NEW CONCEPT FOR FAST, EFFICIENT AND ECONOMICAL INSPECTION OF HIGH VOLUME, HIGH MIX INDUSTRIAL COMPONENTS USING ADVANCED HIGH SPEED COMPUTED TOMOGRAPHY SYSTEMS

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In manufacturing processes, inspection capability is increasingly used as early in the production value chain as possible to ensure that scrap- and rework costs are minimised. As fast radioscopic in-line inspection systems, fully unmanned and equipped with automatic defect recognition e.g. of castings, are now state-of-the-art technology, this paper explains the next evolutionary step within the x-ray technology of utilizing fast computer tomography technology, scanning concepts and algorithms fulfilling high throughput requirements for different applications. We demonstrate that this new generation of CT solutions brings down scanning time from hours to minutes and provides image quality to meet the majority of inspection requirements, today and tomorrow.

With the new generation of CT systems for fast porosity/inclusion evaluation, 3D dimensioning and CAD comparison, the industry now has new tools for totally integrated and unmanned inspection. Fast CT systems include automated scanning- and test protocol generation, up to the point were the inspection results are directly looped back to ensure immediate adjustment of the production process to meet predefined specifications.

Motivation

In recent years the usage of light alloy castings has significantly increased within the transportation industry.

On the one hand, this has been an attempt to decrease total weight and therefore energy consumption and CO_2 emission; on the other hand, it has been used to compensate for the increasing number of added mechanical and electronic features e.g. driver assistant systems and safety features to meet today’s stringent safety requirements.

Light metal structures are increasingly used within the power-train-, suspension- and structural area of a vehicle. All these have different requirements in terms of dimensional accuracy and structural integrity to meet design specification.

As the total number and the complexity of part shapes, sizes and performance requirements increases, there is a need for an integral, precise and efficient method to ensure that all critical parameter are consistently met.

By using more precise inspection methods e.g. for high production volume castings, the productivity increases because of a lower false scrap rate, a decrease in the amount of acceptable components falsely classified as defect using interactive or fully automated inspection.

Furthermore, and dependent on the underlying casting process, a precise inspection method can lead to lowering safety margins at design level which often compensates for margins in the applied production process. As a result energy, material, labor cost and CO_2 emission during production and when in duty on the vehicle can be saved accordingly.

Speed and throughput in accordance with the production

Modern computer tomography (CT) systems are used today to provide entire volumetric information for dimensional accuracy and structural integrity of different parts. However, in many cases the inspection capacity is not sufficient to cover a larger part of the production.

Inspection and analysis of 100% production and 100% of each part ask for a new approach to meet the requirements and catch up with the production rate ensuring that all parts are to spec. Typical throughput requirements range from 10 s for smaller piston or suspension parts up to 80-90s for a complex engine part e.g cylinder head.

To meet this throughput requirement a fully automated inspection method including the entire acquisition and analysis process is therefore vital. Main factors driving the cycle time of a fast Inline CT system are technologies used for efficient data acquisition, reconstruction and analysis.

The right choice of components, operating parameter and algorithmic concepts is necessary to meet and exceed the inspection and analysis requirements of the industry.

The following aspects of a high speed Inline CT system influence overall throughput:

Components / Hardware

- Mechanical handling (conveyor, robot, manipulation)
- X-ray tube
- X-ray detector
- Computer hardware, CPU vers. GPU processing

Settings & Parameter

- Size of inspection envelope
- Number of projections
- Scale of pixel binning
- Type of data acquisition (Helical, axial or others)

Algorithm

- Reconstruction
- Data handling DICOM
- Defect detection / filter
- Defect classification

When considering an inspection solution many of the system requirements are defined by individual inspection requirements and scope of individual parts to the analyzed.

a. The necessary spatial- and contrast resolution within the part is typically defined by the smallest defect size to be detected. Influencing factors to achieve this requirement are
    1. Size of the x-ray tube focal spot
    2. Dynamic range of the x-ray detector
    3. Pixel pitch size
    4. Geometrical magnification.
    5. Number of projections
    6. Further image improvements thru beam hardening and scatter corrections

b. The Inspection envelope and necessary x-ray source power is defined by the part size and resulting overall wall thickness.

