AUTOMATED HIGH SPEED VOLUME COMPUTED TOMOGRAPHY FOR INLINE QUALITY CONTROL

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Abstract: Increasing complexity of innovative products as well as growing requirements on quality and reliability call for more detailed knowledge about internal structures of manufactured components rather by 100 % inspection than just by sampling test.

A first-step solution, like radioscopic inline inspection machines, equipped with automated data evaluation software, have become state of the art in the production floor during the last years. However, these machines provide just ordinary two-dimensional information and deliver no volume data e.g. to evaluate exact position or shape of detected defects.

One way to solve this problem is the application of X-ray computed tomography (CT) [1]. Compared to the performance of the first generation medical scanners (scanning times of many hours), today, modern Volume CT machines for industrial applications need about 5 minutes for a full object scan depending on the object size.

Of course, this is still too long to introduce this powerful method into the inline production quality control. In order to gain acceptance, the scanning time including subsequent data evaluation must be decreased significantly and adapted to the manufacturing cycle times.

This presentation demonstrates the new technical set up, reconstruction results and the methods for high-speed volume data evaluation of a new fully automated high-speed CT scanner with cycle times below one minute for an object size of less than 15 cm. This will directly create new opportunities in design and construction of more complex objects.

Introduction: Increasing competition in the car industry particularly forces the suppliers to enhance their product quality and to optimize the production processes in order to improve or at least sustain the sales opportunities. Regarding the issue of quality control, Austria Alu-Guss (AAG), a wheel casting company, belonging to the BORBET group, is cooperating with the Fraunhofer-Gesellschaft in the field of automated radioscopic inline inspection. Since 1983, this company is producing light alloy wheels by millions for the European car industry each year. However, the changing philosophy to Just In Time (JIT) manufacturing in the car industry significantly increased the demand for quality and reliable supply for the cooperating companies.

In 1996, after the acquisition of Austria Aluguss by Borbet, the programme AAG2000 was started, targeting for increasing the production capacities, linking processes and increasing automation in production processes.

Automation mainly means higher process reliability and productivity. A maximum flexibility is guaranteed by modern automated production and complete quality management. One part in this quality chain is the inspection of the cast wheels by X-ray fault detection. During the casting process, defects like pores, blow holes or cracks can appear. Such defects are, in a certain range, permissible according to size, location and density with criteria prescribed by the car industry. As wheels are safety relevant parts, these instructions usually are very strict and today 100 % completely checked by radioscopic inline inspection of every cast wheel.

State of the Art and Vision: The inspection, in former times done by manual/visual control of the scrolling radioscopic images of the x-rayed wheels, today is performed automatically. The applied ISAR system (**I**ntelligent

System for **A**utomated **R**adioscopy) is inspecting the wheels without any human support immediately after the casting process [2,3]. The software is evaluating the x-ray images, detecting the defects and comparing them to a predefined quality instruction. Objects, classified as defective are rejected.

The state-of-the-art solution, which is based on two-dimensional image processing, however, provides no volume information and thus, no exact defect location and size, regarding the third dimension in beam direction, is available in the case of radioscopic imaging. This is not a real problem for wheels manufactured today because all known and relevant defects can be found by this method. However, according to innovation processes in design, construction and production, future quality characteristics can appear that can no longer be checked by simple two-dimensional radioscopy. The car industry continuously asks for weight reduction, engendering the development of new and innovative wheels. AAG has developed a so called "Nature Wheel" similar to the construction of human bones. In case of this new product, inline computed tomography could help to examine and measure the position of the integrated core (with lower weight than Al), which then could reduce one inspection step of the current production process. Innovations like this are the challenge for the future non-destructive inspection systems and reveal the limits of the current radioscopic methods.

