

Defining the Optimal Beam Hardening Correction Parameters for CT Dimensional Metrology Applications

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Abstract

Recently, X-ray CT technology has entered the application field of dimensional metrology, as alternative to tactile and optical 3D coordinate measuring techniques. Nevertheless, the measurement quality of industrial CT machines is affected by many parameters and phenomenon, among which beam hardening plays a crucial role. It has been proven that the accuracy and uncertainty of CT dimensional measurements is largely influenced by the applied beam hardening correction method. As a routine procedure in industry, the beam hardening effect is corrected by applying hardware pre-filtration complemented with a software correction that implies linearization using predefined polynomial fitting curves. This correction method can largely eliminate beam hardening artifacts e.g. cupping effect and streaks. However, measurement results reveal that the effectiveness of such method is closely related to the selected X-ray power and hardware filter. Over-correction often occurs with inappropriate machine settings, which results in dimensional errors. This paper investigates the correlation between X-ray power, filter and beam hardening correction parameters, and aims at establishing a procedure for defining the optimal beam hardening correction parameters for CT dimensional metrology applications.

Keywords

Computed Tomography, Metrology, Beam Hardening Correction

1 INTRODUCTION

1.1 X-ray CT in dimensional metrology

X-ray Computed tomography (X-ray CT) was initially developed for clinical use. The first commercial medical CT machines were available in the 1970s. Starting from the early 1980s, X-ray CT was also frequently used for material analysis and non-destructive testing. In the spring of 2005, the first X-ray CT machine with sufficient accuracy for dimensional measurements was presented at the Control Fair in Germany [1]. Since then, X-ray CT enters a new application field: dimensional metrology. In comparison to classical tactile and optical coordinate measuring techniques, CT metrology is not yet widespread and still under development: how to define the traceability of CT measurements is still under discussion; Beam hardening artifacts and scattering noises further complicate surface determination and thus hinder accurate measurements. However, it has already been proven that CT dimensional metrology can significantly accelerate the process chain and boosts productivity for many applications [2]. With the fast development of hardware (X-ray source, detector etc.) and software (reconstruction, artifacts reduction etc.), X-ray CT will claim a solid place in the dimensional metrology field.

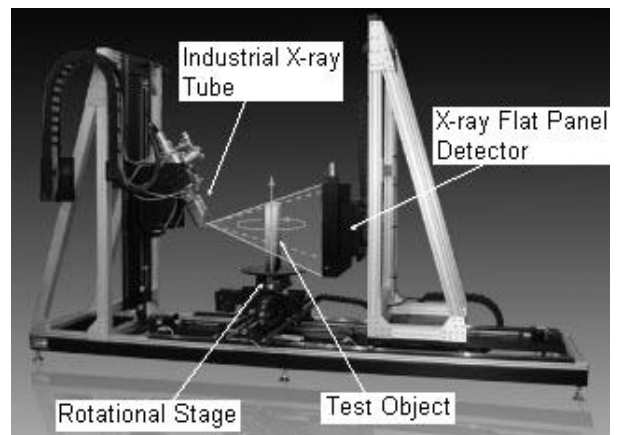


Figure 1 - Structure of Industrial CT machine [3].

1.2 Measuring procedure

The measurement process chain of CT dimensional metrology is shown in Figure 2. It is divided into 4 steps. The first step is data acquisition. 2D X-ray projection images are taken in typically thousands of object orientations. Subsequently, all these images are reconstructed into voxel or point cloud. An edge determination step allows determining the object's surface. This is followed by the actual dimensional measurements. Voxel size calibration might be necessary depending on the accuracy of the magnification axis.

