Advanced Non-Destructive Testing by High Resolution Computed Tomography for 3D analysis of Automotive Components

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For a huge variety of inspection tasks, high resolution computed tomography (CT) has become a powerful inspection tool. CT systems are applied in failure analysis as well as in 3D Metrology. Especially for complex automotive components with hidden internal structures CT offers a wide expansion of customary two-dimensional X-ray inspection capabilities. Depending on the sample size and the material, resolutions down to a few micrometers or even below can be achieved. Internal difference in material, density or porosity within a sample can be visualised and data like distances or pore volumes can be measured. Once scanned, the fully three dimensional CT information allows many possibilities for analysis: the non-destructive visualisation of slices, arbitrary sectional views, pseudo-colour representations and 3D measuring. Furthermore the comparison of the volume data with CAD-data (variance analysis, reverse engineering) is possible.

There is a wide range of available CT-systems for 3D-inspection of automotive components: Large scanner are suitable for CT of whole light metal motor blocks, very compact systems are specialised for the high resolution analysis of the microstructure of small samples. The shows show nanoCT results produced by the nanotom, the first 180kV/15W nanofocus computed tomography system which is tailored specifically to extreme high resolution applications with submicron voxel-resolutions down to 500 nm. Furthermore, CT results of the vltomelx L 300, the first CT system with a unipolar 300 kV microfocus tube for high magnification examinations and measurements of high absorbing automotive components will be shown.

Fig.1: vltomelx L 300
with unipolar 300 kV
microfocus X-ray tube.
ABSTRACT
In today’s quality market, achieving the smallest feature recognition possible in the inspection process has become a higher priority than ever before. Due to complex geometries and miniaturization of many high reliability components in the automotive, electronics and aerospace industries, achieving this level of feature recognition has also become increasingly difficult. Due to inherent limitations, many of the inspection requirements can no longer be satisfied with conventional X-ray inspection methods such as 2D X-ray inspection. For example, the depth of detail is not quantifiable, which in some cases can be vital to the manufacturing process. High resolution Computed Tomography (CT) presents an effective method of mapping the internal structure of components in three dimensions.

With this technique, any internal difference that corresponds to a contrast in material, density or porosity can be visualized and measured. These properties allow the use of CT as an NDT tool, permitting examination of samples for internal porosity, cracks, de-lamination, inclusions and mechanical fit. CT techniques are used to measure internal distances or the internal wall thickness of complex castings and areas, which are often inaccessible for optical scanners or conventional tactile coordinate measurement machines (CMM). The CT volume data provides information for reverse engineering or first article inspection of the entire part by merging it with the CAD model to generate a variance map of both data sets. Combined these capabilities contribute to early detection of process and product weaknesses therefore increasing yield and productivity. Recent studies have proven measurement precision of CT systems.

Modern microfocus and nanofocus systems are not only suitable for examinations of low absorbing materials like synthetics, but also for the analysis of the internal microstructure of higher absorbing metal castings, ceramics or composites containing high absorbing particles. High resolution CT widely expands the spectrum of X-ray detectable defects in process control and failure analysis increasing reliability and safety of components for, e.g., automotive, aerospace, and military applications. It opens a new dimension for 3D quality assurance and will partially replace destructive methods like cross-sectioning – saving costs and time per sample inspected.

For high resolution NDT with Computed Tomography, a wide range of systems is available. This starts with microfocus X-ray systems like xlargos for real time inspection of large castings which may be upgraded for Computed Tomography – this makes the advantages of 3D inspection affordable even for smaller companies. For high resolution high quality CT the nanotom is the first
180 kV nanoCT® system with the capability to analyse small samples with the exceptional voxel-resolution of less than 0.5 microns per volume pixel (voxel). For example, object surfaces of molded plastics, light metal castings and any internal details related to a variation in material, density or porosity can be visualised and precisely measured.