To overcome the limits of standard radioscopic methods, namely the lack of information about the shape of defects, about their exact location or moreover about the inner construction of complex object structures, the three-dimensional computed tomography has to be applied, which has proven its potential for the near future to solve those problems. During the last five years, the 3D-CT has made significant progress fostered by the development of a new flat panel detector technology [4,5] on the one hand and by the continuously increasing power of computers on the other hand. Due to these developments, reconstruction times today are in the range of some minutes for object volumes with diameters up to 15 cm. This time, in this case compared to cycle times of standard inline 2D inspection systems of about 30 s for such objects, is not far away from industrial maturity. The anticipating aspiration is to develop 3D-CT systems, combined with fully automated volume image processing, achieving cycle times in the range of production time for such and even larger objects.
The major tasks for this challenging goal are

- advanced high speed reconstruction algorithms, working with a set of limited projections,
- high speed volume data evaluation,
- more sensitive, faster and larger x-ray detectors and
- high power x-ray tubes.

This presentation will demonstrate that improvements already for the first two items will refute the prevailing opinion that CT is still too slow for industrial application.

Results: The only chance to achieve short scanning times, is to use 3D or cone beam CT which means to get the total set of reconstruction data by one single object scan. Axial Computed Tomography (ACT) can be realized in one-, two- and three-dimensional systems related to the kind of imaging geometry (parallel, fan or cone beam, fig.1).

<ins>2D-CT Systems:</ins>
One object layer (fig.1 middle) is reconstructed by one fan beam scan similar to the medical scanners. To acquire the total volume, several scans of different layers have to be carried out and the slices are subsequently put together to one volume. A volume of 1024^3 voxels still needs a total scanning and reconstruction time of more than 10 hours! Nevertheless, this method has an important advantage due to scattered X-rays, which are superposed to the real X-ray absorption on the detector and thus reduce the quality of reconstruction. As the solid angle of line detectors in relation to the scattering object is much smaller as of array detectors, reconstruction results

consequently should be better in the case of fan beam scanning. Figure 2 demonstrates this effect by comparing two slices, one reconstructed by 2D or fan beam geometry and the other by 3D or cone beam scanning.

Although the fan beam setup was not ideal (the line detector was simulated by collimating a flat panel array detector), the difference is evident. Much better results are possible, if more suitable and adapted line detectors are applied. Especially in case of dimensional measuring, where exactly defined object boundaries are needed, reconstructions of cone beam or 3D systems still are unusable today.

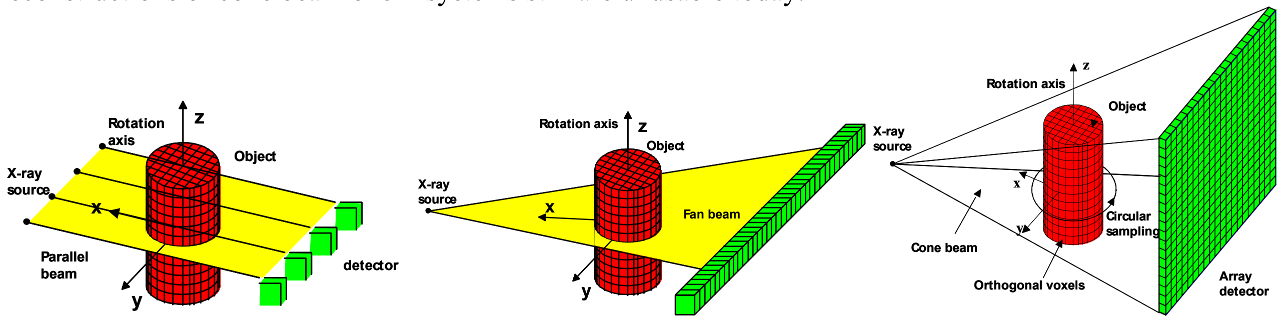

Fig.1: Different CT geometries. Left: parallel or 1D, Middle: fan beam or 2D, Right: cone beam or 3D

3D-CT Systems:

3D or Volume Computed Tomography means scanning the whole object in a cone beam with one single scan (fig. 1 right). Compared to the 2D method, measuring data are provided significantly faster and consequently much more efficient reconstruction algorithms are needed to prevent the creation of a new bottleneck by slow reconstruction. State-of-the-art system performance is shown in table 1.