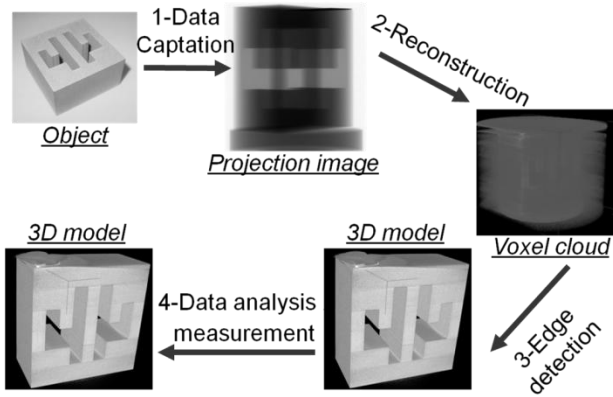


Figure 2 - Overview of CT measurement procedure [4].

2 BEAM HARDENING EFFECT AND ITS CORRECTION

2.1 Beam hardening effect

2.1.1 The nature of the beam hardening effect

The industrial X-ray tube generates a polychromatic X-ray beam which comprises a continuous radiation energy spectrum with certain bandwidth. During CT scanning, X-ray beams will be attenuated depending on the workpiece's geometry and material. This attenuation process is energy dependent. Lower energy photons are more easily absorbed. As demonstrated in Figure 3, in the middle (thin) section, the lower energy beam is absorbed faster than the high energy beam but both of them could penetrate the object and be detected by the X-ray detector. However, in the thick regions, low energy beams completely disappear thus cannot be seen by the detector. Thus, the X-ray beam's frequency spectrum is shifted in the direction of higher energy during the propagation process; this is referred to as "hardening" of the X-ray beam.

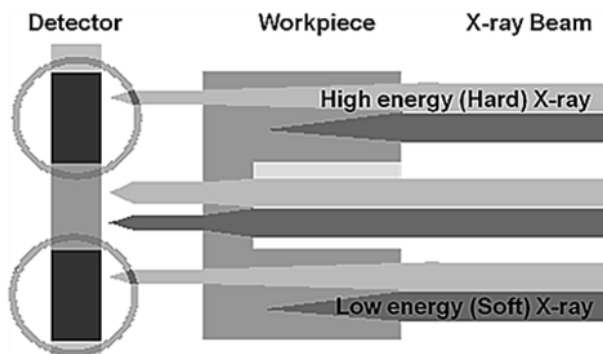


Figure 3 - Beam hardening effect. Dark beam: lower energy photons. Light beam: higher energy photons [5].

2.1.2 Beam hardening induced artifacts

The beam hardening effect results in a non-linear relation between X-ray attenuation and material penetration length. However, most reconstruction algorithms presume linear attenuation. The high absorption of soft X-ray beams at the outer edge

gives a false impression that the workpiece's skin is made of more absorbing material and has a much higher gray value after reconstruction; this is referred to as the "cupping" artifact (see Figure 4). In addition, streaks and dark bands often appear between dense metal parts (see Figure 5). These artifacts strongly degrade image quality and can largely influence the accuracy of dimensional measurements [6].

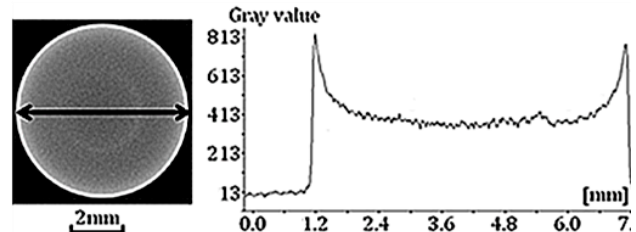


Figure 4 - Reconstructed slice of a steel cylinder and corresponding grey value profile along the arrow line [6].

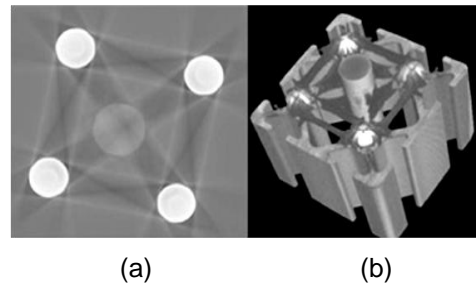


Figure 5 - (a) Streak artifacts visible in the reconstructed CT slice (b) 3D CT voxel model of the objects [6].