**LIMITATIONS OF 2D X-RAY IMAGING**

The image produced with a 2D X-ray imaging system can range anywhere from a 1:1 magnification ratio to well over 25,000 times magnification with an advanced technology x-ray source. Very fine feature recognition is achieved at these very high magnification levels, but there is an inherent limitation; While measurement accuracy can be very high in the vertical and horizontal planes of the image, which represent the height and width of the sample, the depth of the sample is only measurable in terms of grey scale intensity or density values. In other words, it is possible to image a defect in a sample such as shrinkage in a casting or a crack in a weld and measure the height and width accurately, but there is no effective way to measure the depth of such a defect with a single two-dimensional view.

In some instances, a sample could be salvaged if the defect can be accurately three-dimensional located within the sample for removal or repair. In other situations, changes can be made to the manufacturing process that will correct the problem for the production line. Achieving depth recognition in situ with height and width recognition is only made possible by three-dimensional imaging. Computed Tomography shows the exact location of the defect in the sample providing information on size, volume and density of inclusions and cavities. Due to the fact that CT images are rich in contrast, even small defects become detectable.

![Fig. 2a: 2D X-ray image of a cable crimp. Only the overall density can be accessed, single copper strings cannot be seen in the crimp area.](image1)

![Fig. 2b: 3D volume of the crimp with two intersections revealing the number of copper strings at the entry and exit of the crimp.](image2)
HIGH RESOLUTION CT
For challenging x-ray inspection applications, the most remarkable results are obtainable by using high resolution computed tomography with a microfocus or nanofocus X-ray source. The achievable resolution or image sharpness is primarily influenced by the focal-spot size of the X-ray tube, which varies from a few microns for a microfocus tube to 0.8 microns for the latest nanofocus tubes. They achieve detail detectability down to 200 nanometers (0.2 microns), using different focus modes to optimize the X-ray intensity and resolution.

Fig. 3: Microfocus CT provides state of the art for 3D analysis in a large variety of application fields with attainable voxel resolutions down to a few microns. With the use of nanofocus tube technology, nanoCT-systems are pushing into application fields that were exclusive to expensive synchrotron techniques.

Fig. 4: nanofocus-X-ray technique: The smaller the focal spot, the higher the sharpness.

CT volume generation starts with the acquisition of a series of two dimensional x-ray images while the sample is stepped in less than 1° increments through a
full rotation. Each projection contains information on the position and density of X-ray absorbing object features within the sample. This accumulation of data is then used for the numerical reconstruction of the volumetric data which is visualized by slices or compiled in a three-dimensional view which can be displayed in various ways. By means of volume visualization software, the three-dimensional structure of the reconstructed volume is easily analyzed for pores, cracks, and density and distribution of materials with high magnification and image quality.

Fig. 5: CT-setup with X-ray-tube (right), manipulation table (middle) and detectors (left): GE S&IT phoenix|x-ray’s v|tome|x L 450 is equipped with a 450 kV macrofocus and a 240 kV microfocus tube as well as with a large array detector, a line detector or a multi-line detector. It therefore offers a large variety of inspection and metrology applications for samples up to 1000 mm in height and 800 mm in diameter with voxel resolutions down to 2 microns.

In order to reproduce an accurate reconstruction of the volumetric data, there are two conditions that must be met: First, the entire depth/diameter of the sample must remain within the field of view and cone of radiation throughout the entire 360° rotation. Since the full sample diameter must be completely displayed in each projection captured during the acquisition process, the maximum magnification is limited by the ratio of the effective detector width to the sample diameter, hence ideally cylindrical product geometries. However, if the detector is side shifted during the acquisition for a virtual increase in effective detector width, higher ratios (magnifications) are possible. Further the use of optimized reconstruction algorithms allows an increase in resolution by scanning selected Regions-of-Interest (ROI). As second condition, the entire geometry of the sample, meaning every acquisition angle throughout the full 360° rotation, requires full penetration while maintaining the same X-ray energy level during each acquisition. This can be accomplished successfully even for higher density samples with a powerful x-ray source and the proper use of filters to reduce long wavelength X-rays.
Fig. 6: In general, the voxel resolution of CT scans is limited by the ratio of the effective detector width to the sample diameter because the sample should remain in the cone beam (right). However, the use of optimized reconstruction algorithms allows an increase in resolution in selected segments despite this rule (middle). The roiscan of GE S&IT phoenix|x-ray even allows < 360 scans to achieve significant higher magnifications (left).