Analyzing Data for potential Anomalies

As soon as the CT scanner has acquired the volumetric data, individual analysis could be applied on a part type specific manner. By using state-of-the-art CT technology, various aspects of a part can be analyzed for the benefit of the user:

1 **Detect and classify anomalies within the material**.
Typical casting anomalies are areas of less- or denser material then the main alloy (flaws, porosity bubbles or inclusions). To detect anomalies within the material the entire volumetric data set and to meet the speed requirements, the analysis and classification is done fully automatically. The identified anomalies are classified according to a pre-defined specification. Different defect size and density thresholds can be defined for individual areas within the part.
Using volumetric data and three-dimensional analysis, this technology has two major advantages over the conventional radioscopic 2D inspection.

a. Precise definition of inspection specification in 3D ensures that more stringent detection requirements are only applied to the necessary regions.

b. Detected anomalies can be analyzed in relation to final, machined areas. Flaws within areas of a part that will be machined in a further processing step can be identified and disregarded as defects.

c. Identifying porosity in relation to machined surfaces allows the system to determine if the flaws open up to the surface after machining. This is especially helpful when these flaws are otherwise below a critical size for the structural integrity.

By applying Inline CT-based inspection instead of conventional, automatic 2D inspection, all of the above factors combine to offer a significantly reduced false scrap rate and increased productivity. This is also the case even when compared to trained personal reviewing 2D x-ray information on rejected parts on a case by case scenario.

2. **Check for dimensional accuracy**.
Another major benefit of acquiring and analyzing entire volumetric data of individual test parts is that actual part features can be compared against nominal CAD data. With this ability, any variation in shape or size can be identified in a very early stage of the production process. This immediate response to processing parameters will lead to high productivity and low scrap rates.

3. Differentiate between materials.
Conventional 2D x-ray inspection systems have only limited abilities to differentiate between materials and exact locations. Depending on the casting process where different materials are part of the production process these could remain at/with the casting by mistake (e.g. sand or salt core). The foreign material residuals could then lead to a falsely rejected part. Inline CT technology adds the ability to differentiate

between different materials on top of the 3D information. With this information the size and location of such foreign material can be identified and related to inner or outer surfaces. Castings including sand core residuals as a reason of an insufficient cleaning process could be accepted after a more thorough cleaning process. An increased yield and productivity is the result.

Classification of potential Anomalies

Once the potential anomalies or defects described above are identified, different analyses can be applied.

1. Quality requirements based on contractual agreements with the end customer e.g. ASTM-E155 or OEM specific requirements.

2. Statistical analysis to identify trends over time and area to ensure an early response to optimize process parameter and increase yield/productivity (process feedback).

3. Collecting integral information on a part level helps to optimize the production process and gain productivity.

In many cases, today's process information gathered from different inspection/testing methods (e.g. x-ray, UT, pressure, visual) cannot be efficiently translated back to the production process to gain understanding of the cause, whether the interpretation is done automatically or by human operators.

One of the major benefits using volumetric image information from CT is the immediate understanding of anomaly location in relation to the actual part and its critical areas.
As most of today's quality requirements and specification are based on 2D projection data, necessary extensions to the third dimension is indispensable to gain from the extensive benefit using Inline CT for high volume NDT and sizing.

Inline CT Technology

The spectrum of industrial CT System ranges form high resolution systems with a voxel resolution down to a couple of micrometers up to high energy systems, like linear accelerators, which allow penetration of large, dense objects. These systems are mainly used for research and materials science and in early stages of product development. In these kind of industrial applications, image quality is the major concern and acquisition time is of less importance. For CT inspection systems that are integrated into the production line the situation is different: The major concern is to satisfy the throughput requirements. This requires fast data acquisition, reconstruction and volume analysis without any user interaction. In the remainder of this section we discuss the technological aspects for Inline CT inspections while comparing today's industrial CT Technology with the medical CT Technology.

Data acquisition

The required resolution (voxel size) essentially depends on the smallest object size inside the part being inspected. It is well known from sampling theory that the smallest object size should be at least twice the voxel size, and thereby defines the choice of the magnification, detector pixel size and focal spot size. CT reconstruction requires an angular sampling, more commonly referred as projection data acquisition. Therefore, the number of voxels along each particular dimension determines the required number of projections and therefore the acquisition time. For a volume with a number of n voxels along each dimension the number of projections typically varies in the range of [π/4 n,π/2 n] according to the focal spot size.