2.2 Beam Hardening correction methods

There are many approaches for correcting beam hardening artifacts, including hardware filtration using various metal filters; reprojection based methods which calculate a proper correction curve by re-projecting a thresholded 3D model; dual energy methods that model the attenuation coefficient as a linear combination of the photoelectric effect and the scattering and iterative algorithms using the information of simulated sinogram [7-11]. Currently, using hardware filtration and subsequently adapting gray values by predefined polynomial curves for beam hardening correction is still favoured by many industrial users due to the easy implementation and low computing time. Polynomials up to the fourth order are frequently used [6]:

$$Y = a (b + cX + dX^2 + eX^3 + fX^4) \quad (1)$$

Where X represents the initial grey value of a pixel in an X-ray projection image, Y represents the final grey value after linearization, and "a" through "f" represent coefficients that can be fine-tuned in order to obtain cupping free images. A few experience based presets have been applied to the presented data, as listed in Table 1.

Presets	Parameters					
	a	b	c	d	e	f
1	1	0	1	0	0	0
2	1	0	0.75	0.25	0	0
3	1	0	0.5	0.5	0	0

Table 1 - Parameters of Frequently used presets [6]

Preset Nr.1 preserves the initial gray values; preset Nr.2 does slight correction using a second order polynomial curve; preset Nr.3 emphasises more on the non-linear part, thus results in the most severe correction among these three presets.

3 THE INFLUENCE OF BEAM HARDENING CORRECTION ON THE MEASUREMENT UNCERTAINTY

3.1 Measurement results on a calibrated steel cylinder situated in various setups

X-ray Voltage	170kV
X-ray Current	45 μ A
Prefiltration	1mm copper

Table 2 - Main Machine settings

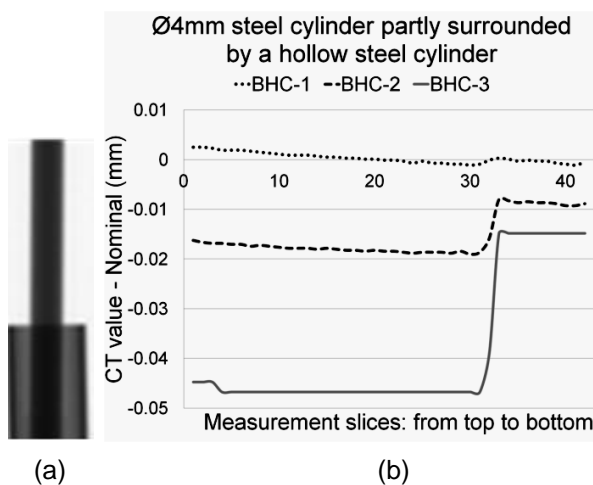


Figure 6 - Influence of BHC on the measured diameter of a $\varnothing 4$ mm steel cylinder partly surrounded by a hollow steel cylinder, "BHC-1 stands for beam hardening correction preset Nr.1": (a) a 2D X-ray projection image. (b) The diameter of the reference steel cylinder is measured on different slices from top to bottom [6]

Dewulf et al.[6] have used a calibrated steel cylinder ($\varnothing 4$ mm, tolerance $\pm 1\mu$ m) for investigating the influence of beam hardening correction on the accuracy and uncertainty of CT dimensional measurements. As shown in Figure 6 (a), this cylinder is partly surrounded by another steel cylinder. The CT scan is treated with three beam hardening correction presets (see Table 1). The

diameter of the inner steel cylinder is measured on a series of equidistance slices from top to bottom, the CT measurement error as a function of the slice number is plotted. Significant dimensional variations can be observed. The diameter of the inner steel cylinder experiences a sudden jump when the surrounding situation varies. The magnitude of such jump is around 2μ m without any beam hardening correction; around 10μ m if applying slight correction and more than 30μ m when more severe correction curves are used. Thus, applying improper beam hardening correction will induce extra error and worsen the measurement uncertainty.