Reconstructed volume	Projections	Image data [GByte]	Volume data [GByte]	Measuring time [min]	Reconstruction time, one PC	PCs for online-reconstruction
511 x 511 pixels 450 slices	400	0.2	225	3 – 15	Online	1
1023 x 1023 pixels 900 slices	800	1.8	1.8	15 - 60	50 min	1 - 3
2047 x 2047 pixels 1800 slices	1600	6.4	14.5	30 - 120	580 min	5 - 20

Table 1: Key performance data for 3D CT, normalized to one PC, Pentium IV, 3.0 GHz

There is, however, a trade-off in speed and quality. As demonstrated by figure 2, cone beam reconstruction delivers poorer image quality compared to fan beam geometry. To achieve comparable reconstruction quality by cone beam CT, the physical aspects like beam hardening and scattered radiation have to be understood and implemented in order to reduce these effects [6]. Nevertheless, this reconstruction quality is satisfactory for many applications in nondestructive analysis.

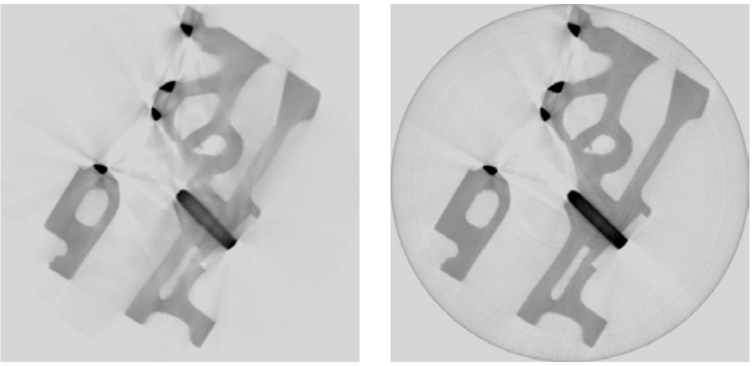

Fig. 2 Left: Layer reconstruction by cone beam scanning of a Al cylinder head;
Right: Reconstruction of the same layer by fan beam scanning (collimation of a flat panel detector).

Figure 3 shows a cone beam reconstruction of one layer of an Al cylinder head as an example for density measurements of blowholes in Al castings.
The effect of scattering becomes less important, if micro CT, based on direct magnification, is applied [7]. This is due to geometric effects, as the solid angle of the scattering profile, seen from the detector, is considerably declining with increasing distance between object and detector (see fig. 1).

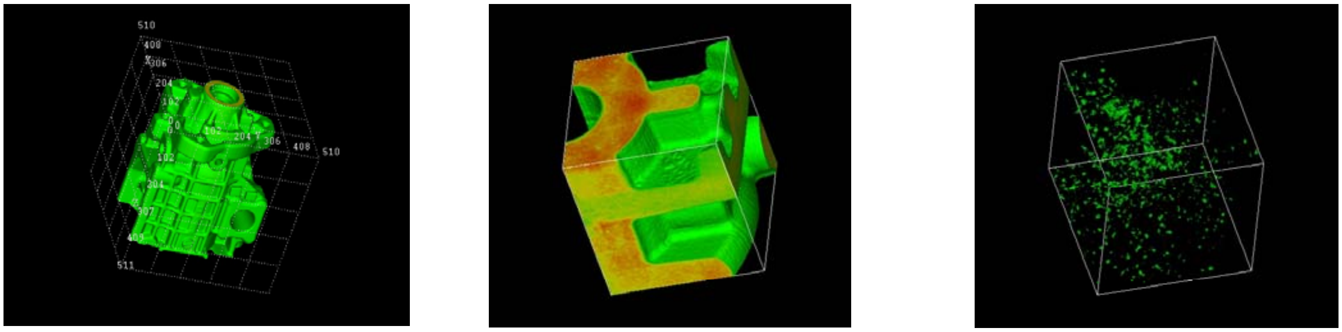

Fig. 3: Left: Volume CT of an Al gear box, Right: Results of an automated defect analysis, applied to an arbitrary segment (middle) of the reconstructed object.