Today’s detector technologies, like the GE DXR-250RT-E flat panel detector with a frame rate of 30 frames per second at 1024x1024 pixels, allow a data acquisition of continuous rotating inspection parts. With this technology we can obtain a CT scan in 30 seconds for a 1024x1024x1024 volume and 1000 Projections. However, the advantage of the commonly used stop and go data acquisition is achieving an additional noise reduction by integrating several images at each position. This is not possible in the continuous data acquisition mode, where the noise level is proportional to the dose.

A decrease of the focal spot size leads to an increase in resolution and a decrease in dose. One reasons for the dose reduction is the heat dissipation capabilities of the industrial x-ray tubes. Rotating anode tubes are mainly used in the medical or security applications and offer an interesting alternative for Inline CT applications. Compared to industrial high power tubes they have small focal spot sizes at a power level ten or more times higher. The high number of emitted x-ray quantums makes medical tubes well suited for short acquisition times with high frame rates. Medical tubes are available for energies up to 140-150KVp. Table 1 shows some typical values of industrial and medical x-ray tubes.

Source	**Focal spot Range**	**Power Range**	**KV Range**
Industrial Macro focus tubes	1mm-6.3mm (high power)	1.5-4.5kW	0-450kV
Industrial Minifocus tubes	0.6mm-1mm	800W – 1.5kW	0-450kV
Medical Tubes	0.7mm – 1.2mm	0 – 50kW or more	0-140kV

Table 1 Typical values of industrial and medical sources

Detector and scanning modes

Flat panel detectors are used for 3D-CT but have a limited horizontal field of view compared to linear diode array (LDA) line detectors, which are available for all most all lengths. If the object dose not fit into the field of view of the flat panel a measurement area extension can be used to increase the scan area, unfortunately leading to a significant increases in acquisition time. CT scans acquired with line detectors usually lead to a better image quality than CT scans acquired with a flat panel detector. The amount of scattered radiation in the fan beam geometry is much less than in the cone beam geometry, because of the smaller region which is penetrated.

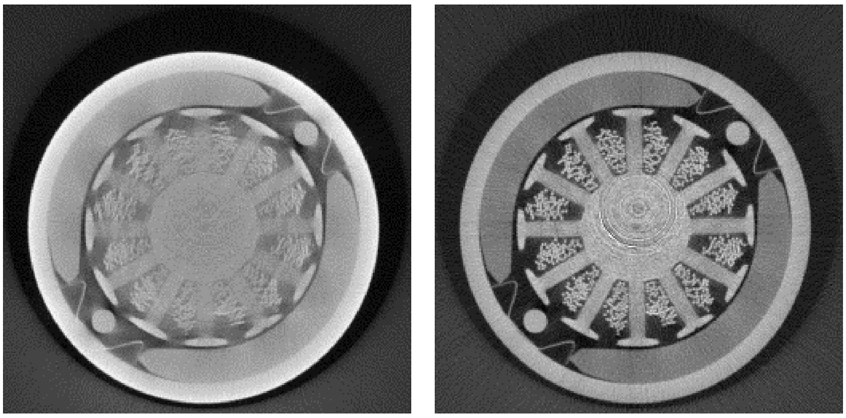

Figure 1 Comparison of a flat panel CT scan (left) and a line detector CT scan (right). See text.

Figure 1shows a comparison between a line detector and a flat panel data acquisition. In this example we simulated the line detector with the flat panel detector by collimating the flat panel down to a line detector on the detector as well as on the tube side. Therefore, this comparison is fair and is not a result of differences of the detector properties. Obviously the image quality in the line detector result is much better than the quality the flat panel result due to the reduced amount of scatter.

The multi-line detectors, mainly used in the clinical CT scanners, give an interesting trade off between line and flat panel detectors. They are available for 4, 8, 16, 32, 64 or more lines, and therefore allow to make the trade of between image quality, in terms of scattered radiation, and scan time, in terms of number of lines or z-coverage.

Typically, a 3D volume is generated with industrial line detector CT systems by scanning the object in a slice-by-slice fashion, which is very time consuming. In order to reduce the scan time with such systems we can make use of a helical scans or sometimes referred as spiral CT. The main difference is that during the rotation the object is moved in z-direction. In many applications a helical pitch factor, the ratio between object translation and detector c-coverage, of 2 is sufficient and reduces the scan time by a factor of two.

Helical scanning can be applied for multi-line and flat panel detectors as well and is frequently used in clinical CT systems. The combination of efficient multi-line detectors, high power tubes and helical scanning allow to scan larger parts, like cylinder heads, in a couple of seconds with a clinical system. Therefore this technology is very well suited for inline inspection systems.