3.2 Simulation verification

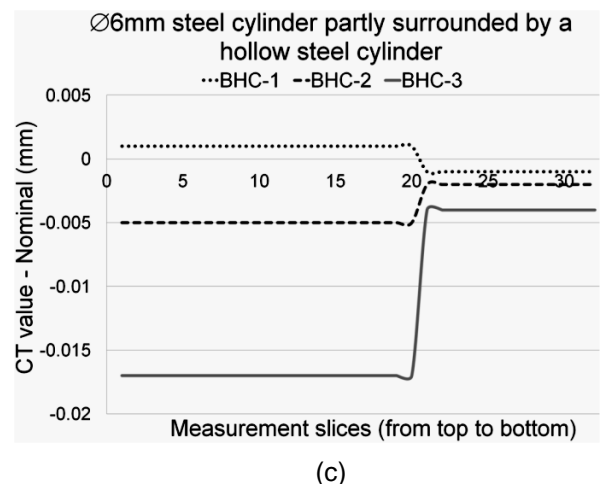
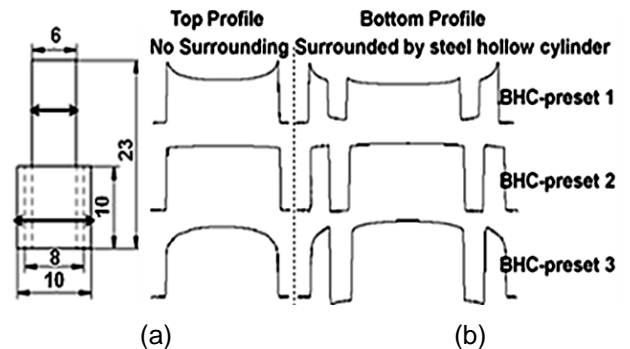


Figure 7 - CT simulation: influence of BHC on the measured diameter of a $\varnothing 6$ mm steel cylinder partly surrounded by a hollow steel cylinder. (a) Dimension of the steel cylinders (in mm). (b) The gray value profile along the arrow line with (right) and without (left) surrounding material, using different beam hardening correction presets (see Table 1). (c) Inner cylinder diameter measured at equidistance slices from top to bottom. The absolute dimensional error is plotted as a function of slice number.

The sudden dimensional variation observed in the previous section is most likely to be a combined result of improper beam hardening correction, changing surroundings and X-ray scattering. However, a CT machine is a complex system, many influencing factors are correlated. In order to verify

our results, X-ray simulation has been used. The simulation includes polychromatic X-ray spectrum generation, x-ray attenuation throughout the workpiece, energy dependant photon accumulation by the X-ray detector and the resulting X-ray intensity is calculated for each pixel. X-ray scattering as well as machine axis misalignment, temperature variation, machine vibration and X-ray detector instability are completely excluded. As shown in Figure 7, a “perfect” Ø6mm steel cylinder is partly surrounded by another steel hollow cylinder (inner Ø8mm, outer Ø10mm). Three beam hardening correction presets have been applied on the simulated scan data. Figure 7(b) demonstrates the gray value profile along the arrow line. Without any beam hardening correction, the cupping effect is obviously visible; when applying preset Nr.2, beam hardening artifacts are largely removed; over-correction is found if using preset Nr.3. The dimensional measurement results are shown in Figure 7(c): similar to real measurement results, dimensional variations are found at the location where surrounding situation changes (in this case, where the inner cylinder enters the hollow cylinder). This sudden dimensional jump is around 2-3 µm for beam hardening correction preset Nr.1 and 2, and more than 12µm if preset Nr.3 is used. This simulation result confirms that applying improper beam hardening correction could enlarge the uncertainty range of X-ray CT dimensional measurements, especially when scanning data are over-corrected.

4 BEAM HARDENING CORRECTION PARAMETER OPTIMIZATION

4.1 Simple empirical parameter optimization

As mentioned before, an industrial CT machine is a very complex system. An operator has to make decisions on many parameters, such as X-ray power, prefiltration, exposure time, magnification and workpiece orientation etc.. The optimal choice of beam hardening correction parameters strongly depends on the selected X-ray voltage, filter material and thickness. Although Section 3 proves that in some situations applying no beam hardening correction is favourable, there are cases in which certain amount of correction is needed.

