WARWICK
THE UNIVERSITY OF WARWICK

Original citation:
Kourra, Nadia, Warnett, Jason, Attridge, Alex and Williams, M. A. (Mark A.) (2017) Metrological investigation of radiation filtration in x-ray computed tomography. In: Instrumentation and Measurement Technology Conference (I2MTC), Torino, Italy, Italy, 22-25 May 2017. Published in: 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 1-6.

Permanent WRAP URL:
http://wrap.warwick.ac.uk/90329

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:
"© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting /republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works."

A note on versions:
The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRAP URL' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

warwick.ac.uk/lib-publications

Metrological investigation of radiation filtration in x-ray computed tomography

N Kourra
WMG, University of Warwick
Coventry, UK, CV4 7AL
Email: N.Kourra@warwick.ac.ukl
Telephone: (+44) 024 76575361

J A Warnett
WMG, University of Warwick
Coventry, UK, CV4 7AL
Email: J.M.Warnett@warwick.ac.uk
Telephone: (+44) 024 76577420

A Attridge and M A Williams
WMG, University of Warwick
Coventry, UK, CV4 7AL
Emails: A.Attridge@warwick.ac.uk,
M.A.Williams.1@warwick.ac.uk
Telephone: (+44) 024 76150755

***Abstract*—X-ray Computed Tomography (CT) is a non-destructive evaluation method that gains recognition in dimensional metrology applications. During a CT scan, 2D radiographs are collected that are then reconstructed to a 3D model which allows non-destructive evaluation of the specimen and assists with the characterisations of defects. This technology has the potential to provide information unobtainable by other non-destructive, non-contact techniques. There are numerous factors that can affect the CT measurement results with varying measurement uncertainty such as shifts and changes of x-ray focal spot, geometrical alignment issues and environmental issues. This study investigates the effect of physical pre and post filtration on the resultant dimensional measurements. Here, a calibrated specimen is used based on one of the considered designs for the proposed ISO 10360-11 CT for dimensional measurements. The resultant in local variations of grey values in the volume is measured for different thicknesses of copper filtering placed before and after the scanned specimen, and the resultant threshold dependent and independent measurements are evaluated. The results provide information that assists the selection of filtration in order to reduce measurement error and improve dimensional measurements, and also demonstrate that post filtration should be considered when scanning specimens that generate large amounts of scatter.**

I. INTRODUCTION

X-ray Computed Tomography (CT) is a technology with well-known medical applications which in recent years gains recognition in industry with its industrial applications including non-contact, non-destructive examinations, characterisations of materials and metrological inspections [1]–[4]. During CT scanning, numerous 2D radiographs are collected while the object rotates 360°, that are then reconstructed with filtered back projection (FBP) reconstruction algorithms to a 3D model by converting the 2D pixels of the radiographs to volumetric pixels called voxels [5]. The grey value of each pixel of the radiographs is equivalent to the amount of radiation reaching the detector after penetrating the investigated part [1], [6]. The grey values of the reconstructed voxels represent the nature of the materials examined, defects, assembly structures and complex external and inaccessible internal geometric designs such as in additive layer manufacturing (ALM) parts [4], [7]. Other applications of CT include failure analysis, research and development (R&D) investigations and dimensional measurements.

The quality of the results is affected by the operator selected CT settings that dependent on the size, material and structure of the examined part. The spatial resolution of the scans depends on the voxel size and unsharpness of the images. These factors as well as the x-ray focal spot drift, geometric alignment of CT hardware, non-linearity of x-ray physics, environmental factors and reconstruction settings affect the distribution of grey values and therefore the threshold selection that separates background from material and affects dimensional measurements [1], [8]–[13]. X-ray CT machines, as any other measuring instrument, has several influencing factors that affect the quality of the results. In order to understand the influence of these factors in metrology, a quantification of measurement uncertainty is required. The reduction of the effect of the influencing factors and the measurement uncertainty of x-ray CT measurements can be achieved by following the recommendations provided by VDI/VDE 2630 Part 1.4, a guide to obtain dimensional measurements through CT [14]. Following these guidelines can reduce the uncertainty of the measurements; however, numerous variables influencing the CT results that were identified in the early stages of medical applications of CT have not yet been sufficiently resolved, such as beam hardening and scattering radiation [15].