Scatter radiation effects caused by highly absorbing samples may be avoided by using line detectors or simulate same with a collimator for flat panel detectors.

Fig. 7a: flat panel detector with multi-line collimator

Fig. 7b/c: ankers of an electro motor become visible with multi-lines (right)

There are a few physical effects influencing the CT quality, such as beam-hardening within the sample or ring-artifacts, which cannot be completely avoided. To optimize the quality of the 3D volume, advanced microfocus and nanofocus CT systems include a variety of effective software tools to reduce ring-artifacts and correct beam hardening either automatically (for mono-material products, e.g. Al castings or plastic parts) or interactively (for multi-material products, e.g. particle filters or electronic control units) or drift effects which occurred during data acquisition.
Fig. 8a: Ring-artifacts in CT-volumes are caused by defective detector pixels. Fig. 8b: For improvement of CT quality, the rar|module of GE S&IT phoenix|x-ray corrects them automatically.

Fig. 9a: beam hardening artifacts in a Al product, penalizing for measurements. Fig. 9b: best manual correction of the beam hardening artifacts (bhc|module). Fig. 9c: automatic beam hardening correction by the new bhc+|module of GE S&IT phoenix|x-ray, significantly improving the CT volume quality.

**AFFORDABLE CT SYSTEMS**

Until recently most CT systems were priced well outside the budget of many small to medium sized businesses since high-quality CT required an expensive flat panel detector. A recent development at GE S&IT phoenix|x-ray now provides a low budget CT solution with the use of a digital image chain (image intensifier + 2 MPixel CCD camera). One tool employing this technology is the xlargos. This device allows even larger castings to be scanned using a directional microfocus tube and a digital image chain. With its 6 axis CNC manipulation, including a C-arm for the tube and detector and its high power directional tube, the xlargos provides accuracy and microfocus resolution for the inspection of samples up to 100 kg. The size of the manipulator allows for the widest possible sample range – anywhere from very small samples with very high resolution to castings 3 feet tall.
Fig. 10: With its 240 kV high power tube, the xlargos provides microfocus resolution for the live-inspection of samples up to 100 kg as well as affordable 3D Computed Tomography.

Fully automatic inspection programs allow for large-scale samples testing in a production environment. Additional modules may be created using Xe², the X-ray Evaluation Environment of GE S&IT phoenixlx-ray. This program allows the user to create modules based on edge detections, greyscale measurements, and void percentages, creating a truly customizable tool. With all these features, the xlargos represents a multitool with 2D inspection capability as well as the benefits of computed tomography. This unique combination provides an excellent cost-benefit ratio and opens a new dimension of quality control.

Fig. 11: Semi-transparent CT volume after automatic defect analysis. The aluminum casting was scanned with the xlargos system.
Fig. 12: Axial slice of the same aluminum casting as in Fig. 8 showing pore density and length measurement of a pore.

**NANOFOCUS CT (nanoCT®)**

For scanning samples of up to 1 kg and 120 mm diameter with voxel-resolutions down to < 500 nm (0.5 microns), the ultra-precise high-resolution CT system nanotom® by phoenix|x-ray is a good choice. The nanotom® is the first nanoCT® system in the world with a 180kV nanofocus X-ray tube, set up for extreme high resolution applications in a variety of fields such as injection moulding, materials science, micro mechanics, electronics and geology. The 180 kV high power nanofocus tube offers different modes from nanofocus scans of low absorbing materials up to high power scans of high absorbing samples. Therefore, it is particularly suitable for nanoCT® examination and measurement of molded parts, sensors, complex mechatronic samples, microelectronic components as well as for material samples such as synthetic materials, metals, ceramics, sintered alloys, composite materials, mineral and organic samples.

