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Advanced multi-sensor and multi-source industrial computed tomography systems

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To extend the range of applications for industrial computed tomography systems, different approaches making use of several X-ray sources and detectors are presented. The combination of microfocus sources with high-voltage and high-power sources makes it possible to combine micro-CT and macro-CT applications in a single system. Digital flat panel detectors combined with line detectors allow for fast volumetric scanning and high-quality data acquisition over a wide range of part size. The benefit from multi-sensor and multi-source X-ray tomography systems is demonstrated by results from different applications, with a focus on light metal parts.

1. Introduction

Over the past few decades different types of industrial X-ray tomography systems (CT) have been developed. A system classification can be made by the part size and material to be scanned. As quality criteria of CT systems, primarily the spatial resolution, contrast resolution and the accuracy of dimensional measurements are used.

For CT service providers, a combination of high resolution, high accuracy, high scanning speed, combined with the capability to scan a large range of applications, is valuable. This ideal situation can be best approached by a cone beam CT system making use of a microfocus X-ray tube. By means of cone beam CT, a volume can be scanned with only one rotation; the reconstruction can be performed in parallel with the scan. A magnification technique utilising a microfocus tube that allows to adjust the focal spot size leads to high resolution and short scan times[1].

However, for a given system the limitations of magnifying cone beam CT are mainly: (a) the maximum amount of material that can be penetrated, depending on the X-ray energy; (b) the source focal spot size corresponding to the required energy and power; and (c) artefacts resulting mainly from photon scattering and beam hardening. In the case of an elevated level of scattered photons a beam collimation reduces the artefacts, but increases the scan time. New software approaches to correct the artefacts caused by scattered radiation are under development[2] but not yet available for integration into an industrial CT system.

In this article we describe several combinations of X-ray sources and detectors, show their limits and introduce combined systems to overcome limitations and to extend the range of applications for the main applications: defect detection and dimensional measurement.

2. Resolution of cone beam CT systems

In magnifying cone beam CT the resolution mainly depends on the part size. As a minor but still considerable effect, the material plays a role. Both can vary significantly for CT scan service providers since they need to be able to cover a wide range of applications. Materials to be scanned are typically light metals, steel, polymers, ceramics and composites. The dimensions range from millimetres up to typically 0.5 m. More details are described in the literature[3].

In Figure 1, the resolution of cone beam CT that can be theoretically achieved in state-of-the-art systems is shown. The resolution for well-tuned systems is typically 1/1000 – 1/2000 of the object diameter provided that artefacts derived from scattered photons or beam hardening do not deteriorate the result (see below).

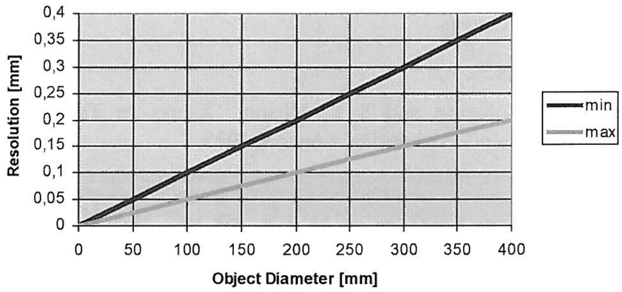

Figure 1. Theoretical resolution of state-of-the-art cone beam CT systems

A major application is the inspection of aluminium castings for small objects and magnesium die castings. Small Al or Mg castings can be found, for example, in consumer electronic products such as mobile phones and optical disk readers. Large aluminium castings are typically present in the automotive industry. Due to the broad spectrum of applications we will focus on the inspection of aluminium parts using different techniques. Another factor is that aluminium gives rise to beam hardening artefacts. If necessary, a beam hardening correction can be applied to minimise the resulting artefacts. However, in order to be able to compare the limits of different techniques, the following examples are presented here without any beam hardening correction.

3. Microfocus cone beam CT (225 kV)

Small-to-medium sized objects in the range of some centimetres can be scanned efficiently by magnifying cone beam CT. In Figure 2, a pick-up base for optical disk devices is shown. Porosity and shrinkage analysis were performed by cone beam CT, see Figure 3.

Another application of microfocus cone beam CT is the optimisation of casting processes. For this reason, casting simulation is performed and after manufacturing of the casting, a cone beam CT scan is carried out. Porosities are compared to the simulation, see Figure 4.

If the size of the aluminium object is significantly great (Figure 5, left) that the available X-ray energy is not sufficient to penetrate the object, severe artefacts are present (Figure 5, right).