This study investigates the effect of pre and post filtration of radiation in dimensional measurements. This is achieved by examining the results of CT scanning with different physical radiation filtrations and by comparing the achieved dimensional measurements to demonstrate the effect of the different filters. In particular, the advantage of physical post filtration is highlighted that has been previously unrecognised.

II. METHOD

Numerous research projects examine x-ray CT applications in order to identify its limitations and explore new methods to overcome them while a new standard on CT, ISO 10360-11, is being developed so as to provide guidelines and procedures that will provide accurate CT measurements. Different calibrated specimens are considered to accurately measure length errors. One of the proposed designs of calibrated specimens [16] is used in this study in order to examine the effect of scattered radiation in measurements and how the results can be improved with pre and post filtration of the radiation. All of the

TABLE I: Machines and Software used in this method

Machines & Software Used	Name	Producer
X-ray CT scanner	XT H 225 LC	Nikon Metrology, UK
Optical CMM scanner	NEXIV VM2	Nikon Metrology, UK
CT Reconstruction software	CT Pro 2.4	Nikon Metrology, UK
CT Inspection software	VG Studio Max 2.2	VG GmbH, Germany
Analysis Software	Matlab 2015b	MathWorks, USA

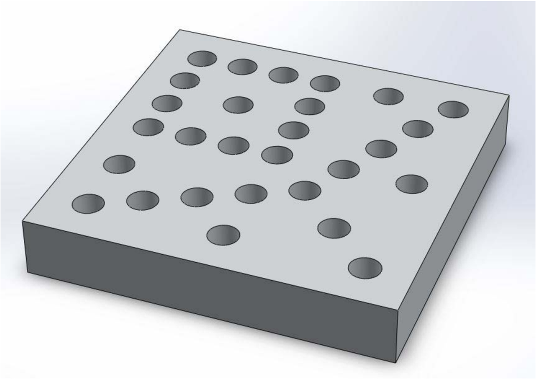


Fig. 1: Design of calibrated CT specimen

scanners and software packages used in these investigations are provided in Table I.

A. Workpiece

This metrological investigation utilises a proposed design of a calibrated specimen with 28 drilled holes that can be used for centre to centre measurements, independent to threshold selection. In this investigation, this specimen was selected to identify the influence of pre and post filtration on threshold dependent and independent dimensional measurements.

The design of the specimen is provided in Figure 1 and produced by the milling machines Schaublin 53 and DMG Mori, DMU40 eVo Deckel Maho. The size of the part is $48\,mm \times 48\,mm \times 8\,mm$ and the holes are 4 mm diameter. The tolerances are provided in Table II.

B. CT scanning and reconstruction

Numerous settings have to be selected in CT scanning such as orientation of the specimen, positioning in the scanner, voltage, power, exposure time as well as radiation filtration. The specimen was scanned once without any filtration, three times with pre-filtering, six times with different combinations of three pre filters and four post filters and once with post-filtering with total of 11 scans. The orientation of the part, positioning in the scanner and voltage was constant for all of the scans while power was slightly modified by 1 W in order to achieve similar x-ray penetration of the part across all scans without altering the resolution and unsharpness. The achieved span of grey values for all of the scans is similar and the average value was approximately 40000 ± 5000, by changing the exposure time as required. The specific settings per scan are provided in Table III. The name of the scan demonstrates the selection of pre and post filters, the first number indicates the thickness of pRe filter and the second number indicates the thickness of the poSt filter. The orientation of the part was approximately 45° while the achieved voxel size is 32.5 μm and unsharpness is 33 μm ± 0.24 μm.

TABLE II: Machining tolerances of specimen

Tolerances Type	Symbol	Tolerances (mm)
Diameter	Ø	0.005
Circularity	○	0.002
Positioning	⌖	0.005
Flatness		0.005
Parallelism	//	0.005
Perpendicularity	⊥	0.005

The scans were reconstructed to a 3D model with the same settings with no beam hardening and noise reduction algorithms in order to demonstrate the effect of pre and post filtration. The reconstructed 3D data was exported as 2D DICOM images that were imported into VG Studio Max 2.2 and MATLAB for further analysis and measurements. The positioning of the 3D model in the volume was not altered with any post-scanning alignment to ensure the original voxel structure of the reconstruction.

