

Simulation Aided Study for Optimising Industrial X-ray CT Scan Parameters for Non-Destructive Testing and Materials Characterisation

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Abstract. This paper presents a simulation aided study on scan parameters for industrial X-ray computed tomography (CT). The used simulation tool is able to predict the results of real CT scans and could help technicians to minimise artefacts and optimise the data quality by determining applicable scan parameters. We present a procedure based on the optimisation of selected quality measures calculable without a CT reconstruction of the specimen to determine utilisable scan parameters for X-ray CT in the field of non-destructive testing (NDT). Common NDT applications are the detection of pores, cracks and inclusions within a specimen.

The proposed optimisation is applied on a selected real world part. Furthermore a series of simulated and real CT scans with different parameter combinations is done to discuss and verify the parameter selection.

1. Introduction

X-ray computed tomography (XCT) is a powerful tool providing information on the geometry and internal structures of a specimen. This information can be used to characterise specimen for NDT. Typical applications of NDT are the detection and quantification of pores, cracks and inclusions within components or material samples.

The achievable data quality of XCT mainly depends on the specimen's geometry, material, the XCT setup and especially on the selected scan parameters. Nowadays the selection and optimisation of these scan parameters have to be done by an experienced operator. This leads to subjective and often non ideal scan results. Since the optimisation for a specific evaluation task is very tedious and time-consuming a XCT simulation software could optimise the acquisition automatically and generate user independent parameters and results, if preliminary knowledge of the specimen is available [1,6].

The acquisition results are mainly influenced by following scan parameters [1]:

- specimen placement
- X-ray source voltage
- X-ray source current
- filter plates
- detector gain
- detector integration time
- number of projections

This paper focuses on the simulation based optimisation of CT scans for NDT. Metrology [1] is not part of this work. The proposed procedure of chapter 3 is applied on a typical NDT application described in chapter 2.1.

2. Experimental

2.1 Specimen description

Figure 1 shows the disc shaped specimen, which is 16 mm thick and 152 mm in diameter, made of an magnesium (Mg) alloy ZK31 containing 3 weight percent Zinc (Zn) and 1 weight percent Zirconium (Zr).

The goal of the specimen investigation is to detect and quantify pores, cracks as well as Zn or Zr oxide inclusions by visual analysis of the CT data. The maximum expected diameters of pores and inclusions are about 1 mm. This preliminary knowledge of the specimen is additionally used to generate a virtual specimen and further more generate optimised scan parameters by the use of the simulation tool. The optimisation is based on the evaluation of selected quality parameters and on the minimisation of artefacts. In order to verify the suggestion of the tool, a series of real CT scans have been done and evaluated.

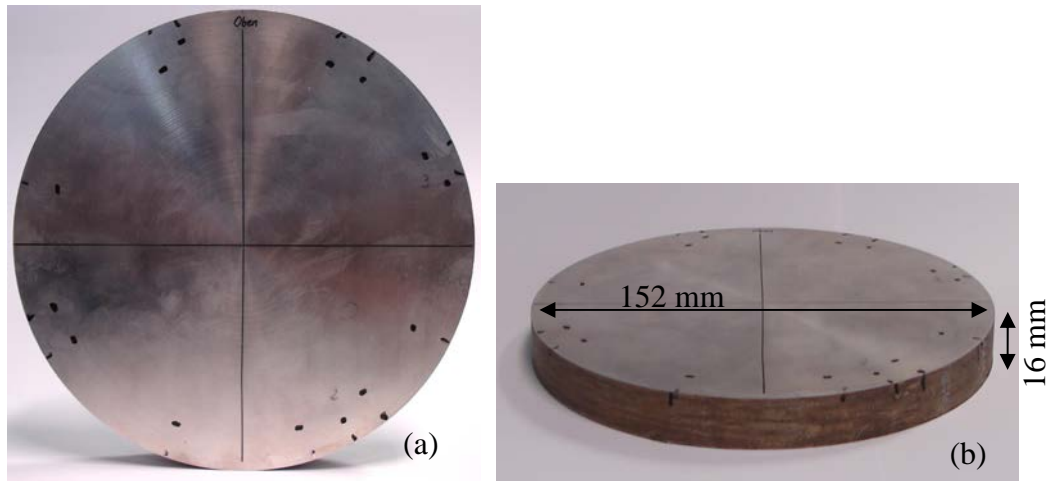


Figure 1. Photos of the specimen. Two different placements on the rotary table: (a) disc standing and (b) disc lying. The disc is made of an magnesium alloy ZK31; diameter 152 mm; thickness 16 mm; In the marked regions pores, Zinc oxide (ZnO) and Zirconium oxide (ZrO₂) inclusions with diameters of about 1 mm are expected.