A similar setup (Figure 8, (a)) as in Figure 6 (a) is scanned under a different machine settings (as listed in Table 3). The dimensional measurement results are shown in Figure 8 (b). For both beam hardening correction presets Nr.1 and 2, obvious dimension changes are present. Moreover, the directions of these jumps are opposite to each other. “Optimal” correction curve coefficients can be found by “trial and error” using values between presets Nr.1 and 2. Another noticeable trend is that the diameter of the inner cylinder keeps decreasing from top to bottom, with a magnitude of around 6µm over a total length of 70mm. Such trend is present in

many measurement results reported in this paper. This dimensional error is caused by a hardware misalignment between the rotation axis and the detector; in addition, a deformation of the flat panel X-ray detector could also contribute to this error. Though annoying, this trend does not influence the conclusions related to the impact of the beam hardening correction methods, which is characterized by sudden discontinuities rather than by steady decreases.

X-ray Voltage	195kV
X-ray Current	100µA
Prefiltration	0.5mm copper

Table 3 - Main Machine settings

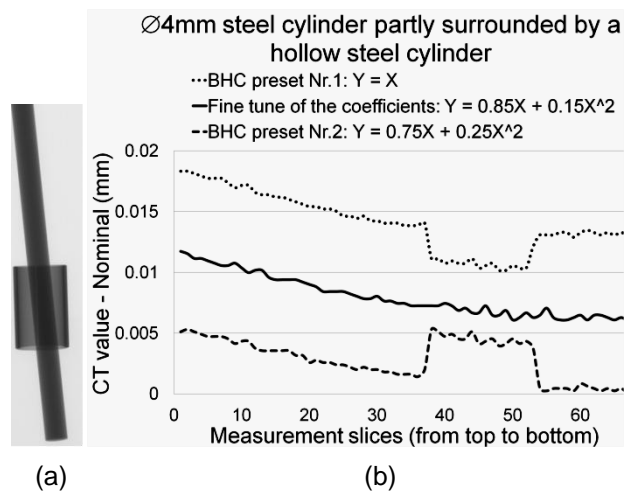


Figure 8 - (a) X-ray projection image: Ø4mm steel cylinder partly surrounded by a hollow steel cylinder. (b) Dimensional error plotted as a function of slices number.

4.2 Investigation on the correlation between the optimal beam hardening correction parameters and machine settings

As discussed above, X-ray power, filter and beam hardening correction method are closely correlated. Higher X-ray power demands a thicker filter to avoid pixel saturation; more prefiltration will demand less post correction of beam hardening effect through software. The minimum transmission ratio is a suitable criteria for assessing these correlations, because it can reflect the effects of both X-ray power and the filter. It is defined as the gray value of the darkest pixel divided by the gray value of the brightest pixel. Systematic measurements have been done in order to search for a general guideline for selecting the scan strategy. Both single material and multi-material cases are investigated.

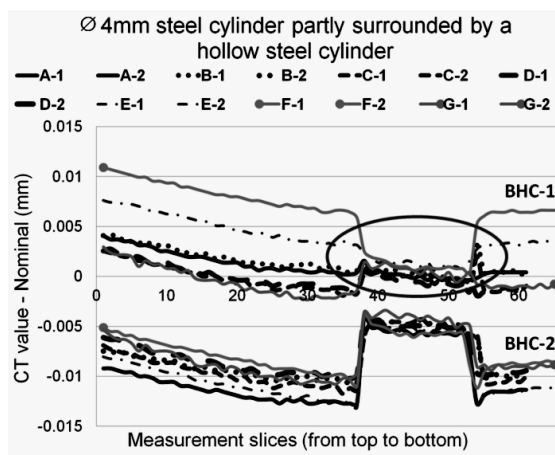
4.2.1 Single material case

The same setup as shown in Figure 8(a) is scanned under 7 different conditions as listed in Table 4. Two criteria for choosing the settings are to make sure that the darkest pixel's gray value is above 10000