Speed and resolution: The total scanning time for 512^3 volumes today is approx. 3 minutes (table 1). As mentioned in the introduction, the main task for high-speed volume computed tomography, i.e. reducing the scanning, reconstruction and evaluation time below 1 minute, is to develop advanced high speed reconstruction algorithms, working with a set of limited projections without reducing the state-of-the-art radioscopic detection resolution. There are two principle ways of operation:

- Image acquisition by continuous object rotation with a free running read out detector mode
- Acquisition by Stop-and-Go operation and synchronized triggering of manipulator/detector system

Both methods have several advantages and disadvantages. Continuous object rotation is easy to realize, can be very fast and is not limited to a certain object load because of no acceleration during constant rotation, provided a rotation axis with high stability in rotation velocity. On the other hand, the reconstructed resolution is not constant and declining with increasing object diameter and rotation speed (fig. 4).

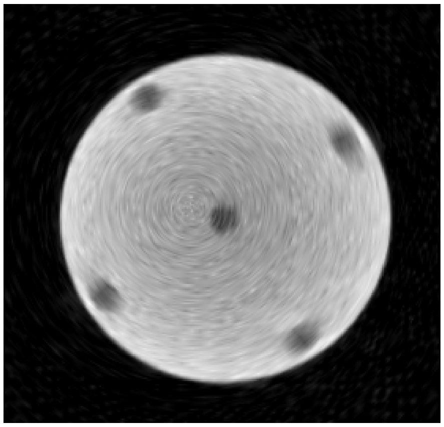

Fig. 4: Cylindrical Al test sample with five equal drillings, the blurring of the outer drill holes is due to the larger angular velocity (reconstruction by 100 images, 400 ms exposure time for each image).

Stop-and-Go CT does not show this dependency of resolution on the object diameter and can be operated by cheaper stepper motors but needs a much more complex synchronization of detector and manipulation system. Further on, this method is limited in object load due to the stop-and-go accelerations. Both disadvantages are, however, not principal barriers but technical challenges that can be solved by engineering and application of appropriate hardware in the near future.

Current detector panels with a sensitive field of view of 20 cm x 20 cm provide a minimum read out time of 134 ms per image. During an additional delay time of 134 ms for the detector read out (ready for next image acquisition), the incremental stepping from one position to the next (100 images with angle increments of 3.6 °) is performed. This means that approximately 3.6 images per second can be acquired, leading to a total scanning time of about 27 s for objects with a size of 15 cm in diameter. As the incremental stepping is below 100 ms, further time could be saved, if the detector delay time would decline. Figure 5 shows one representative slice of such a total volume CT, reconstructed by 400 projections (corresponding to a scan time of 108 s) and just 100 projections (27 s). The object size is 12 cm in diameter.

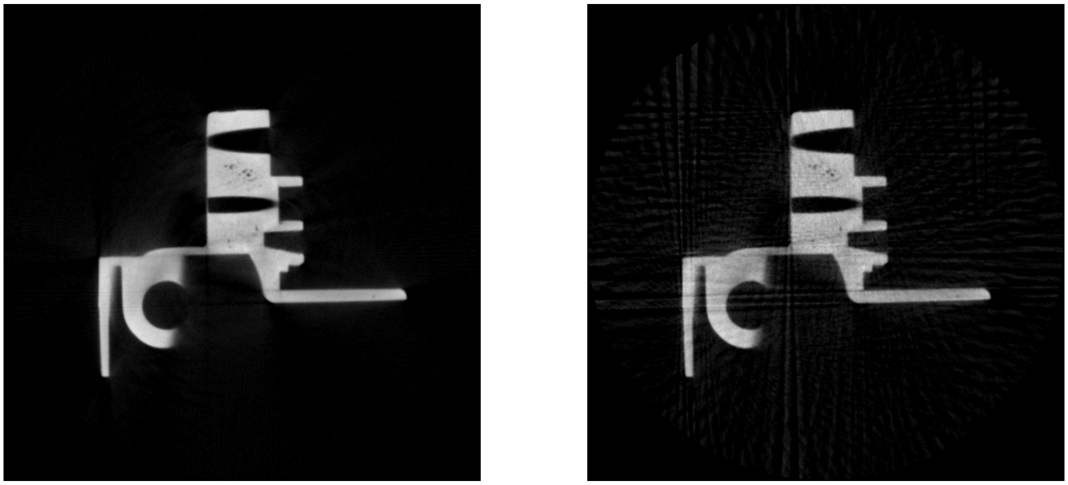

Fig. 5: Left: Reconstructed layer of an Al object (12 cm) by 3D CT with 400 projections (optimal data set);
Right: Reconstructed layer by reduced data set, 100 projections; the defects are still visible

High speed volume data evaluation: As demonstrated in the previous section, a total volume CT with scanning times below 30 seconds for objects with dimensions smaller than 15 cm can be realized. This means that the data evaluation for defect recognition must be performed in the same time range [8].