Fig. 13: With its small footprint of only 163 x 143 x 74 cm, the nanotom® is suited for laboratory applications.
Computed Tomography at such exceptionally high spatial resolutions requires careful design, taking into account any features which might influence the resulting resolution. These special needs for extreme precision require special manipulation systems, detectors and X-ray tubes. For example, the nanotom uses a unique 180 kV high power nanofocus tube which can penetrate even high-absorption samples like copper or steel alloys. A 5-megapixel flat panel detector with an active area of 120 x 120 mm (2300 x 2300 pixels, 50 µm pixel size) and a 3-position virtual detector (up to 360 mm detector width) give rise to a wide variety of experimental possibilities. To avoid any negative influence of vibrations or thermal expansion, tube, detector and rotation unit are mounted on a high-precision granite-based manipulation system. Furthermore, special materials and construction techniques are used to guarantee high stability for long-term measurements. The precision of this system setup allows the high resolution and accuracy of the measurement results. Furthermore, the system includes phoenix|x-ray’s easy-to-use proprietary reconstruction software datoslx, which includes innovative tools for geometry calibration, detector calibration, noise and beam hardening reduction and region-of-interest-CT.

**HIGH PRECISION METROLOGY BY CT**

The 3D-volume of an object can provide the information required to extract internal or external surfaces. The generated data is measured by the fitting of geometrical primitives or by variance analysis against CAD-data. To ensure outstanding ease-of-use and geometrically correct surfaces, innovative extraction methods are used in the surface extraction of the nanotom® software.

Physical effects like sample induced beam hardening and scattering leave residual and inevitable imperfections in the volume data set that will affect the accuracy of the surface extraction if not dealt with. The nanotom® eliminates these errors by using a specifically designed surface extraction algorithm for much higher precision than common threshold algorithms (ISO). This generates geometrically correct surfaces even when unavoidable beam hardening artifacts are present. Based on the precise surface data of all internal and external surfaces of the object, the user may now proceed with further evaluation such as variance analysis, element fits, reverse engineering, etc.

Thanks to the long term experience of GE S&IT phoenix|x-ray in microfocus and nanofocus X-ray technique, a range of innovative, modular and highly precise CT systems has been created, offering precise and reliable measuring results which compare with traditionally used coordinate measuring machines (CMMs).
Fig. 14a: Virtual CT cut of an injection nozzle showing the internal geometry as well as the injection channels (diameter 150 microns).

Fig 14b: the point cloud extracted of the 3D volume with GE S&IT phoenix|x-ray’s surface|extraction represents the surface points of the injection nozzle. The accuracy of the extracted surface data determines the precision of metrology.

Fig. 15: Cone and cylinders fit to the polygon representation of a scanned injection nozzle. The channel diameter is 150 microns.

To verify the precision of measurements provided by high resolution CT, a 20 x 20 mm Zerodur® sphere plate (figure 13), designed and calibrated by the National German Metrology Institute PTB was measured with the nanotom. The 3D-calibration of the PTB included uncertainties of 1.5µm (positional) and 2µm for the form.
As in the variance-analysis in figures 16b and 16c demonstrates, the deviation of the extracted surface from the ideal form can be significantly reduced by using image correction techniques like advanced beam hardening correction.

Fig. 16a: A calibrated Zerodur® sphere plate was used for nanotom CT measurements.

Fig. 16b: Variance analysis of volumetric data reconstructed without beam hardening reduction showing a position-dependent deviation from the ideal form.

Fig. 16c: Using the advanced beam hardening module of GE S&IT phoenix|x-ray provides significant better comparison results.
The sphere plate was used to determine the length measurement error of ± 1 µm at 15 µm voxel size according to the new VDI/VDE-standard 2630 for CT systems’ calibration and for determination of their precision, resp. repeatability.