2.2 XCT device and modelling

CT scans are done on a RayScan Technologies - RayScan 250E device consisting of a Viscom XT9225D 225 kV-microfocus tube with a tungsten target and a Perkin Elmer XRD 1620 AN14 CTS flat panel detector.

The modelling process of a cone beam CT system has to cover the following sections, an X-ray source model, interactions of X-rays with the specimen and the detector. The proposed CT simulation uses fully analytical models and has been implemented using C++ and the NVidia toolkit CUDA [1]. The reconstruction method used within this work is the filtered back-projection algorithm published by Feldkamp et al. [2].

3. Simulation aided selection of CT scan parameters

Since the achievable data quality of XCT depends on selected scan parameters an optimisation of those is desirable. When selecting device parameter for a specific scan task, like described in the chapter 2, some general conditions regarding the transmission and geometric blur by the focal spot has to be fulfilled for a preliminary selected position and orientation of the specimen on the rotary table. The selected placement should result in a minimised maximal and average absorption during the CT scan and in minimal artefacts due to an inexact cone beam reconstruction [3].

An X-ray spectrum, defined by acceleration voltage U and pre-filter plates, is in general applicable for the scan of a specimen at a certain placement on the rotary table if the following conditions are fulfilled. The transmission of radiation through the specimen, which is the minimal grey value divided by the maximal grey value of the projection images, has to be in an acquirable range for the detector. CT standards, which are still in development, suggest transmission values of 14% (ISO 15708) or 10% (prEN 16016) at the path of highest absorption for optimal scan quality. But in addition it is mentioned that users should rely on test. Once polychromatic X-rays are used for the acquisition of penetration images additional artefacts are included due to the beam hardening effect. In combination with scattered radiation the beam hardening effect causes a non-linearity between attenuation μd and penetration length d (equation 1) which leads to cupping artefacts and bright or dark bands or streaks between high absorbing structures in the reconstructed volume data. A proper selection of U and pre-filter plates can minimise these artefacts. Equation 2 is a measure for this linearity, which gives values in the range of 0 to 1 and can be calculated using projection images. It contains the root mean square error (RMSE) between a scaled attenuation and an ideal linear attenuation. This ideal linear attenuation is the imaginary line from the origin to the first data point of attenuation(d).

$$\text{attenuation}(d) = -\mu d = -\log\left(\frac{gv(d)}{gv(d=0\text{mm})}\right) \quad (1)$$

$$\text{linearity} = 1 - \text{RMSE}_{\text{linear,real}} = 1 - \frac{\sqrt{\sum_{d=0}^{d_{\max}} (-\mu_{\text{linear}} d + \mu_{\text{real}} d)^2}}{-\mu_{\text{linear}} d_{\max}} \quad (2)$$

The geometric blur caused by the focal spot of the X-ray source has to be negligible in regard to the detector's pixel size and used magnification. In common micro focus tubes a defocusing of the electron beam is done, to prevent the target from thermal destruction, due to the limited power on the target. An electron spot 7 μm in size impinging a target material with 12 W of energy would induce localise melting of Tungsten [7]. That is the reason why the focal spot diameter is proportional to the applied power and has to be limited with regard to the geometric magnification.

Generally lowering the detector's gain while increasing the integration time raises the number of detected X-ray photons and thus the signal to noise ratio (SNR). Although the maximum achievable SNR is limited by the structure noise of the used detector [4,5]. In addition the white grey value $gv(d=0\text{ mm})$ should be near the maximal possible output value of the detector (PE XRD 1620: $\sim 95\%$ of $2^{16}=65535$) to use the digitalisation of X-ray intensities as good as possible.