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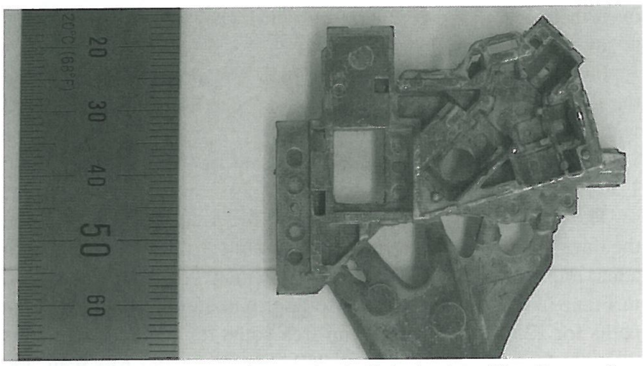

Figure 2. Pick-up base for optical disk device, Mg die casting (hot chamber)

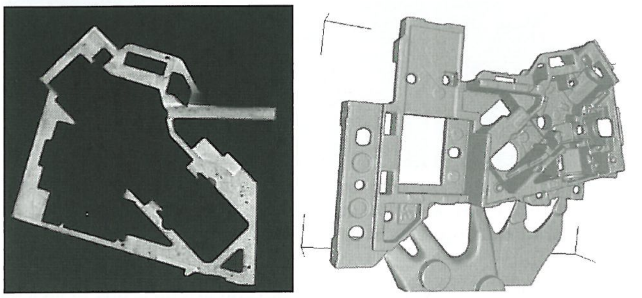

Figure 3. Cone beam CT of the pick-up base, slice (left) and 3D visualisation (right): shrinkage and porosity analysis

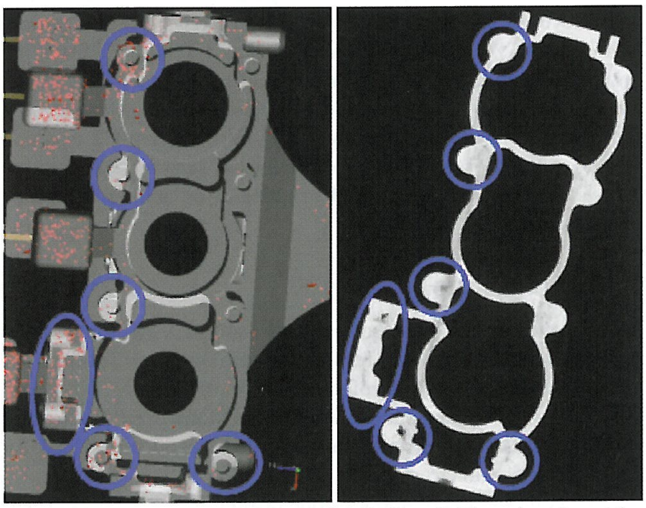

Figure 4. Comparison between simulation (left) and real part by microfocus cone beam CT (right)

4. Multi-source cone beam CT

In order to extend the area of application towards large objects, a CT system with two sources was developed: a 225 kV microfocus source and a 450 kV mini focus source, Figure 6.

Depending on the absorption characteristics of the object it can be switched between the two sourced by software. The system is based on a seven-axis high-precision granite manipulator allowing

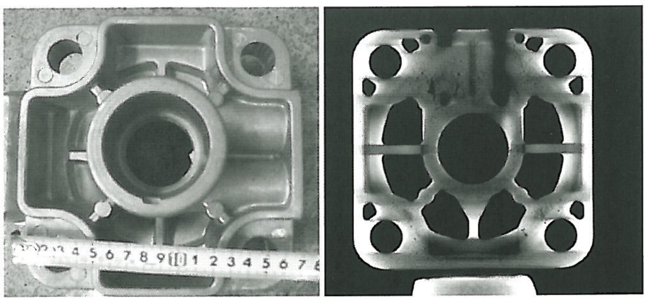

Figure 5. Larger aluminium casting and a slice of the 225 kV cone beam CT scan: Artefacts due to lack of penetration

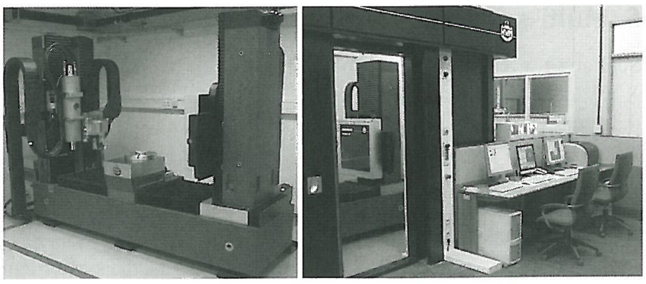

Figure 6. CT system RayScan 250 for cone beam CT with two X-ray sources

for both defect analysis and metrology. It provides a high flexibility to accommodate different applications.