Two different methods have been developed and applied to the data:

First, a two dimensional defect detection algorithm [9] has been advanced and applied to each slice of the reconstructed object volume with subsequent composition of the defect information to a total volume defect. The evaluation time of about 10 ms per slice means a total time of 4 s for 400 slices. To avoid artefacts, which means the detection of structures not related to real defects, the same procedure is repeated for orthogonal slices, leading to an aggregated evaluation time of 12 s. Another 8 s are needed for a subsequent correlation of the defect information. Figure 6 demonstrates the application of advanced ISAR to one representative layer of the volume reconstruction, presented in figure 5. The white spots in the left image show the detected defects from an optimal reconstruction by 400 projections. The right image shows the ISAR result applied to the reconstruction by limited data sets (100 projections, scanning time 27 s) and nearly all defects were found.

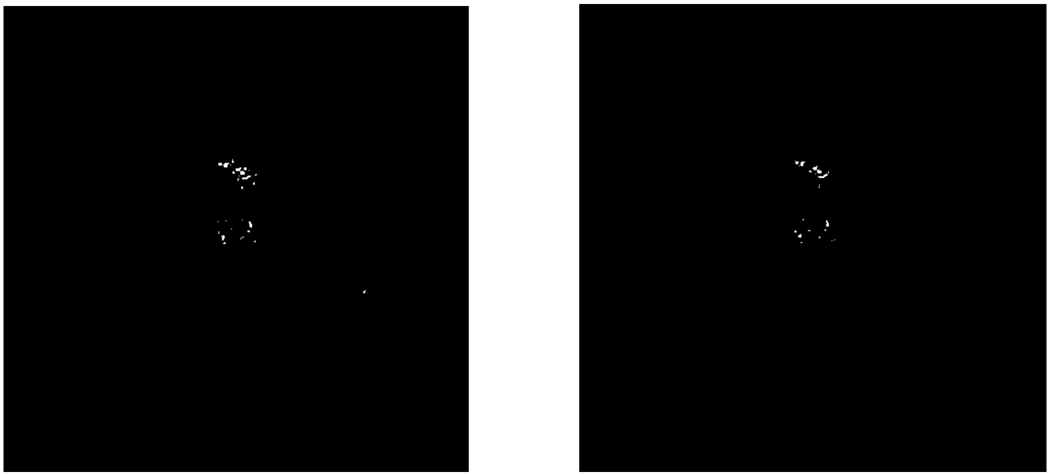

Fig. 6: Automatically detected defects (between 0.5 mm up to 3 mm), corresponding to the reconstructed layers of fig. 5. As can be seen, there is nearly no difference in classification performance even though projections for reconstruction have been reduced to 100 (right image).

A second method is the evaluation of the complete volume data by real three-dimensional image processing. The background modeling approach for the two dimensional defect detection is based on the application of two-dimensional, modified and adapted median filtering [9] in order to reduce defective structures regarded as local deviations from the normal structure (= zero defect background model). This method is now expanded to a three dimensional median filtering applied to the complete volume data set [8].

Besides the advanced pseudo defect reduction, this method will give the additional improvement to differentiate between bulk and surface defects. This is done by a first calculation of the curvature of every surface point and a second subsequent three-dimensional median filtering of this curvature. It is obvious that defects, located at the surface, will lead to a local deviation and thus can be evaluated as real surface defects.

Figure 7 shows the complete reconstructed volume of the test sample in a transparent presentation. The detected volume defects are included and indicated by red color. The left image results from a 400 projection reconstruction, the right one from 100 projections. The difference in detection performance shows still a slightly higher detection rate for the reduced data set, however, every defect could be found. It is the future task to enhance the current algorithms e.g. by additional texture analysis to achieve exactly the same results with limited angle CT reconstructions.