Furthermore, a contrast to noise ratio (CNR) value using equation 3 can be calculated for every suitable parameter combination in the projection image, to quantify the ability of pore or inclusion detection at the path of highest absorption. This CNR_{proj} value can be used as optimisation criteria for NDT applications, in order to further preselect

parameters without using detailed knowledge of the specimens geometry. μ_b of equation 3 is the mean background grey value (gv) acquired at the path of maximum absorption by the specimen. μ_f is the mean foreground grey value at maximum absorption of the specimen while taking into account an attenuation change by a virtual pore or inclusion. σ_b is the standard deviation of μ_b . The virtual pore or inclusion is assumed to be much smaller than the matrix.

$$\text{CNR} = \frac{|\mu_f - \mu_b|}{\sigma_b} \quad (3)$$

The mentioned values and conditions can be calculated and checked within a few minutes on a standard personal computer using the proposed simulation tool. The advantage of this procedure in comparison to full CT simulations is that the selection of scan parameters for simple geometries (e.g. cylinder, cuboids) can be done without the need of several time-consuming reconstructions. For more complex geometries with high aspect ratios of its dimensions full CT scan simulations are suggested to optimise the acquisition.

4. Evaluation and results

The inspection of a disc, like described in 2.1, represents a bad case scenario for the measure CNR_{proj} , since its dimensions have a high aspect ratio. An optimisation of the transmission (ISO 15708 / prEN 16016) or the proposed CNR_{proj} for the path of highest attenuation may therefore not result in optimal pore or inclusion detectability for this application. Figure 2 shows a plot of the penetration length through a virtual defect free and standing disc in the centre of the detector during a full rotation of the object. The dashed line is the average penetration length which shows a big difference to the path of highest attenuation lengths.

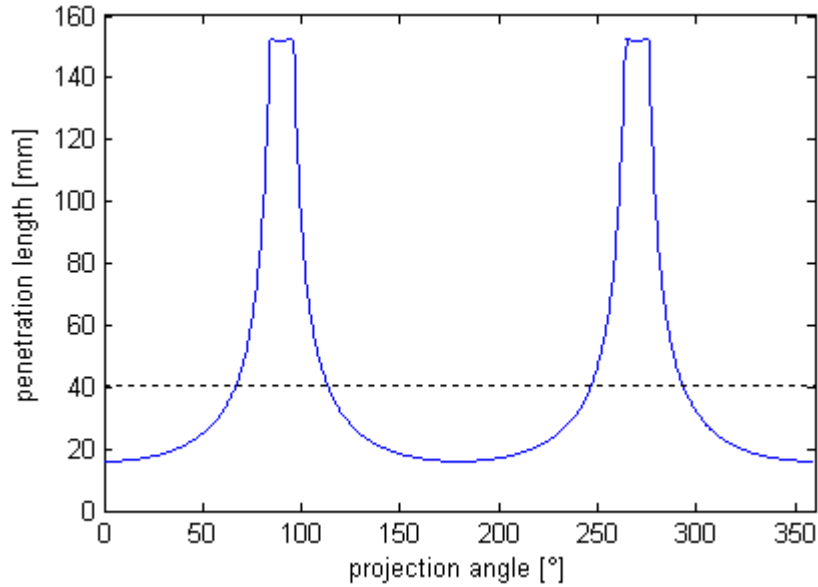


Figure 2. Plot of the penetration length through a virtual defect free and standing disc (dimensions see figure 1) in the centre of the detector during a full rotation of the disc. The dashed line is the average penetration length with 40.19 mm.

There are obviously two suitable disc placements. Either the disc is standing on the rotary table (figure 1a) which gives a low average attenuation (average d through an ideal disc in the complete stack of projections $d_{\text{avg}} \sim 22$ mm) or the disc is lying (figure 1b) which gives a higher average ($d_{\text{avg}} \sim 109$ mm) but similar maximum attenuation ($d_{\text{max}} \sim 153$ mm). Due to the small extent of the lying disc along the rotation axis, less cone beam reconstruction

artefacts are expected. Both placements are considered for the selection of suitable device parameters. Placements with slight tilts of the disc are not considered.