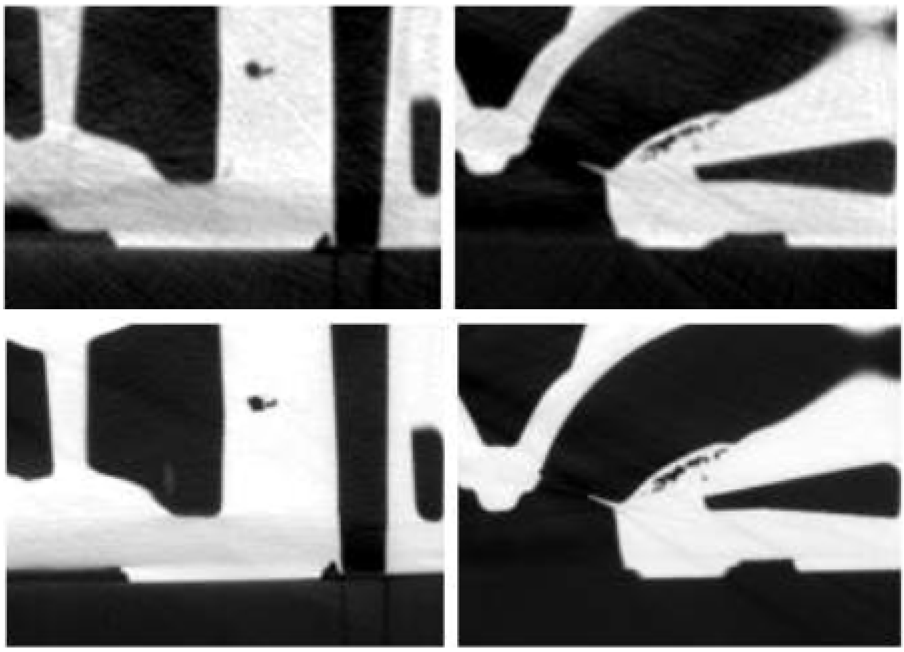

Figure 2 Comparison between CT system with medical components (top row) and a standard line detectors system (bottom row)

Figure 2compares a standard industrial line detector systems with a 450kV tube a multi-line detector CT-scan with a medical 140kV tube. For better comparison both systems are operated that the same tube power level of 3.5kW. The results of medical image chain give comparable results to industrial CT system at much lower kilo voltages in less time. The scan of the entire part took several hours with the industrial CT system and a couple of seconds on a CT system utilizing medical components.

Image generation

The reconstruction of a three dimensional volume or just a single 2D slice through the object from the projections is computationally expensive. Even with today's multi-core processor technology the reconstruction takes a couple of minutes for volume sizes in the order of 512^3 to 1024^3, and will make it difficult to fulfill high throughput requirements. Recently, this bottleneck has been overcome by implementing the reconstruction on standard PC graphic cards, which allows a reconstruction of those data sets within a couple of seconds. For Inline CT applications it is now possible to finish the reconstruction shortly alter the last projects as been has been acquired, and thereby enable high throughput inline CT Systems.

Volume Analysis

The 3D Volume analysis has some additional advantages compared to the actual 2D radioscopic inspection systems. The 3D Information allows us to obtain precise information about the 3D locations of voids inside the volume and measuring their sizes in 3D. Precise measurements inside the volume, like sizing or comparing against CAD models, open new possibilities and may replace some of the CMMs inside a production line in the future.

The role of CAD models

In industry, CAD models are often utilized to order to compare the surface of a given part against a reference CAD model. As result, we obtain a dense measurement of the surface deviation over the entire part which allows a dimensional control. In practice, the X-Ray inspection takes place at an early stage in the production phase followed by several machining steps. Therefore, these measurements can only be taken at points or regions of interests that are critical and of importance.
Any material that will be machined after CT scanning **doesn't** need to be analyzed for structural integrity, voids and defects as these are not relevant for the final product performance.

