Cone beam tomography for quality control and rapid product development

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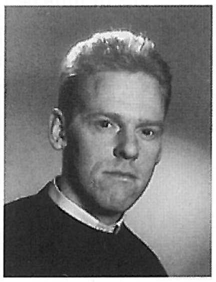
Modern quality standards require highly optimised production methods. For this purpose, reliable inspection techniques are needed. To date, the quality control is performed with a variety of different tools. Inner structures of complex bodies can often not be evaluated because of limitations of the measuring devices.

A 3D X-ray tomography system is described that allows the inspection of components of any complexity. With a single scan, 3D objects can be reconstructed and any virtual slice inside the object can be analysed. Since both material and geometry data can be retrieved from the measurement, the results can be used for the detection of flaws as well as for the investigation of geometrical and material variations. An analysis of the 3D shape and position of flaws, dimensional measurements of inner and outer structures and a comparison of the measured geometry with CAD data can be carried out.

1. Introduction

New materials and improvements of conventional materials play a key role in many industrial areas for the design of innovative products. Development times have to be as short as possible. For this reason there is a growing demand for new inspection systems that allow a fast and non-destructive characterisation of materials. The complexity of industrial products is continuously increasing. Also, at the same time the safety requirements increase. For a rapid product development the inspection system needs to be able to characterise material properties in any section of components with complex inner structures. This task can often not be fulfilled with NDT methods like ultrasonic or eddy current testing.



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In this paper an innovative 3D tomography and radioscopy system is described that allows to perform a variety of different inspection tasks with a single device. Examples from casting materials as well as fibre-reinforced composite materials will be given to demonstrate the potential of the NDT method in view of quality assurance and rapid product development.

2. Cone beam X-ray tomographic and radioscopic system

The X-ray tomographic systems which are in use in industry to date produce in most cases two-dimensional sectional images. Figure 1 shows the principle scheme of such a system which is used in industrial as well as in medical applications. An X-ray fan from an X-ray source penetrates the object and the attenuation is measured by a linear detector.

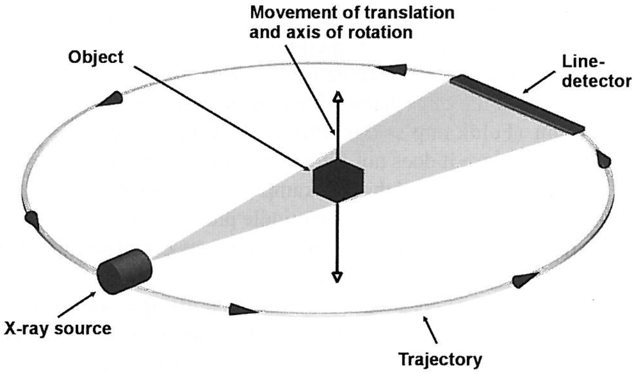

Figure 1. Principle scheme of conventional 2D tomography

In medical tomographs the source and detector rotate around the object (patient). In industrial applications it is in most cases advantageous to rotate the object. During the rotation a set of one-dimensional projections is measured and reconstructed. The result is a two-dimensional image. For further details on two-dimensional tomography see R A Brooks and G Di Chiro [1]. To get a three-dimensional image with such a conventional tomograph, the object has to be moved in the direction of the axis of rotation and several scans have to be performed. A stack of slices has to be mounted to get a three-dimensional image.

Since the described procedure is very time-consuming, the tomographic system 'RayScan' allows the reconstruction of three dimensional structures with a single rotation. A conical beam from an X-ray source penetrates the investigated object. The attenuated radiation is measured by a large area detector (Figure 2). In order to irradiate the object from all sides, the X-ray source and the detector are either rotated around the object, or the object rotates in the X-ray cone. During rotation a set of projections is measured and stored. The set of projections is then used to reconstruct the 3D structure of the object.