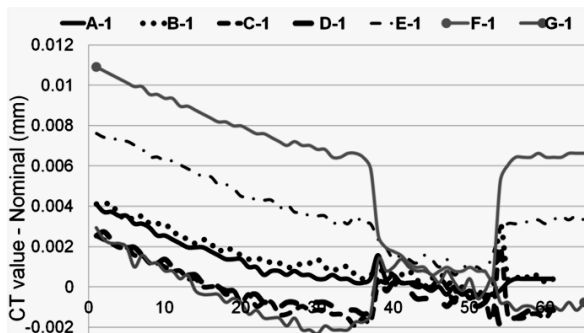
(in the range 0-65535) in order to ensure a proper X-ray penetration and that the brightest pixel's gray value is below 62000 to avoid saturation. Data of each scan are processed using three beam hardening correction presets (Table 1). The diameter of the inner cylinder is measured at equidistant slices from top to bottom. The measurement results using presets Nr.1 and 2 are shown in Figure 9. Beam hardening correction preset Nr.3 induces large dimensional errors in most cases, thus is excluded from further discussion.

Parameters	Measurement sequence						
	A	B	C	D	E	F	G
U (kV)	110	125	140	170	175	185	195
I (μA)	35	35	45	40	75	75	90
Cu filter(mm)	0.1	0.25	0.5	1	1.5	2	2.5
Min-Tran (%)	10.6	12.3	15.9	19.3	24.3	26.3	27

Table 4 - Machine settings of 7 CT scan (A-G).



(a)



(b)

Figure 9 - (a) Dimensional error plotted as a function of slices number. "A.1" implies measurement "A" using beam hardening correction preset Nr.1. (b) local zoom-in image of the circle in "a".

It can be concluded that beam hardening correction preset Nr.1 gives relatively good results with all scanning machine settings. Significant dimensional changes are observed for both presets Nr.2 and 3.

This result coincides with the conclusions in section 3.1 and differs from Figure 8. It is further observed that the machine settings listed in Table 2 are improper because the X-ray power was too high; hence X-ray saturation occurs during CT scanning. As presented in Figure 9(b), Fine tuning of the scan machine settings can improve the dimensional measurement results. Both too high and too low transmission will result in large dimensional errors. Optimal minimum transmission ratio can be found around 14%~16%, within which the magnitude of the varying surrounding induced dimensional variation is limited to around 1.5μm. As a general conclusion, when dealing with workpieces consisting of one material, it is advisable not to use any beam hardening correction on condition that proper prefiltration is applied. This can be ensured by checking the minimum transmission ratio. This ratio should be kept between 14% and 16%.

4.2.2 Multi-material case

A multi-material setup has been investigated in the same way. A Ø4mm steel cylinder is partly surrounded by an aluminium hollow cylinder as shown in Figure 10(a). Four different machine setting combinations have been tested (Table 5). The same criteria are applied for choosing the parameters: a filter was first chosen, followed by adjusting the X-ray power to ensure a proper signal to noise ratio and to avoid saturation.

Parameters	Measurements			
	A	B	C	D
X-ray Voltage (kV)	140	170	180	190
X-ray Current (μA)	45	50	70	75
Copper filter (mm)	0.5	1	1.5	2
Minimum Transmission (%)	14.8	18.8	21.9	23.7

Table 5 - Machine settings of 4 CT scan (A-D).