C. Measurements

The 2D DICOM images were imported in MATLAB and 3D matrix was produced reconstructing them to a 3D model. The corners of the specimen were identified based on the positioning of the specimen in the matrix volume by using a threshold identified based on Otsu method [17]. The corners were then used to place 3D lines in the matrix and the grey values on these lines were used to demonstrate the variations of grey values between material and background in histograms to examine the effect of the filtration on the grey values.

The variation of the grey values within the sample and background was calculated as the difference of maximum and minimum values by utilising Otsu threshold method to separate them. The distribution of grey values was examined by visualising the data in box and whiskers diagrams that demonstrate the median and four standard deviations of the data. The histograms of the grey values are heavily skewed and this method demonstrates an overview of the distribution. The outliers were removed from the diagrams in order to highlight the distinctions of distributions achieved by utilising different filtrations and their average was calculated and provided.

Systematic measurement errors can be reduced from 1% to 0.2% with nominal/actual comparison between the scanned data and reference measurement [18]. The threshold dependent and independent measurements are examined to demonstrate the effect the different combinations of filtration. The voxel size is the same for all of the scans since the specimen remained in the same position for all of the scans, the x-ray spot size and unsharpness was similar to the voxel size for all the scans due to the consistent power selection.

TABLE III: CT settings of each experiment. RxSx where R is the level of pRe filtration and S is the level of poSt filtration.

Scan	V (keV)	P (W)	Exp. Time (s)	Pre-filter (mm)	Post-filter (mm)
R0S0	210	8	1.00	No filter	No filter
R1S0	210	7	1.42	0.15	No filter
R2S0	210	7	1.00	0.35	No filter
R3S0	210	8	2.00	0.50	No filter
R1S1	210	7	1.42	0.15	0.125
R1S4	210	7	2.00	0.15	1.000
R2S1	210	7	1.00	0.35	0.125
R2S3	210	7	1.42	0.35	0.500
R3S1	210	8	1.00	0.50	0.125
R3S2	210	8	1.42	0.50	0.250
R0S4	210	8	1.42	No filter	1.000

III. RESULTS

The results of this investigation are separated in two sections; the examination of the effect of pre and post physical filtration on the grey values and its influence on CT measurements. The examination of the effect of different combinations of filtrations was achieved by examining the grey values of the material or background at specific positions. Three different lines are considered in this investigation from different angles, line (a) passes diagonally through the sample and through five holes, line (b) passes horizontally from the middle of the specimen and through five holes and line (c) passes horizontally at lower set of holes through three holes, the positions of the lines are demonstrated in Figure 2. The grey values of each point of the lines are demonstrated in the graphs that show their variations through material and background; material is represented by higher grey values while background has lower values. The ideal values of background are close to zero with minimum variations while the opposite conditions demonstrate scattered radiation.

