3D-CT scans of the whole vessel and region of interest (ROI) scans during the development phase as well as accompanying serial production. The ultimate objective is to develop a full system concept for 100% inspection of pressure vessels in serial production.

2 Test object and used CT system
2.1 CFRP pressure vessel
In general, the pressure vessels for hydrogen are designed with a central cylindrical part, two spherical domes and polar openings. Currently, five types of vessels (I-V) are distinguished, which differ in terms of the materials used and the load distribution among the materials [6]. The test objects for this study are model size Type IV pressure vessels approx. 900 mm in length, 320-360 mm in diameter with a wall thickness of 20-30 mm (cf. Figure 1). The gas tight polymer liner is equipped with both metal boss parts and subsequently overwrapped with carbon fibers embedded in a thermoset matrix using the wet winding process.
Figure 2 shows a longitudinal section through the vessel, marking size and position of the various components. The composite layers are wrapped applying a combination of circumferential, helical and polar angle layers according to the stress distribution necessary for the respective strength requirements. Other angles may occur due to design and nature of the winding process.

![Figure 1: Pressure vessel geometry for 700 bar design.](image)

![Figure 2: Metal boss, polymer liner and CFRP wall as seen in full vessel scan.](image)

2.2 X-ray CT system

The dual source RayScan+ system used for these investigations is equipped with a 225 kV micro-focus source, a 450 kV mini-focus source and a 2k flat panel detector. The detector has a pixel size of 200 µm and can be operated in extended field-of-view (FOV) mode. In addition, an 820 mm linear detector array is available for fan beam scans. The system has a large source-detector distance of up to 2000 mm and the column height reaches more than 2000 mm. Given these specifications, the theoretical maximum object size for a full cone-beam 3D-CT is 580 mm x 2000 mm. Practical issues when scanning hollow cylinder objects such as pressure vessels are presented in the following chapter.

3 Scanning strategies

3.1 Geometrical issues of pressure vessel X-ray transmission

In a hollow cylinder, the maximum transmission length is the tangent to the inner diameter, connecting two points on the outer diameter (see Figure 3). This length is dependent on the outer diameter $d$ and wall thickness $t$ of the cylinder. For example, a cylindrical object with an outer diameter of 320 mm and a wall thickness of 20 mm has a maximum transmission length of 155 mm. Assuming a material density of 1.5 g/cm³ for CFRP and a specific absorption of 0.16 cm²/g, a 225kV µ-CT beam can penetrate a maximum length of approx. 230 mm with sufficient signal strength at the detector. This means if wall thickness increases due to higher-pressure applications, the outer diameter of the pressure vessel should not exceed 350 mm, if a µ-CT resolution in the 100 µm range is still desired. For larger and thicker pressure vessels, more powerful X-ray sources can be used, though significantly reducing resolution due to a larger focal spot size.
3.2 3D µ-CT during vessel development and design

Multiscale CT analyses play a significant role in the development phase of CFRP pressure vessels. Size, shape and location of unavoidable imperfections resulting from the wet winding method need to be detected in order to evaluate the manufacturing process as well as the final structure of the vessel. In a first step, the relevant material imperfections and their critical values are defined. These include pores, delaminations, resin pockets and fiber ondulations, which have been investigated for fiber composite materials in numerous studies in recent years [7]. Regarding this, the following focuses on various challenges and uncertainties related to porosity analysis by µ-CT. For the analysis of other imperfections, we refer to a future publication by the project partners. In porosity analysis, many geometrical and X-ray parameters strongly influence pore segmentation, with voxel size being one of the major factors [8]. However, the geometry of the test object and the parameters of the CT system limit the selection of the voxel size. Experiments with different setups allow for the evaluation of suitable pore segmentation and setting respective thresholds for minimum pore volume. For this, both mini-focus and micro-focus source are used with different magnifications (resp. voxel sizes). In order to achieve an optimal reference resolution, cutout pieces of the pressure vessel are scanned by high magnification µ-CT (Figure 4 left). The geometrical setup in Figure 4 (right) corresponds to the geometry of an ROI scan with the full vessel present on the turntable. Excerpts of the resulting differences in resolutions are given in Figure 5.

A simple threshold method averaging gray values of representative air and material values makes the accuracy of porosity analyses comparable across a wide range of scanned volumes. For these post-processing analyses, VGStudio Max 3.2 by Volume Graphics is used.
After the definition of imperfections and the specification of scanning geometries and resolutions on vessel cutouts the findings can be transferred to the full vessel scan. Given the available CT system and the size of the objects, scans are performed at 210 kV and 400 kV, each with a voxel size of 167 µm. Depending on the outer diameter of the vessel, an extended FOV setup is necessary (Figure 6 left).

Figure 6: Top view of extended field-of-view full vessel scan (left) and positioning of vessel for ROI scans (right).