Figure 7 shows the same part as in Figure 5 scanned with the 450 kV source. Comparison of the two results reveals that the artefacts can be significantly reduced by increasing the X-ray energy. The remaining artefacts are due to beam hardening which can be corrected.

By further increasing the part size for cone beam CT with a 450 kV source, one can notice that different kinds of artefacts appear, as can be seen in the scan of a cylinder head in Figure 8. In areas with only a small amount of material the result is rather free of artefacts. However, in areas with a lot of material, artefacts are present which are due to an increasing number of scattered photons. For defect analysis the quality of the scan is sufficient. For metrology applications the accuracy of the determination of the position of surfaces is significantly reduced by scattered photons.

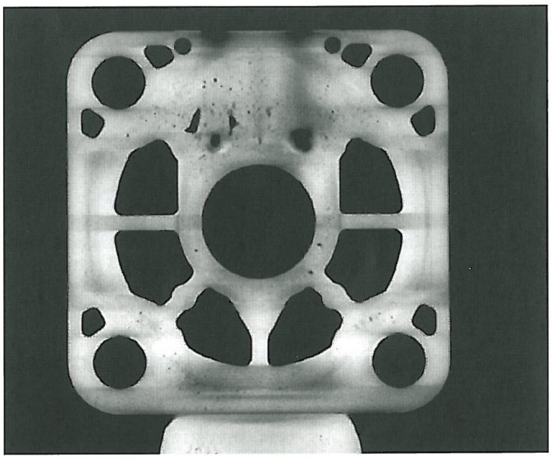

Figure 7. 450 kV cone beam CT of aluminium casting (no beam hardening correction applied)

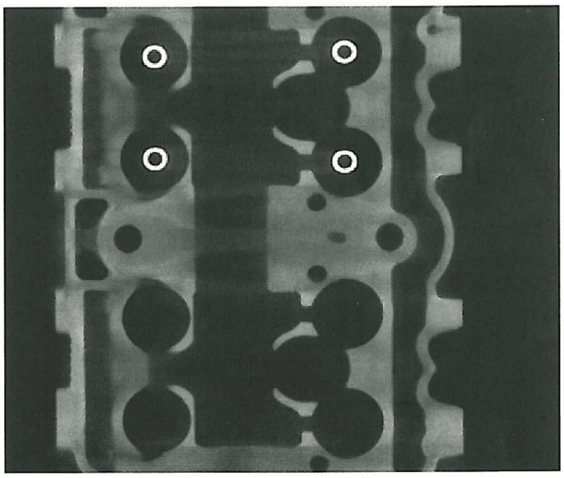

Figure 8. Cone beam CT 450 kV of an Al cylinder head with steel inserts

5. Multi-sensor CT

Scattering artefacts can be efficiently reduced by collimating the X-ray cone to a fan. A line detector is used instead of an area detector. Obviously, the scan time is higher for a fan beam CT system due to the lower detection area and the lower numbers of photons that can be used for each projection. In order to benefit from both systems, a combined system using two sensors, a flat panel area detector and a line detector, Figure 9, was developed.

Depending on the object and on the requirements, the system can quickly change between cone beam and fan beam CT by software. The cylinder head shown in Figure 9 was scanned in both modes, cone beam and fan beam CT. Figure 10 reveals the difference. In the case of cone beam CT, severe scattering artefacts superimposed by beam hardening artefacts are present. On the other hand, the fan beam result shows no scattering artefacts. Again, up to a certain extent the cone beam CT can be used for defect analysis, whereas for metrology applications fan beam CT has to be applied.