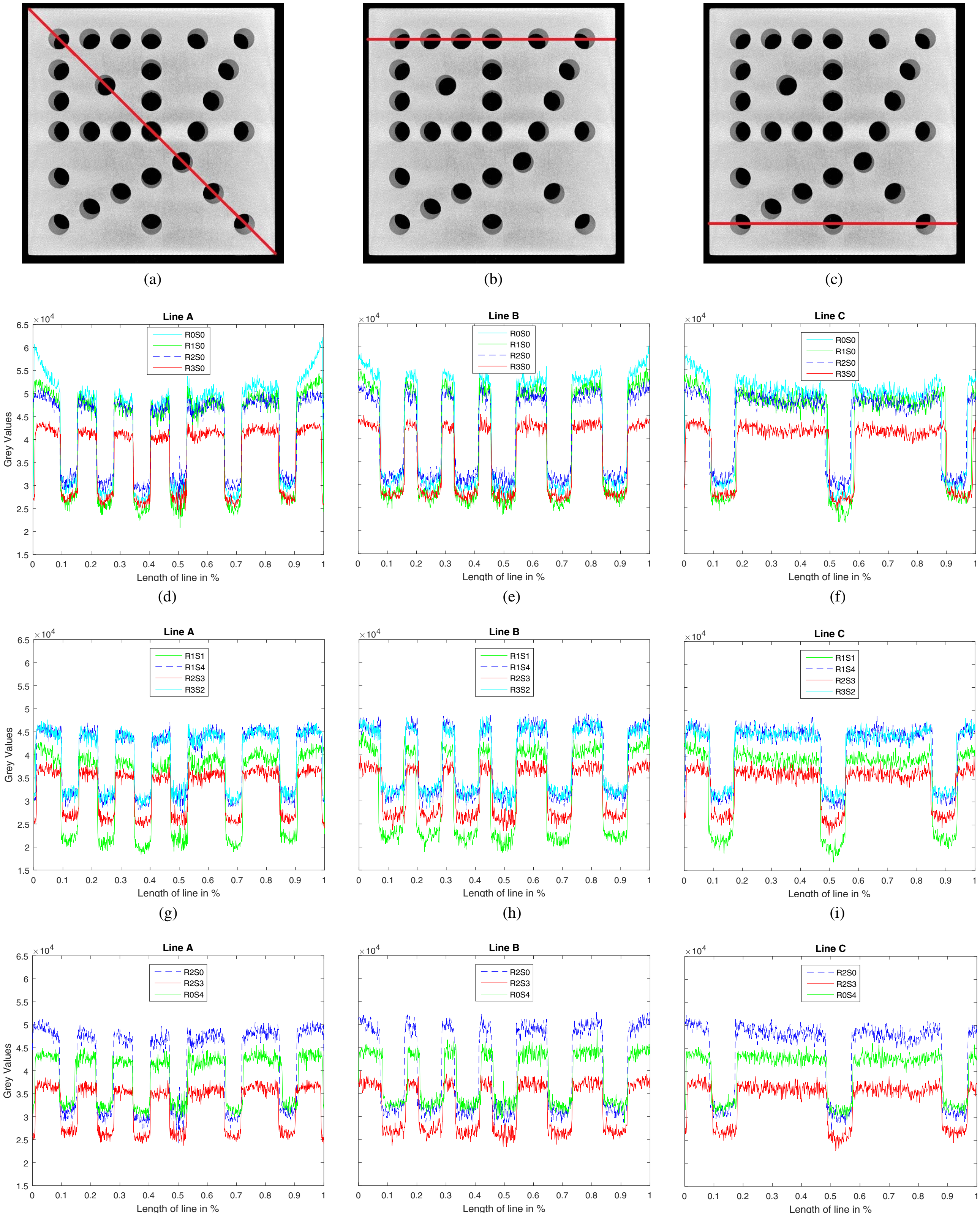
The results of different combinations of physical filtration are shown in Figure 2. Scan R0S0 demonstrates greater grey values in the edges of the part indicating beam hardening and greater variations of grey values in the rest of the line indicating scattered radiation. Pre-filtration of the radiation improves both issues with significant change achieved with 0.5 mm copper while less filtration reduces the issue but does not eliminate it. The combination of pre and post filtration eliminates variations at the edges and reduces variations in the rest of the line with different combinations achieving different grey values and variances between material and background. Scans R1S4 and R3S2 give similar grey values and difference between material and background even though different combinations of filtration were used. Scan R1S1 with minimum pre and post filtering delivers greater difference between material and background but with greater variations of grey values in the middle of the line. The last row of graphs in Figure 2 demonstrates the results achieved with pre-filtering, Scan R2S0, pre and post filtering, Scan R2S3 and post filtering, Scan R0S4. The grey values of Scan R2S3 have small difference of 10 000 grey values separating the material from the background but the variations of grey values in the matter and background are smaller.

TABLE IV: Calculated range of grey values in background and matter

Scan	Gr. Values Range	
	Background	Material
R0S0	21982	13531
R1S0	15709	13366
R2S0	11273	13092
R3S0	8844	9770
R1S1	11424	11280
R1S4	9485	9817
R2S1	9552	9558
R2S3	8489	6237
R3S1	8961	8909
R3S2	9662	8311
R0S4	8510	7125

The fluctuations of the grey values were examined further by calculating by the difference of maximum and minimum grey values for both background and matter, the results are provided in Table IV. The reduction of range of the grey values in the grey values of the material demonstrates reduction of variations. The results demonstrate that the thickest pre filtration in scan R3S0 reduces variations as well as all of the combinations of pre and post filtrations except in R1S1 where minimum pre and post filtrations were used and the best results were achieved in R2S3. The fluctuations of the grey values of the background indicate noise and scatter radiation and the results of this examination indicate a significant reduction of the grey values range when filtration is utilised. The combination of thicker pre and post filters indicate reduction of scattered radiation and the best results are achieved in R2S3.