The high quality reconstruction of the system is based on a careful qualification and optimisation of the individual components. The

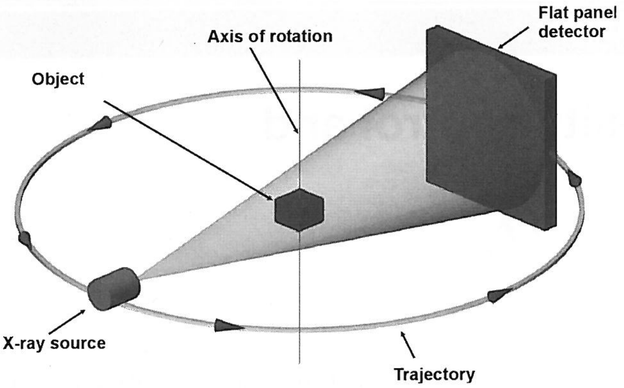

Figure 2. Principle scheme of 3D cone-beam tomography

detector, which is made of amorphous silicon coated with a scintillator, proved to have a dynamic range of better than 75 dB and a linearity of better than 1%. A major source of reconstruction error is the X-ray photon counting statistics. We determined the statistic fluctuations of individual pixels at an optimal irradiation level (70-80% of the saturation value) for different integration times. For the integration time of 200 ms per frame fluctuations under 1% were determined, which guarantee a reduced level of noise in the final reconstruction.

Two main families of reconstruction algorithms have been developed for cone beam X-ray tomography with circular source trajectories: the generalised filtered back-projection methods (Feldkamp *et al* [2]) and the 3D Radon transform inversion (Grangeat [3]). In Rizo *et al* [4] it was demonstrated that both methods are only approximative. The Grangeat's algorithm provides a density accuracy within 1% for a cone aperture up to 24°, while Feldkamp's algorithm is reasonably accurate (within 2-3%) for cone apertures below 20°. On the other hand, along vertical planes the 3D back-projection (Feldkamp's algorithm) has a higher geometrical resolution because it does not filter along this direction.

The authors optimised the Feldkamp algorithm to reduce density errors in planes far away from the middle plane and to achieve low reconstruction times. The hardware design was optimised to keep density errors due to the cone angle low.

The advantage of cone beam tomography utilising modern digital flat-panel X-ray detectors is, besides the feature of fast volume scanning, the possibility to perform radioscopy with the same device. A comparison of radioscopy and 3D tomography is shown in Figures 3 and 4. The investigated specimen is made of polyethylene with an outer ring of aluminium. There are two rows of drillings with different diameters. In the radioscopy (Figure 3) the aluminium ring is visible, but the drillings cannot be individually detected. Instead, the visualisation of the 3D tomography result shows that the information about the geometry of the specimen as well as the material is present (the aluminium ring is visible in light grey in Figure 4). It can be concluded that for bodies with complex inner structures, 3D tomography is the appropriate inspection method, whereas for bodies with a simple geometry and especially for flat objects, radioscopy can be applied (see section 4).