Thanks to its precision and temperature stabilization as well as to the beam hardening correction software created by GE Sensing & Inspection Technologies, the nanotom is a metrology capable tool, proven by repeatability studies carried out with calibrated sphere sticks of 2 mm, 4 mm and 40 mm length at different magnification, hence voxel resolution levels. The sphere distance error observed in all three cases was < 1 um, cg value in all three cases was > 1,34.

Highly accurate extractions of the surface data facilitate high precision 3D metrology and reverse engineering processes.

Fig. 17: Calibrated sphere stick, a carbon rod with ruby spheres at each end.

Fig. 18a: 2D X-ray image of an injection nozzle. The internal injection channels are visible, but non-destructive metrology is impossible.

Fig. 18b: Dimensioning of an injection nozzle. To ensure high CT quality, the beam hardening correction and surface extraction modules of GE S&IT phoenixx-ray were used. The max. deviation to nominal cone geometry is 5 µm.
APPLICATION EXAMPLES
One important task in metrology is the comparison between CAD data and a prototype of a products by using CT. The CT volume is extracted into a STL surface or a point cloud and then compared with the CAD model. The variance analysis, carried out after a best fit of both, the surface and CAD model, reveals the differences. Thanks to CT, both internal and external variances are shown.

Fig. 19: Variance analysis between the extracted surface of the measured volumetric CT data and the CAD data of a miniature chess rook (height 2.09 mm) made by means of laser stereo lithography. The voxel size is 1.2 µm. Deviations are displayed using pseudo-colours and may also be virtually sectioned.

The multi-line detector allows for doing CT scans of large and highly absorbing products such as e.g. cylinder blocks at an outstanding quality. Porosities of less than < 0,3 mm size may be revealed, wall thickness may be analyzed, exhaust channels may be traced and properly measured.

Fig. 20a: rendered CT volume of a cylinder head (3 cylinder motor), scanned with GE S&IT phoenixlx-ray’s CT system for large castings, vtomelx L 450.

Fig. 20b: automatic wall thickness analysis of a cylinder head (3 cylinder motor) scanned with GE S&IT phoenixlx-ray’s CT system for large castings, vtomelx L 450.
In practise, coordinate measurement machines (CMMs) have been used in automotive industry to fulfil metrology tasks as outlined above. Today, due to the fact that the interest to measure is no longer limited to exterior features, high-resolution computed tomography can access interior features of interest to be measured. CT is even capable to achieve results of both, interior and exterior features in a faster way. The metrologist’s key question is: “which accuracy and repeatability can a CT system achieve in comparison with a traditional CMM?”

The following example shows a comparative measurement of performances of a 3D-CMM GE S&IT phoenixlx-ray’s v|tomelx L 450 (Fig. 4), taken on an aluminium valve block. On both systems, 30 features (distances, diameters, angles) were carried out – on the CMM in about 2 hours, on the CT system in about 30 minutes. The measurement results on all 30 features varied on both systems from the nominal values by max. 35 μm, whereas the results between the CMM and the CT system varied by +/- 7 μm.

Fig. 21a: Aluminium valve block, used for a performance comparison between a 3D-CMM system and GE S&IT phoenixlx-ray’s v|tomelx L 450.
Fig. 21b: STL measure data, alignment and variance analysis of the valve block

CONCLUSION
High resolution CT performed with microfocus and nanofocus technology serves a wide range of application in failure analysis, quality control and metrology. Precise three-dimensional imaging and measurement of all internal and external absorbing structures now provides non destructive measurement with an accuracy that was only previously available on external surfaces with conventional CMM technology. Hence high resolution CT represents a new CMM generation of faster, more precise metrology even of internal surfaces. For many automotive applications, microfocus CT and nanoCT® provide the same performance level in terms of measurement precision as CMM systems.