All CT scans are processed with beam hardening correction presets Nr.1 and 2. The diameter of the inner steel cylinder is measured in the same way: from top to bottom at different slices. Figure 10(c) presents the measurement results: sudden jumps are observed at the transitions: positions where the steel cylinder enters and leaves the surrounding aluminium cylinder. Both BHC-1 and BHC-2 reveals an upward jump. Thus, negative coefficients might be necessary for fine tuning the polynomial fitted curve. On the other hand, the dimensional variations are doubled when BHC-2 is applied. Moreover, a difference between these 4 measurements could be noticed (Figure 10(c)): measurement A-1 generates the best results among all. The magnitude of the jump is around 2μm. Thus, it can be concluded that in case of steel parts surrounded by aluminium, negative coefficients for the polynomial fitted curve (to be used for beam hardening correction) need to

be considered. However, good measurement results could be achieved by limiting the minimum transmission ratio in the range of 14%~16%.

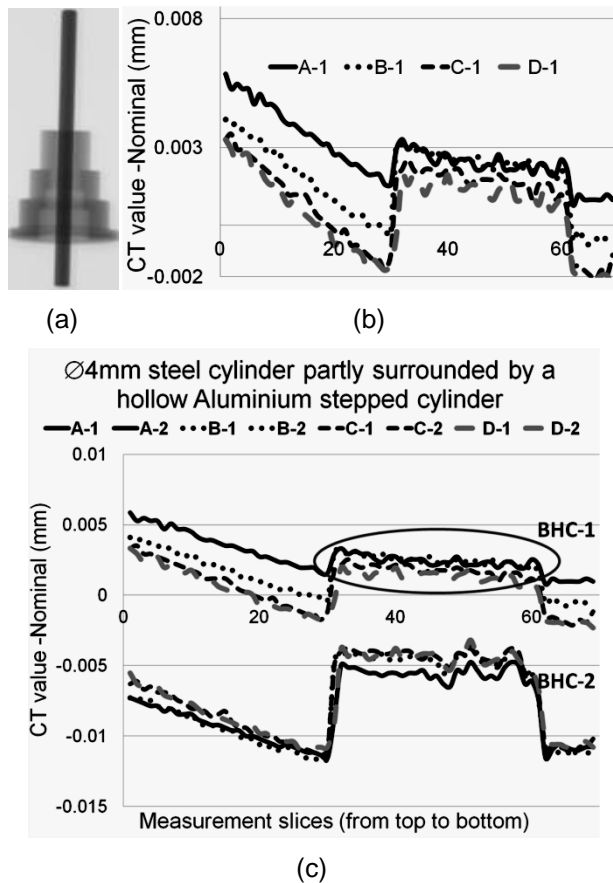


Figure 10 - (a) 2D projection image: Ø4mm steel cylinder partly surrounded by aluminium stepped cylinder. (b) zoom in image of the circle in “(c)”. (c) Dimensional error plotted as a function of slices number. “A-1” stands for measurement “A”, BHC preset Nr.1.

5 DISCUSSION AND CONCLUSION

Beam hardening correction has been a major research topic for X-ray CT and especially important for CT dimensional metrology applications. Beam hardening effect strongly influences the uncertainty of dimensional measurements. Overcorrection should be avoided because it introduces non-systematic errors which are difficult to compensate. The choice of a proper beam hardening correction level is closely related with X-ray power and pre-filtration. In most cases “optimal” parameters for the polynomial correction curve can be found by trial and error. However, this is purely empirical and difficult to implement. As a general guideline, on condition that good signal to noise ratio is ensured and saturation is avoided, one could minimize the size variation induced by surrounding material and the beam hardening induced local dimensional changes by choosing a combination of machine settings with which the minimum transmission ratio is around 14%~16%. Under these conditions, no

post beam hardening correction is needed. However, only polynomial fitted curves for beam hardening correction is investigated in this paper. Thus, further research on other algorithms is necessary.

6 ACKNOWLEDGMENTS

The authors acknowledge the support of the Research Foundation Flanders (FWO) via project G.0711.11 and G.0618.10.

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8 BIOGRAPHY



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Frank Welkenhuyzen is a PhD student of KU Leuven. His main research focus is to investigate the influencing factors of industrial CT system aided by software simulation.



Ye Tan is a PhD student of KU Leuven. He is focusing on optimising the measurement Accuracy of Industrial Computer Tomography for Dimensional Metrology of Multi-material Objects