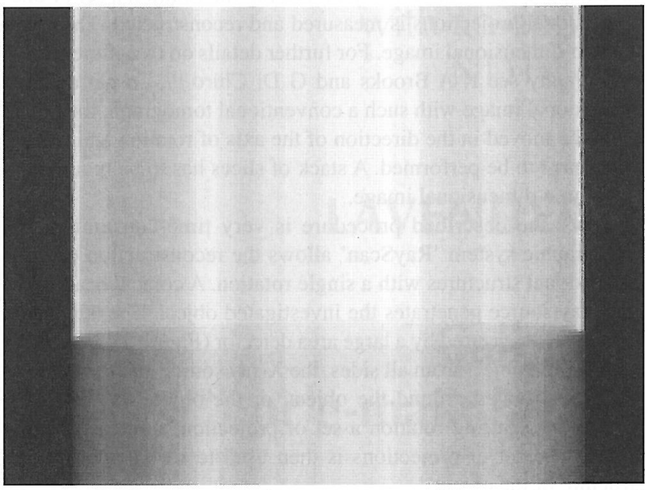

Figure 3. Radioscopy: the inner structure of the specimen is not visible

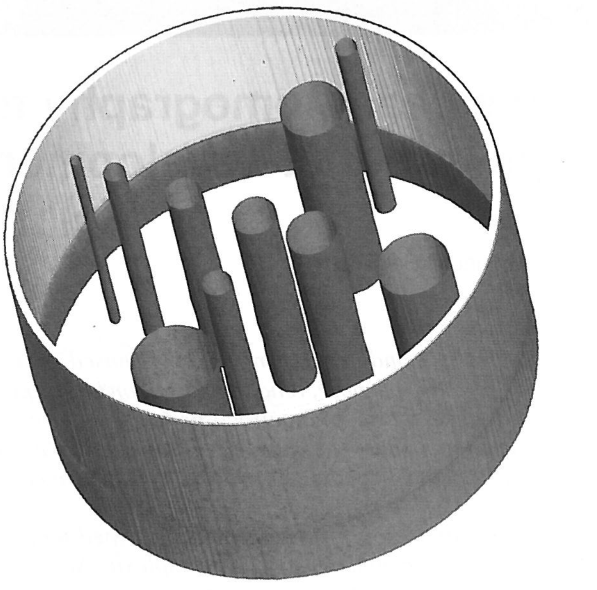

Figure 4. 3D tomography: the inner structure of the specimen is visible

3. Cone beam tomography applied to quality control of castings

In this section the application of the 3D cone beam tomography system RayScan to quality control of light metal castings is described. Light metal castings are widely used in applications such as automotive, telecommunication, mobile computing, etc. The advantages of the material, such as high strength-to-weight ratio and the ability to produce almost any geometry in few production steps, are diminished in some cases by production uncertainties. Therefore, the foundry companies as well as their customers need to perform quality control to guarantee the required specifications.

Quality control of castings focuses on two main aspects: detection of flaws and dimensional measurements, which includes the control

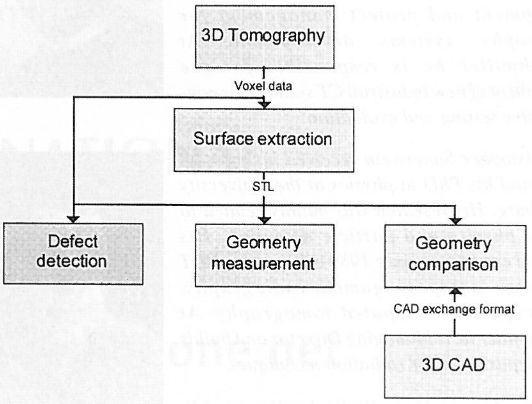

Figure 5. Quality control based on 3D tomography

of dimensions and the analysis of the deviation of the real geometry from the nominal geometry. Since the described tomographic system generates 3D data, dimensional measurements can be done utilising post-processing software tools. Figure 5 shows the structure of the software modules and the generated data. The following sections will describe methods for flaw detection and dimensional measurements based on a single non-destructive measurement utilising state-of-the-art 3D X-ray computed tomography with an adequate post-processing.

3.1 Flaw detection

Nowadays, foundry companies need to reduce the product development cycle time in order to be competitive on the market. Therefore, defects in castings such as gas porosity, voids and inclusions, have to be detected in the early phase of the production process optimisation. The most common NDT method for this purpose is radiography. Often, this inspection method does not allow the detection and localisation of defects in complex bodies. In the automotive industry it is still common to evaluate the homogeneity of large casting parts like engine units by cutting it in slices. Apart from being destructive, the method is very time-consuming. Ultrasonic and eddy current measuring techniques can only be applied in simple geometries. Often, due to the lack of appropriate test methods, foundry engineers do functional tests such as leak tests. In this case defective parts cause high costs because the test is usually carried out at the very end of the production chain.