Dimensional measurements of threshold dependent and independent distances were evaluated by using VG Studio Max 2.2 by fitting cylinders in the holes after using ISO50 threshold selection method that utilises the average grey value of background and material to identify and separate them. The cylinders were placed using least squared method and three diameters were used to identify and demonstrate the influence of filtration to the measurements error calculated by the optical CMS measurements, Figure 3. The cylinders were also used to measure three centre-to-centre distances and the results of the measurement error are presented in Figure



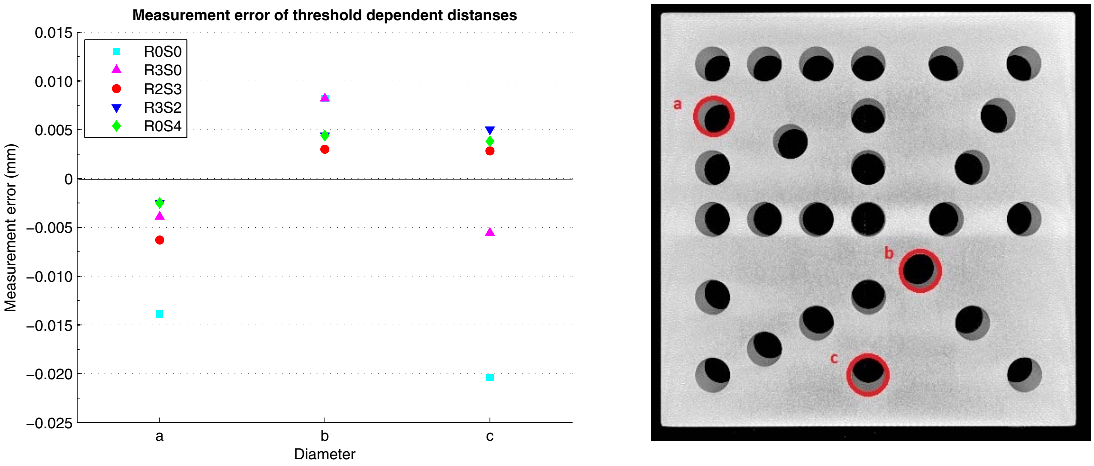
(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

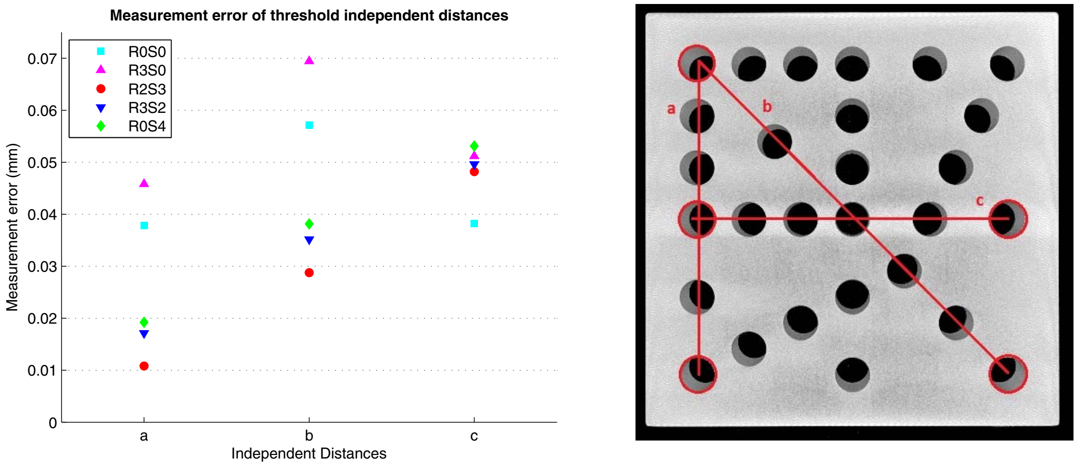
(j) (k) (l)

Fig. 2: The graphs demonstrate the histograms for lines (a), (b) and (c) of the resultant grey values for different combinations of physical filtering. (d), (e) and (f) demonstrate the resultant grey values for no filtering and three different pre-filtering. (g), (h) and (i) show the results of pre & post filtering and (j), (k) and (l) demonstrate the results of R2S0, R2S3 and R0S4.