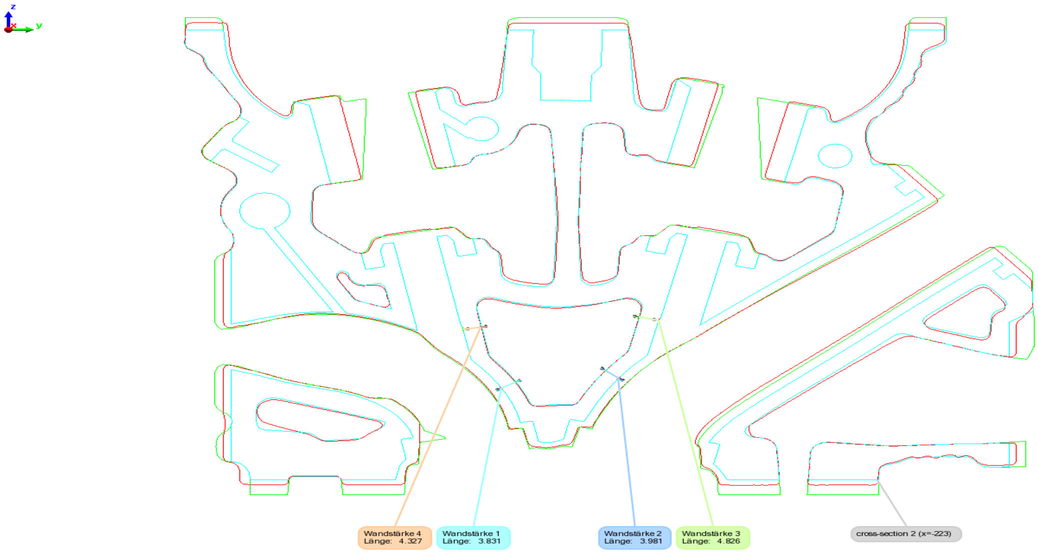

Figure 3 Intersection of 3 Surface mode: Casting CAD mode (green), CT Surface extraction (red) , final part after machining (turquoise)

Figure 3 shows intersection of three surface models. The red curve represents the extracted surface of a part from a CT scan. The green curve the CAD model for the casting process and the turquoise curve the final part after machining. The advantage of taking the CAD model of the final part during the defect detection into account is obvious: Defects inside regions that are cutoff during the machining need not to be considered and do not lead to a rejection of the part as they would do in 2D X-Ray inspection. In addition we can identity if small porosities whose sizes are below the reject threshold will be opened and thereby connected to the surface in a later machining stage. This is an important question at sealing regions, because surface-connected porosities may case leakage.

Defect Detection and Analysis

After finishing the reconstruction the volume is transferred to a volume analysis station. During the defect detection the following steps are taken:

1.) Object Segmentation

The object segmentation, sometimes referred as calibration, is used to identify the part inside the volume. This information than can be used for the defect detection or for supporting the registration.

2.) Registration with reference Part

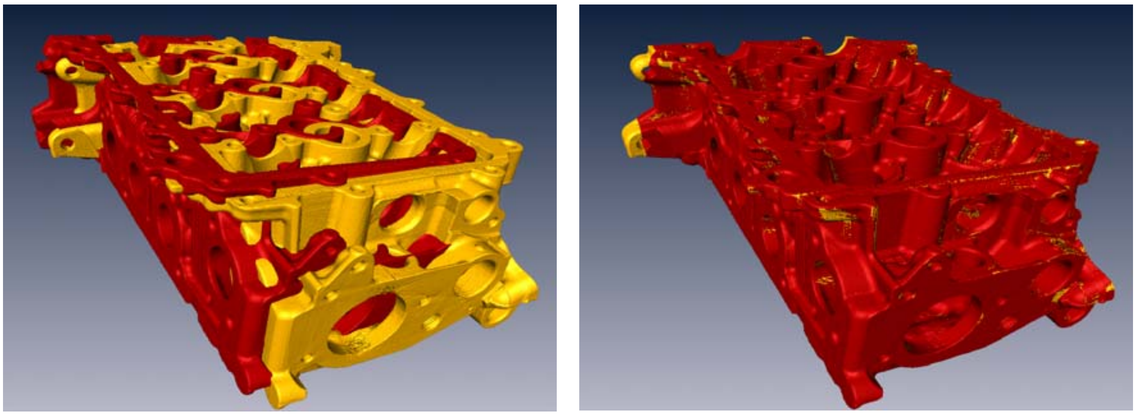

Figure 4 Registration between volumes of two cylinder heads. Left before registration; right after registration

The registration compensates for positioning uncertainties during the part handling. The part inside the volume is registered or mapped to a reference part. All regions (ROI's) for defect detection and classification are those defined for the reference data set and can now be applied to the actual volume.
An example for the registration of two cylinder heads is shown in Figure 4.