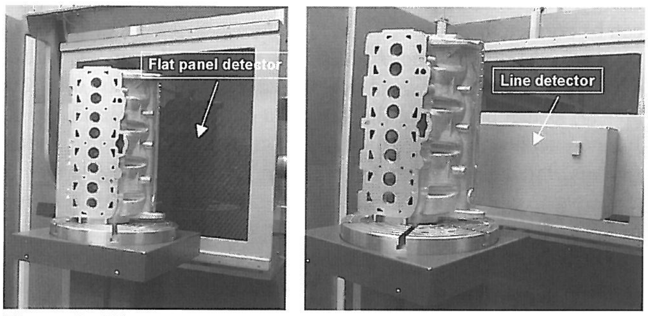

Figure 9. CT system RayScan 500 for combined cone beam and fan beam CT

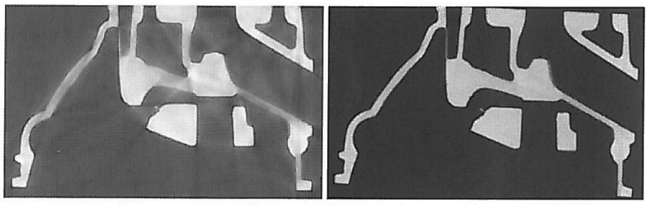

Figure 10. Comparison between cone beam CT and fan beam CT of a cylinder head

6. Theoretical investigations and discussion

The effect of scattering on the reconstructed image quality in cone beam computed tomography was investigated by Monte Carlo simulations. Calculating the direct transmission for monoenergetic X-rays *versus* sample size expressed in mean-free path units, one obtains that for three or four mean-free paths of material the direct transmission is less than 5% respectively 2%. The scattered photons are detected on top of primary (not-scattered) photons.

The effect of scattering for cases where the object has to be placed close to the detector is very strong. For example, for cylindrical aluminium samples of 100 – 120 mm diameter (more than four mean-free paths) the X-ray build-up factor corresponding to a microfocus source of 225 kVp is at least 1.5 – 2. This could represent several times more scattered photons than directly transmitted photons. Even in a configuration where the object can be placed further away from the detector, the amount of scattered photons is higher than the amount of directly transmitted photons.

For a voltage of up to 450 kVp the simple rule of three/four mean-free paths for satisfactory cone beam tomography will limit the maximum size of the sample to 100 – 140 mm. One should note that due to higher voltage and focus size the photon intensity is overwhelmingly stronger than for microfocus sources, which leads to smoother and relatively streak-free reconstructions.

Finally, for fan beam scanners at 450 kVp one can estimate that the scattering intensity drop at only a few percent of that associated with cone-beam geometries. For example, a scattering build-up of 10-20% in cone beam configuration could be reduced to less than 1-2% by collimation to a fan beam.

The results are demonstrated by a direct comparison between the three systems with an aluminium casting with steel inserts with a maximum penetration length of approximately 150 mm, as shown in Figure 11. This corresponds to approximately seven mean free paths for 225 kV and four mean-free paths for 450 kV. The scans were performed with RayScan 250 (Figure 6) and RayScan 500 (Figure 9), as described above.

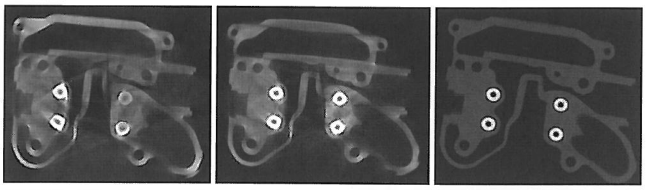

Figure 11. Comparison between cone beam CT 225 kV (left), cone beam CT 450 kV (middle) and fan beam CT 450 kV (right) of a large Al casting with steel inserts

The 225 kV cone beam CT shows several artefacts due to lack of penetration, scattered photons and beam hardening. Approximately seven mean-free paths for this configuration is by far too much to achieve good results. The object is too large for such systems. With a 450 kV source and cone beam CT the artefacts are significantly reduced, approximately four mean free paths are just acceptable for some applications of defect detection. However, if the quality requirements are high, 450 kV fan beam CT needs to be performed. For metrology applications of such large aluminium parts, fan beam CT is required in order to be able to determine surfaces accurately.

7. Conclusions

The benefit from multi-sensor and multi-source X-ray tomography systems is demonstrated by results from different applications. The combination of 225 kV microfocus cone beam CT and 450 kV cone beam CT is advantageous for small-to-medium sized aluminium objects for defect detection and metrology applications and for defect detection in large objects.

The combination of 450 kV cone beam CT and fan beam CT is advantageous for medium-to-large aluminium objects. Cone beam CT is applied for fast and accurate defect detection, whereas fan beam CT is applied especially for dimensional measurement in large objects.

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