3D tomography is a non-destructive method that has the potential to detect flaws in any geometry. The reconstruction of the tomograph generates 3D voxel data. It is a three-dimensional array with attenuation values which are proportional to the density of the material. This allows to detect voids and inclusions. Defects can be detected either by analysing voxel data or STL data after a surface extraction (Figure 5). Here, the flaw detection based on a voxel data analysis will be shown. The voxel data can be visualised in several ways. It is possible to generate any kind of cuts, slices or isosurfaces. Figure 6 shows a 3D visualisation of an aluminium casting. Displayed is the outer surface of the body as it would be in a photograph. Since we have the full 3D information of the body, virtual cuts of any orientation can be done. In Figure 7, a virtual cut through the centre of the body reveals gas porosity defects.

Figure 6. Visualisation of 3D tomography data: outer surface of an aluminium casting

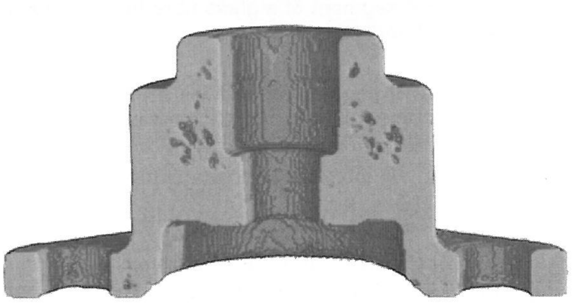

Figure 7. Visualisation of 3D tomography date: virtual cut of an aluminium casting

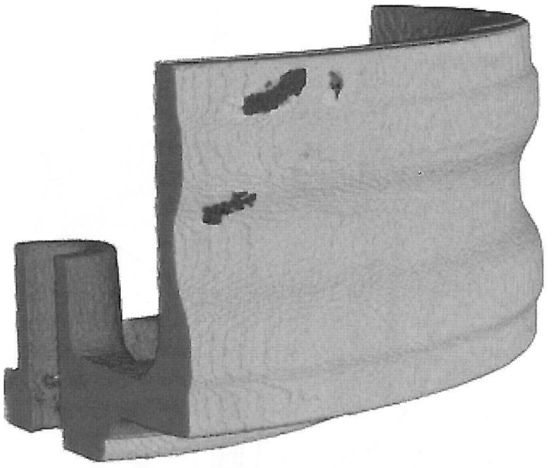

Figure 8. Isosurface plot with marked voids

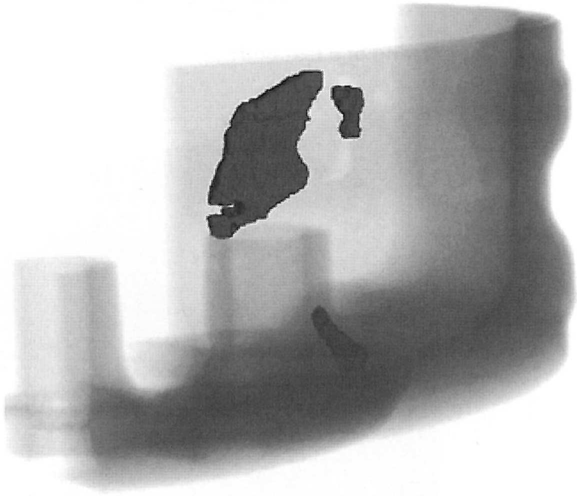

Figure 9. Semi-transparent isosurface plot with marked voids

In Figure 8 an isosurface plot displaying a section of the outer surface of a casting is shown. The voids are marked. The voids that appear on the outer surface of the body are visible. However, the real size, shape and orientation of the voids only become visible if the aluminium is displayed semi-transparently (Figure 9).

The demonstrated visualisation methods offer to the foundry engineers the possibility to analyse the three-dimensional shape and position of flaws. This information can be used to optimise the casting process to ensure a high quality standard.

3.2 Dimensional measurements

For dimensional measurements, the voxel data that have been generated by the tomographic system need to be converted into a surface in a first step (Figure 5). The most common format for data exchange is STL (Stereo Lithography) which is the basis for different software modules that will be described in this section.