3.) Defect detection

The defect detection algorithms can be further separated into reference-based and non-reference-based defect detection algorithms. The assumption of the non-reference-based defect detection algorithms is that defects are always encapsulated by material. If a defect has a connection to the surface it dose not satisfies this assumption and will therefore not be recognized as defect.

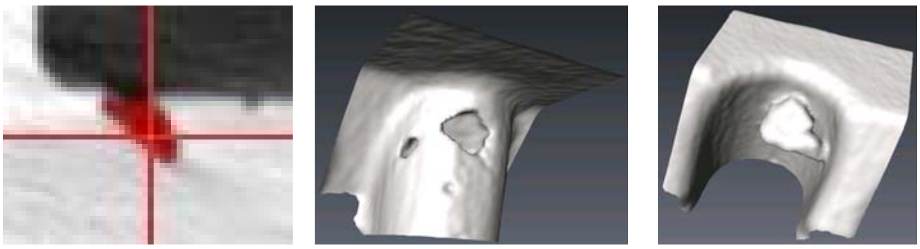

Figure 5 Surface connected: detection result (left), surface rendering of the defect form outside (center); surface rendering from inside (right)

Reference-based approaches allow the detection of both kind of defects, internal as well as defects connected to the surface. However, they need to be able to deal with the part-to-part variations, which usually causes a lot of false alerts.

Figure 5 shows an example of the detection of a large surface connected defect that was detected by one of our defect-detection algorithms. The defect is detected very well and we cannot observe any false alerts from the part-to-part variation that is present in this case too. This reference-based algorithm utilizes a shape adaptive filtration to cope with the part-to-part variation.

The complexity of the applied defect detection algorithms defines the overall throughout of the volume analysis system.

4.) Defect classification

The found defects are further grouped according to the pre-set classifications specified by the costumer. The simplest classification rule is a threshold for the defect size. If the size of one defect is larger as the threshold that the part will be rejected. More complex rules may allow a certain number of defections larger than a predefined size in a region or consider their spatial relations to each other.

5.) Report generation.

Finally, at the end of the volume analysis, the part will be accepted or rejected and a report will be generated and send to the production plant system.

Sand core residuals and flashes are often sources for pseudo rejects of a part in 2D X-ray inspection. Flashes are often treaded as part structure during the defect detection in 3D and will therefore not lead to a part rejection. Similar, sand core residuals on the object surface do not cause a reject of a part, since we can detect it in 3D as being out side of the part and not inside as in a case of an inclusion.

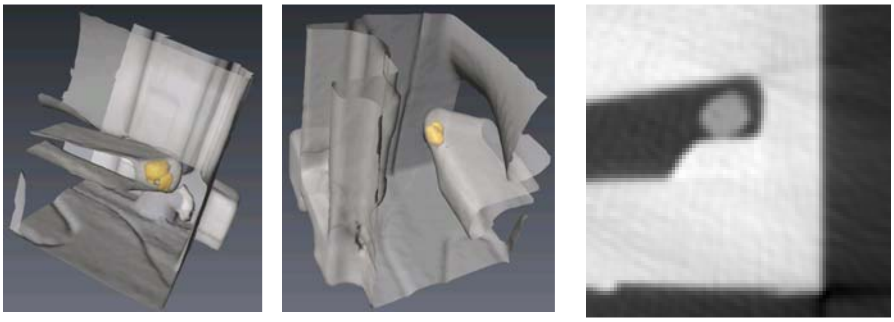

Figure 6 Sand core remain: segmentation (left, middle); CT image (right)

Figure 6 show an example of a segmentation of a sand core residual inside a channel of a cylinder head. This residual can be removed, and its detection will reduce the reject rate.

Summary

Industrial CT inspection systems are commonly used in the casting industry for R&D and sample evaluation. These inspection systems are designed to operate even in harsh environments.

Introducing high speed Inline CT Systems based on state-of-the-art CT technology as described above, opens up new applications for in-process, high volume and high mix inspections. By applying this new inspection technology, the established infrastructure of x-ray inspection can be extended to the third dimension to meet increasingly stringent quality requirements.

Key benefits over conventional x-ray inspection systems are improved productivity and less energy-, CO_2 - and material consumption during production.

Furthermore using more precise inspection on a 100% rate can lower design safety margins, which means that the need to add material weight to ensure safety at critical areas can be obviated. As a result component weight can be reduced, with benefits to the castings manufacturer and the end user.