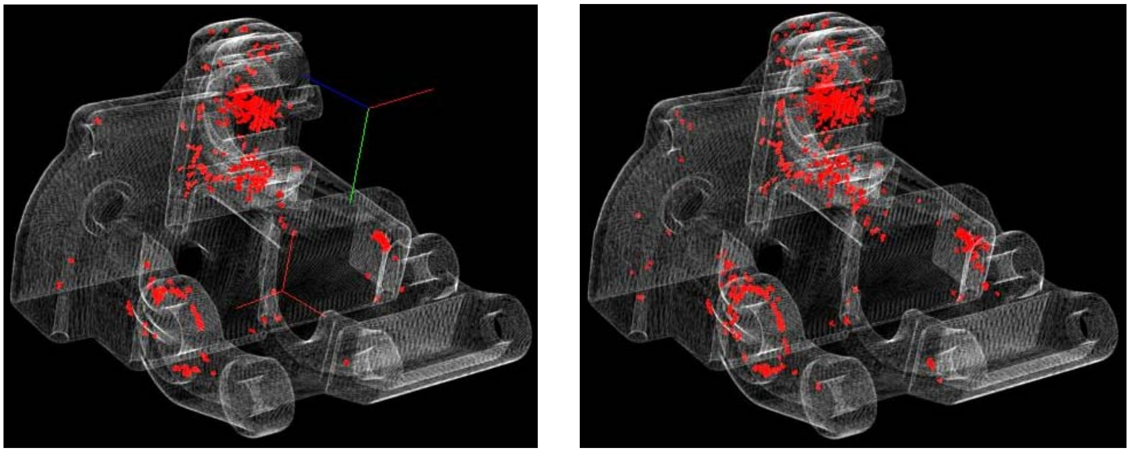

Fig. 7: Completely reconstructed volume, transparent imaged, and detected defects by three-dimensional image processing. Left image by 400 projection CT, right image by 100 projection CT

Discussion of Future Advantages: As already mentioned, increasing complexity in cast products (hybrid, structured or foamed objects) call for a significantly higher performance in non-destructive quality control during the production process in the near future. State of the art radioscopy for automated cast inspection will not be able to offer the features needed for a reliable quality characterization of modern light alloy cast products.

The demonstrated progress in CT according to speed and quality as well as the progress in automated volume data evaluation creates the opportunity of a new high performance inspection tool for volumetric non-destructive testing by combination of these two methods.

The results presented today, however, still are limited to object sizes in the range of the sensitive detector field and the corresponding detector data read out time. Commercially available detectors with mentioned read out frequencies of about 8 Hz (127 ms exposure time) have a sensitive area of 20 cm x 20 cm. To overcome these limitations, either larger detectors with at least the same read out characteristics or new algorithms for artefact free region of interest reconstruction have to be developed. Both directions are under development and it is supposed that in the near future prototype results will be available that can be applied for an automated high- speed CT on complete wheels with typical diameters up to 17 ”.

This new method of inline 3D-CT will offer several opportunities like

- definition of much more specific cast or wheel inspection instructions than possible today,
- controlling of dimensional features like object size, drillings and so on,
- controlling of integrated components like cores (Nature Wheel),
- more detailed knowledge about inner defects like pores and blow holes, i.e. information about exact position, shape and volume (different defect instructions according to size and density depending on the object location) will help to reduce rejection rates,
- better wheel development, since CT will lead to a better understanding of origin and meaning of volumetric cast defects,
- feed back loop, i.e. immediate feed back of more precise defect characterization to the production process to control production processes online → improvement of yield.

Conclusions: It has been shown that computed tomography no longer needs to be a tool for laboratory application, known as to be too expensive and too time consuming. Modern detector technology, combined with new high-speed 3D CT reconstruction algorithms, implemented on economically high performance parallel processing PC clusters, and subsequent fast volumetric data evaluation will open up the chance to introduce this powerful NDT method into the production floor in the very near future.

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