Table 1 shows suitable parameter combinations which fulfill the boundary conditions, described in chapter 3, for a scan of the magnesium disc on the described XCT system. The conditions have been checked for combinations of acceleration voltages ranging from 30 to 210 kV in 30 kV steps and copper pre-filters with a thickness increasing from 0 to 1.5 mm in steps of 0.5 mm. To ensure scan times with less than 40 minutes on the mentioned micro XCT system the integration time limit is 1000 ms at a charge amplifier capacity of 1.0 pF and binning 2. Parameter sets with minimal transmissions lower than $1e^{-4}$ are discarded, which results in a minimal acceleration voltage of 90 kV for the investigated specimen. For further selecting optimal CT parameters out of table 1 two different procedures have been used (see chapter 4.1 and 4.2). Criterion for the best scan quality is the detectability of defects within the specimen.

#	U [kV]	I [μA]	T [ms]	pre- filter [mm]	max. trans- mission	min. trans- mission	min. linearity	max. linearity	CNR _{proj,pore}	CNR _{proj,ZnO}	CNR _{proj,ZrO2}
0	90	979	500	0	0.147	0.0001	0.616	0.696	0.213	0.254	0.511
1	120	965	285	0	0.206	0.0005	0.623	0.704	0.372	0.363	0.713
2	120	1038	1000	0.5	0.406	0.0013	0.864	0.961	0.617	0.587	1.150
3	150	641	285	0	0.243	0.0009	0.631	0.716	0.473	0.409	0.785
4	150	578	1000	0.5	0.435	0.0022	0.862	0.962	0.740	0.623	1.186
5	180	465	285	0	0.266	0.0013	0.639	0.727	0.535	0.431	0.813
6	180	758	500	0.5	0.450	0.0030	0.861	0.962	0.806	0.630	1.179
7	180	621	1000	1	0.497	0.0040	0.906	0.981	0.925	0.704	1.309
8	210	356	285	0	0.281	0.0016	0.646	0.737	0.574	0.444	0.826
9	210	546	500	0.5	0.459	0.0035	0.860	0.962	0.845	0.632	1.168
10	210	439	1000	1	0.505	0.0047	0.905	0.980	0.967	0.704	1.292
11	210	630	1000	1.5	0.533	0.0057	0.927	0.987	1.053	0.748	1.363

Table 1. Shows suitable parameters for scanning the specimen of figure 1. Viscom XT9225-D 225 kV-microfocus tube; Perkin Elmer XRD 1620 AN14 CTS; detector averaging=1, binning 2, 1.0 pF; distance source-object=673.13 mm, distance source-detector=1538.58 mm; 16Bit grey value range; voxel size=175 μm; pre-filter plate material copper; 900 projections; simulated maximum transmission and linearity at 16.26 mm magnesium; simulated minimum transmission and linearity at 153.53 mm magnesium; CNR_{proj,pore} for the detection of a pore with d=1 mm at the path of highest absorption (d~153.53 mm magnesium); CNR_{proj,ZnO} and CNR_{proj,ZrO2} for the detection of an inclusion with d=0.1 mm at the path of highest absorption (d~153.53 mm magnesium)

4.1 Simulation based parameters selection using projection images

Table 1 shows calculated CNR_{proj} values for the detection of pores, Zinc oxide (ZnO) and Zirconium oxide (ZrO₂) within the magnesium disc. CNR_{proj,pore} is calculated for a pore with a diameter of 1 mm and CNR_{proj,ZnO} respectively CNR_{proj,ZrO2} is calculated for inclusion diameters of 0.1 mm at the path of highest absorption. Maximum absorption means 153.53 mm of magnesium. Attenuation linearity values in the range of 0.616 to 0.987 show that the pre-filter thickness is the main cause for the non-linearity between

penetration length and attenuation. The parameter combinations #7, #10 and #11 are expected to have best capabilities to detect any kind of defects.

4.2 Simulation based parameters selection using reconstructed slices

A more sophisticated way to optimise CT scans is to use preliminary knowledge of the specimen to design a virtual specimen with incorporated defects, which can be used by the simulation tool. For the example of figure 1 an constructive solid geometry has been created consisting of a cylinder that includes a pore, a ZnO (5.61 g/cm³) and a ZrO₂ (6.15 g/cm³) inclusion, each 1 mm in diameter, located near the disc's centre of gravity. Figure 3 gives simulated CNR_{reco} values of pore and inclusions in the reconstructed volume of the virtual CT scans. The selection of a parameter set would depend on the type of defect.