(a) (b)

Fig. 3: The threshold dependent measurements examined were the diameter of the highlighet holes in (b).



(a) (b)

Fig. 4: The threshold independent measurements examined were the distances between holes centres as highlighet in (b)

4. Physical filtration of radiation reduces the measurement error significantly for threshold dependent distances such as diameters with the best results achieved with combinations of pre and post filtration. The results of threshold independent measurements demonstrate a greater measurement error for scans with no filtration and radiation pre-filtration only while the measurement error is reduced by utilising a combination of pre and post filtration or post-filtration of radiation.

IV. CONCLUSION

X-ray CT is emerging in dimensional metrology after establishing applications in non-destructive evaluations. CT can provide information about examined parts that are otherwise unreachable by visualising the internal structure and allowing inspection and quantitative analysis. The limitations of this technology influence the measurement uncertainty that is required in any measurement. The factors that influence the uncertainty of the measurements include the nature of polychromatic x-rays and x-ray spot size, the geometric alignment of the CT system, the reconstruction algorithms used to create the volume and environmental influences such as temperature. This investigation examines the effect of the combination of pre and post physical filtration in order improve dimensional measurements.

The results of this study demonstrate that the combination of pre and post filtration of radiation provides less variations between grey values of the same matter, indicating reduction of scattering and beam hardening. Scattered radiation and beam hardening cause streaks, inhomogeneities, cupping artefacts and loss of contrast in CT and influences negatively on dimensional measurements due to causing blurred edges and shadowing which reduce the effectiveness of the threshold selection when using threshold methods such as Otsu threshold method. These issues can also lead to incorrect readings and obscure cracks and voids [19]. The result of these issues is random and its intensity distribution is low background signal that reduces the contrast and signal to noise ratio [6]. There are numerous techniques to reduce these effects; either suppress scattered radiation in the scanning process or correct scatter related artefacts in post-processing. Both suppression and correction techniques are used in medical and industrial applications with suppression techniques able to reduce scattered radiation but unable to eliminate scattered related artefacts and correction techniques, requiring longer computations [19].

The range of grey values within material is dramatically reduced with the utilisation of filtration that demonstrates significant reduction of beam hardening. The combination of pre and post filtrations also reduces the difference of grey values between matter and background and as a result the contrast is affected and similar grey values are difficult to be manually distinct and analysed. However, automatic selection of threshold of grey values uses the mean of grey values distribution to separate background and material and it is not affected by the individual grey values. The reduction of variation of grey values and automatic selection of threshold can provide the required results and reduction of measurement uncertainty in single material scans but manual selection of grey values would be required in multi-material scans. A precise threshold selection of grey values leads to accurate results for both threshold dependent and independent measurements. Consequently, the results indicate the positive influence of utilising a combination of pre and post filtration.

The measurement error of threshold dependent measurements is dramatically improved with any filtration while the best results are achieved with a combination of pre and post filtration of radiation. Similar results were achieved with post filtration of radiation and that is contributed to the removal of the low energy radiation. The results of measurement error of threshold independent measurements demonstrate similar results with the threshold dependent measurements with best results achieved with a combination of pre and post filtration and similar results achieved with post filtration of radiation. Finally, the results demonstrate that further potential improvement can be achieved with the combination of pre and post filtration of radiation, although further examinations and observations are required in order to achieve the optimum selection of different filters for different materials and sizes of specimens.

ACKNOWLEDGMENT

The authors would like to thank BAE Systems and EPSRC for funding this project.