In the phase of prototype manufacturing it is essential for the engineers to know the deviation of the manufactured geometry from the geometry of the CAD drawing. For this purpose the CAD drawing is imported via an exchange format in a software module that compares the STL surface data with the CAD data. Figure 10 shows the CAD drawing of a test body. It was manufactured and afterwards scanned in a 3D tomograph. The result is shown in as an isosurface plot in Figure 4.

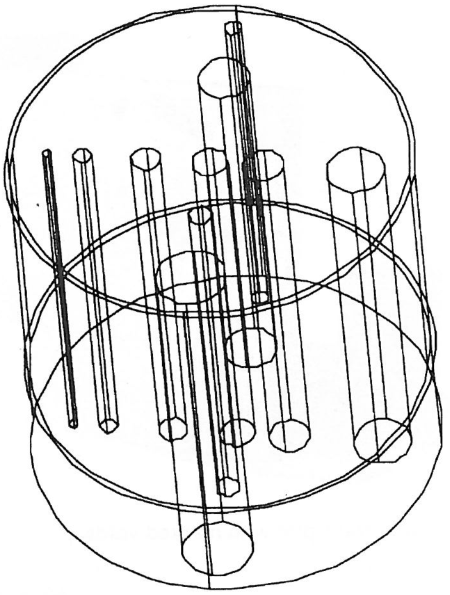

Figure 10. CAD drawing of a test body

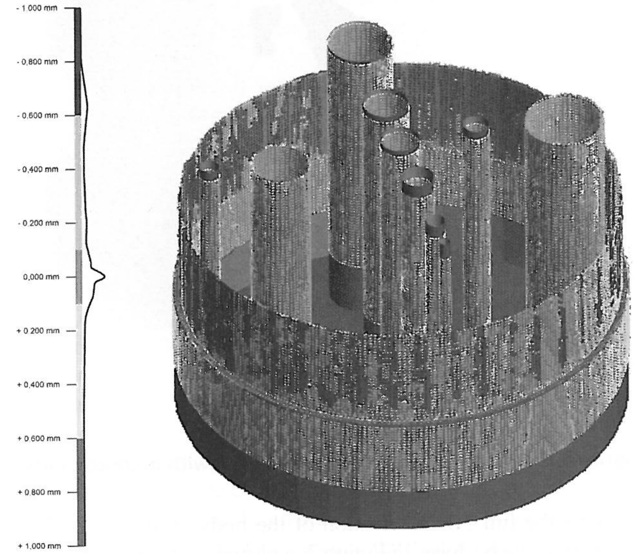

Figure 11. Comparison of CAD data with tomography data [1]

The deviation from real to nominal geometry can be documented in tables showing statistical data like maximum, minimum and average deviation. More informative are graphical representations such as in Figure 11. The picture shows the deviation in different colours.[1] Positive and negative tolerances are given and the tolerance band can be adjusted to give the maximum information about the deviation.

Another demand from quality control is the dimensional measurement of cast parts. Based on the 3D tomography data, measurements can be done in a similar way as in a CAD program. Figure 12 shows an example of measurements of the test body. Distances, radii, etc. can be measured in all directions of the 3D space.

4. Inspection of fibre-reinforced composites

Polymeric composites reinforced by glass fibres have been replacing metals in a variety of applications in mechanical and civil engineering in the past years. It is an often used material for high strength engineering applications for pipes, storage tanks and other high risk areas. Attractive properties are high strength-to-weight ratio, low weight and availability.