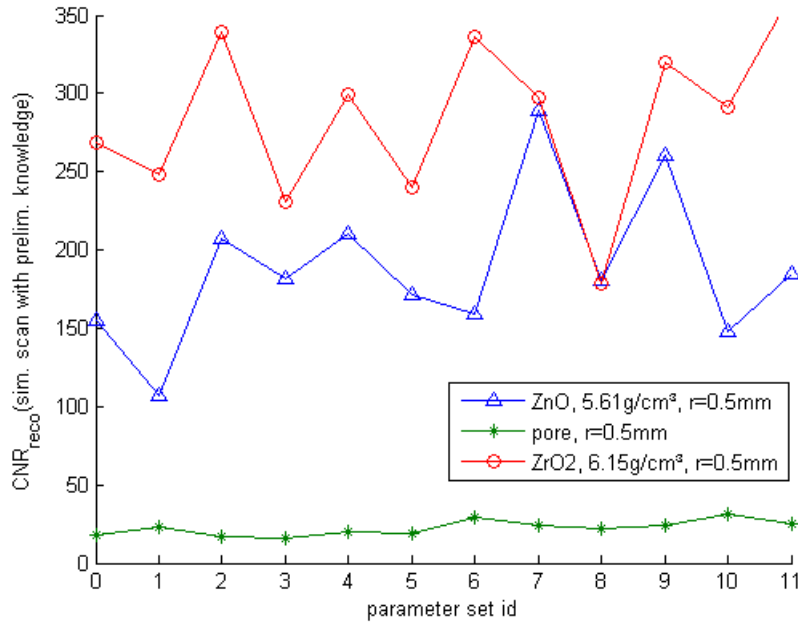


Figure 3. Simulated CNR_{reco} plots of two inclusions and one pore determined within a virtual scan of the specimen standing on the rotary table. On the abscissa the unique id of the 12 different parameter combination shown in table 1.

4.3 Results and discussion

For detailed evaluations a series of CT scans using the parameter sets of table 1 have been done. Figure 4, shows reconstructed slices of a pore, which is located near the outer surface of the disc. Scanning the disc lying on the rotary table with the parameters #11 (figure 4a), yield to a low CNR_{reco} value, but represents the best device parameter set, which is possible for the lying specimen. A standing disc gives overall better scan results, thus further investigations on the scan parameter optimisation are focused on this placement. The grey value profiles of figure 5 correspond to the pore of figure 4. An enhanced CNR_{reco} for this pore improves the detection of smaller pores at similar locations in the specimen.

Figure 6 shows the influence of CT parameters on cupping artefacts and dark streaks around a high absorbing inclusion. The best (figure 6a) and the worst case (figure 6b) regarding artefacts are shown for a standing disc.

Figure 7 is a plot of the achieved CNR_{reco} values in real CT reconstructions for two different inclusions and one pore. Since the material compositions, positions and dimensions of the defects are not exactly known, a direct comparison of the absolute values to the simplified simulation of figure 3 is not possible.

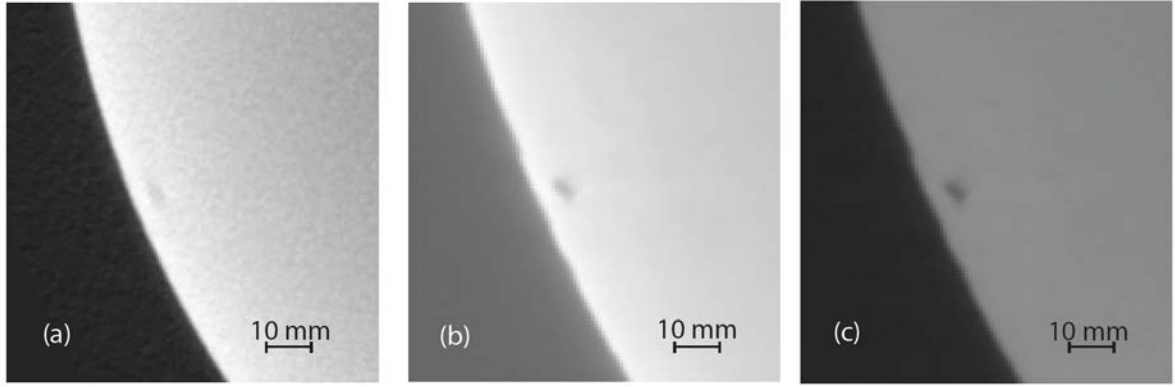


Figure 4. Slice images of a real scan at the position of pore #1; Scanned with parameter set #11 disc lying with a CNR_{reco} of ~ 3 (a), #0 disc standing with a CNR_{reco} of ~ 8 , (b) and #10 disc standing with a CNR_{reco} of ~ 16 (c).