REFERENCES

[1] Kruth, J. P., Bartscher, M., Carmignato, S., Schmitt, R., De Chiffre, L., Weckenmann, A. , 2011. Computed tomography for dimensional metrology. *CIRP Annals 2011 - Manufacturing Technology* **60** pp. 821-842.

[2] Warnett, J. M., Titarenko, V., Kiraci, E., Attridge, A., Lionheart, W.R.B., Withers, P.J., Williams, M.A., 2016. Towards in-process x-ray CT for dimensional metrology. *Measurement Science and Technology* **27**, pp. 035401(14pp).

[3] Kourra, N., Warnett, J. M., Attridge, A., Dahnel, A., Ascroft, H., Barnes, S., Williams, M. A., 2016. A metrological inspection method using micro-CT for the analysis of drilled holes in CFRP and titanium stacks.*Int J Adv Manuf Technol* , doi:10.1007/s00170-016-8691-4, pp. 1-11.

[4] Thompson, A., Maksery, I., Leach R. K., 2016. X-ray computed tomography for additive manufacturing: a review.*Meas. Sci. Technol* **27** pp 072001 (17pp)

[5] Buzug, T. M., 2008. Computed tomography: from photon statistics to modern cone-beam CT. Berlin: Springer.

[6] Hsieh, J., 2009. Computed Tomography - Principles, Design, Artifacts, and Recent Advances. 2nd ed. Washington: SPIE Press.

[7] Sun, W., Brown, S. B., Leach, R. K., 2012. An overview of industrial x-ray computed tomography, Teddington: Queen's Printer and Controller of HMSO.

[8] Dewulf, W., Kiekens, K., Tan, Y., Welkenhuyzen, F., Kruth, J. P., 2013. Uncertainty determination and quantification for dimensional measurements with industrial computed tomography.*CIRP Annals - Manufacturing Technology* **62**, pp. 535-538.

[9] Ferrucci, M., Leach R. K., Giusca C., Carmignato S., Dewulf W., 2015, Torwards geometrical calibration of x-ray computed tomography systems - a review.*Meas. Sci. Technol* **26** pp 092003 (30pp)

[10] Kiekens, K. et al., 2011. A test object with parallel grooves for calibration and accuracy assessment of industrial computed tomography (CT) metrology.*Measurement Science and Technology* **22**.

[11] Schmitt, R., Niggermann, C., 2010. Uncertainty in measurement for x-ray computed tomography using calibrated work pieces.*Meas. Sci. Technol.* **21** 054008(9pp).

[12] Welkenhuyzen, F., Kiekens, K., Pierlet, M., Dewulf, W., Bleys, P., Kruth, J. P., Voet, A., 2009. Industrial Computer Tomography for Dimensional Metrology: Overview of Influence Factors and Improvement Strategies. Antwerp, Shaker, pp. 401-410.

[13] Kumar, J., Attridge, A., Wood, P. K. C., Williams, M. A., 2011. Analysis of the effect of cone-beam geometry and test object configuration on the measurement accuracy of a computed tomography scanner used for dimensional measurameent.*Measurement Science Technology* **22**, pp. 35105-35120.

[14] VDI/VDE, V. D. I., 2010. 2630 Part1.4: Computed tomography in dimensional measurements, Measurement procedure and comparability, Dusseldorf: VEREIN DEUTSCHER INGENIURE.

[15] Lifton, J. J., Malcolm, A. A., McBride, J. W., 2016. An experimental study on the influence of scatter and beam hardening in x-ray CT for dimensional metrology.*Measurement Science and Technology* **27**.

[16] Borges De Oliveira, F., Bartscher, M., Neuschaefer Rube, U., 2015. Analysis of combined probing measurement error and length measurement error test for acceptance testing in dimensional computed tomography. Belgium, Digital Industrial Radiology and Computed Tomography.

[17] Otsu, N., 1979. A threshold selection method from gray-level histograms. *Automatica* **11**, pp. 23-27.

[18] Lifton, J. J., Malcolm, A. A., McBride, J. W., Cross, K. J., 2013. The application of voxel size correction in x-ray computed tomography for dimensional metrology. Singapore, s.n.

[19] Schorner, K., 2012. Development of methods for scatter artifact correction in industrial x-ray cone-beam Computed Tomography, Munich: Technische Universitat Munchen.