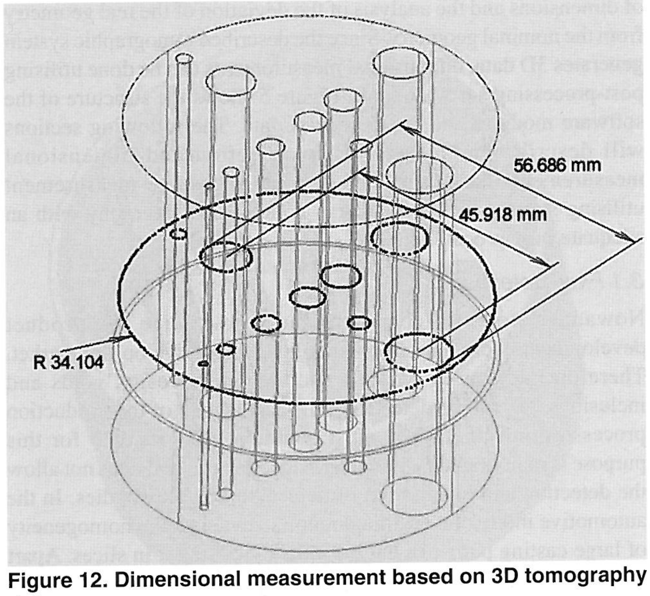

Figure 12. Dimensional measurement based on 3D tomography data

Fibre-reinforced composites often have a flat shape which allows the inspection by means of radioscopy rather than tomography that is more time-consuming. X-ray imaging of fibres and fibre bundles combined with strength tests are important, because the consequences of different defects on the performance of fibre-reinforced composites are still little known. The aim is to predict the influence of the population and location of defects, of different fibre orientation in the reinforcement or of the manufacturing processes on product performance for fibre composites. The material is difficult to inspect, owing to very similar response of fibres and matrix material on X-rays. In order to define the potential and the limits of X-ray related real-time techniques, a series of samples of different fibre geometry have been inspected systematically.

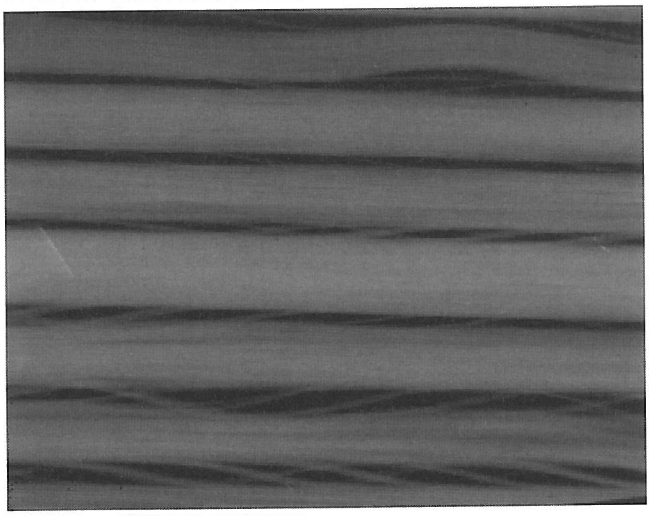

Figure 13. Enlarged segment of a glass fibre bundle. Individual fibres of the fibre bundles are visible (5)

RayScan was used to visualise not only the fibre bundles but also the individual fibres of the samples. This was possible because RayScan is equipped with a microfocus X-ray source with a focal spot size of about 10 microns in combination with the above described flat-panel detector.

An example of microfocus radioscopy of a glass fibre reinforcement is shown in Figure 13. The fibre bundles are orientated as unidirectional woven roving, which is normally used for the so called hand-lay-up process. A high magnification by means of a lower source to object distance makes individual glass fibres inside the bundles visible.

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[1] The black and white print gives only a rough impression of the original colour plot

5. Conclusions

The cone beam tomographic system RayScan was shown to be a versatile tool for quality control in view of a rapid product development. The system allows a fast tomographic volume scanning as well as magnification radioscopy. With a single NDT tool and a single measurement, defects in complex bodies can be detected and analysed regarding their 3D shape, orientation and position. Dimensional measurements of outer and inner structures can be performed to verify the geometry of parts. The comparison of the real geometry with the nominal geometry allows a fast and non-destructive quality control. Therefore, the system gives new opportunities to rapidly optimise products aiming at the minimisation of defects and deviations from the nominal geometry.

References

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5. Results were obtained within project No BE97-5129, funded by the European Community.