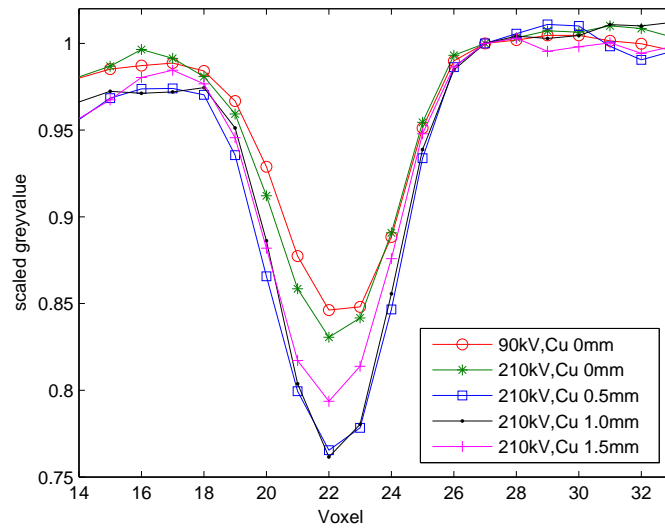


Figure 5: Scaled grey value profiles through pore #1 (diameter ~ 0.5 mm) corresponding to Figure 4 for 4 different parameter combinations.

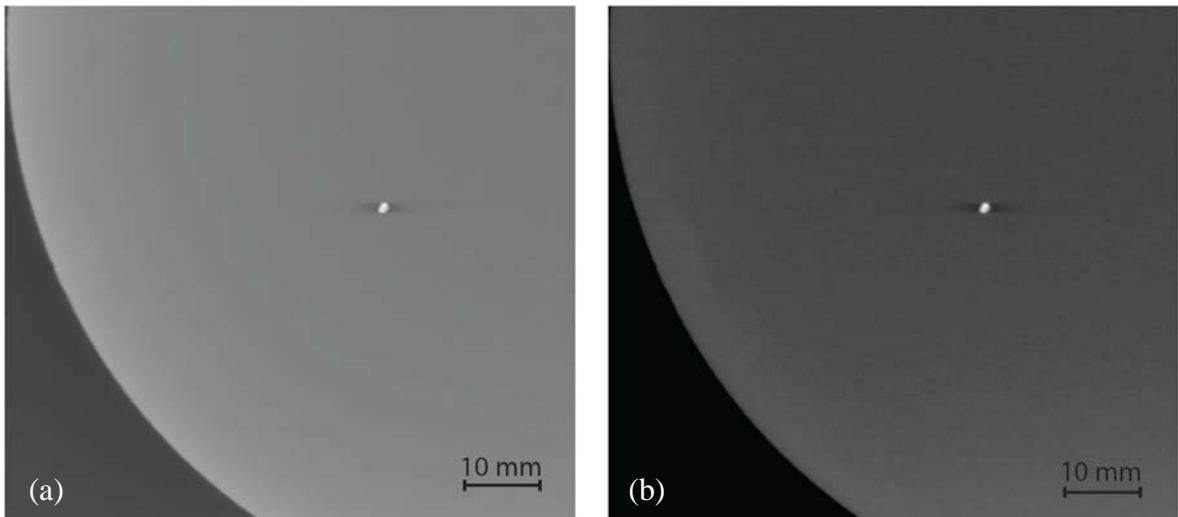


Figure 6. Slice images of a real scan at the position of inclusion #1, which represents the highest absorbing inclusion in the specimen; Scanned with parameter set #0 with a CNR_{reco} of ~ 49 (a) and #10 with a CNR_{reco} of ~ 74 (b). Disc standing on the rotary table.