After screening the full vessel scan for relevant defects in critical areas of the laminate, these are marked digitally in the reconstructed volume. In order to locate these ROIs on the actual vessel for further high-resolution scans, a cylindrical coordinate system $(r, \varphi, z)$ and the radian measure on the outer diameter are used as shown in Figure 7 (right). Additionally, a clamping adapter allows for suitable fixation of the vessel and precise adjustment of the angle $\varphi$ (cf. Figure 7 (left)). The clamping adapter is part of a specially designed device for accurate positioning of the ROI in radial and angular direction, schematically shown in Figure 6 (right).

Figure 7: Left: clamping adapter for suitable fixation of the vessel and more precise ROI scan angle adjustment. Right: locating digitally marked ROIs (red boxes) on the actual vessel for high resolution ROI scans.

The resulting high-resolution ROI data can be further analyzed with regard to the imperfections defined earlier. Figure 8 illustrates the difference in detail recognizability between the ROI scans and the full vessel scan.

For analyzing details in the cylindrical part of the pressure vessel such as the intersection of two tape layers (cf. Figure 9) as well as for data volume reduction, it is suitable to use the non-planar resampling of the unrolled cylinder. This way, reconstructed air volume is eliminated, reducing the memory requirements by more than 80 %. Addressing the same issue, a novel reconstruction algorithm only taking into account the relevant regions of the object is in the planning stage (cf. chapter 4).
3.3 CT scans accompanying serial production

In serial production, cycle time plays a key role. For this reason, the CT-system needs to be clocked in with the production cycle. Due to the diameter of the pressure vessel exceeding the detector width, an extended FOV is necessary for a full vessel scan. This mode takes two images for every projection, which significantly increases scan duration. For this reason, the other time-consuming factors such as number of projections, integration time and averaging have to be optimized regarding overall scan duration while still achieving an image quality good enough to detect the relevant features.

In this study, image quality is evaluated by contrast-to-noise ratio (CNR)[9]. In order to evaluate the degree of correlation between image quality and scan duration, parameters are systematically varied. Scan duration is expressed by a time factor $T$, which is defined as the respective scan duration in relation to the scan duration of the fastest scan within this investigation. Thus, a time factor of $T = 4$ means the scan took four times longer than the scan with the lowest image quality. As a result, Figure 10 indicates CNR as a logarithmic function of the time factor. This seems plausible because image quality must show a certain saturation behavior, since it cannot go to infinity by increasing parameters related to scan duration.
Figure 10: Dependence of contrast-to-noise ratio (CNR) on time factor (scan duration normalized to fastest scan). Results of scans A, B and C are depicted in Figure 11.

Figure 11 shows three representative scan results, varying only number of projections and averaging as given in Table 1. It is obvious that scan C has the highest CNR and detail detectability. However, a more than eightfold increase in scan duration compared to scan A does not seem reasonable in serial production. A compromise can be found when parameters surrounding scan B are applied.

Table 1: Scan parameters for selected scans with the same integration time.

<table>
<thead>
<tr>
<th>Scan parameter</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of projections</td>
<td>1080</td>
<td>1080</td>
<td>4680</td>
</tr>
<tr>
<td>Averaging</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
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Given these aspects, an optimum set of scan parameters for a 100% inline inspection can be found as long as the resolution requirements defined earlier are met. To further enhance scanning speed, multiple sources and detectors can be used simultaneously, also including several scanning methods. This is all part of the above-mentioned system concept to be developed. One approach is a helical CT scan of the spherical domes containing the metal boss pieces using a beam stop array to minimize scatter artifacts while a continuous 3D-CT scan is performed on the cylindrical part (for \(d < 320\) mm). For vessels with a larger diameter, a 3D-CT with extended FOV is applicable. In this case, linear detector arrays are used for scanning the domes, also reducing scatter artifacts caused by the metallic boss pieces. If critical values for imperfections are detected, a subsequent high resolution \(\mu\)-CT ROI scan can be performed either on the same CT system or off-line on another system, to not interfere with production cycle times.
4 Discussion and outlook

This paper describes approaches for time efficient and high quality non-destructive full inspection for CFRP pressure vessels by X-ray CT. However, object handling and data analysis are carried out manually at the moment while both have a particularly high automation potential for serial production. Therefore, the developed concept for a fully automated 3D-CT test facility for pressure vessels includes an automated object feed and handling system as well as automated defect recognition considering critical porosity, delaminations, resin pockets and other potential imperfections.

Another aspect to be considered is data generation and management. Using the common FDK-based reconstruction algorithm, a large fraction of the reconstructed volume is the air inside the pressure vessel. This results in the amount of generated data per vessel well exceeding 100 GB, which may lead to long loading times and memory requirements. For this reason, we suggest an efficient reconstruction algorithm, only including material voxels. A corresponding design is currently subject to further development, i.e. based on previous work in this regard [10].

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