Selecting parameters via simulated CNR_{reco} values would result in slightly different parameters than using the real scenario. This could be explained by an inexact simulation

model and different appearances of artefacts, due to the simplified virtual geometry. Investigations on the CNR_{reco} have shown that high values may origin from artefact constellations. For example the CNR_{reco} values of a small high absorbing inclusion, positioned in the centre of the disc, within a low absorbing matrix are extremely affected by cupping artefacts. Parameter suggestions would lead to parameters without pre-filters since the beam hardening effect enhances the contrast in the described scenario.

The parameter combinations #7, #10 and #11 lead to a spectrum with high effective photon energies, which maximise the transmission, minimise beam hardening and yield to high values of CNR_{proj} (table 1) and CNR_{reco} of real scans (figure 7). The transmission values of table 1 show a correlation to the linearity values and confirm the dependency on the used spectrum. The minimal transmission is way beyond 10%, suggested by CT standards, but since the transmission in average is sufficient, a high scan quality is possible. For the shown sample CNR_{proj} and CNR_{reco} generally improve with an increasing copper pre-filter thickness (Figure 3,5,7).

The interpretation of all plots lead to the conclusion, that #10 and #11 deliver the best scan quality with respect to artefacts and CNR_{reco} values. The potential for improving the CNR_{reco} values by selecting good parameters is between 50 and 100%. Although the CNR_{proj} consider just the path of maximum absorption the parameter selection is identical, and it seems to be suitable as global and fast optimisation for NDT applications.

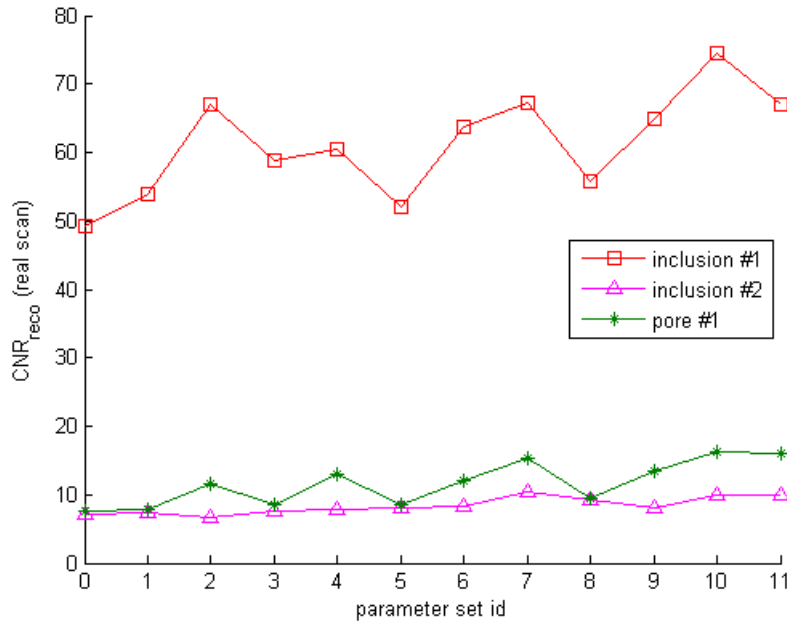


Figure 7. CNR_{reco} plots of two selected inclusions and one pore determined within a real scan of the specimen standing on the rotary table. On the abscissa the unique id of the 12 different parameter combination shown in table 1.

Summary

Contrary to the transmission optimisation suggested in the standards ISO 15708 or prEN 16016 we propose a simulation based optimisation of scan parameters. Criterion for the optimisation of NDT scans is a contrast to noise ratio value CNR_{proj} calculated within projection images. CNR_{proj} is a measure for the ability of detecting pores or inclusions at the path of maximal attenuation of the specimen. The optimisation procedure has been applied to a real world NDT application. CT parameter suggestions were verified by evaluations of real and simulated CT scan series. The correlation between the simulated CNR_{proj} and the CNR_{reco} of real scans could be shown for the selected application, although

suboptimal parameter suggestions were expected, due to the high aspect ratios of the specimen's dimensions.

Acknowledgements

The presented work has been funded by the K-Project for non destructive testing ZPT, grant number 820492, and by the Bridge-Project SmartCT, grant number 818108 of the Austrian Research Promotion Agency (FFG). See <http://www.3dct.at> for more details.

Thanks to the CT group of the Upper Austrian University of Applied Sciences - Wels Campus for support in designing this method.

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