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Abstract

A study of the secondary source phenomenon due to the presence of off focal radiation in industrial micro-focus cone-beam X-ray computed tomography (XCT) systems and its influence on dimensional measurements is presented. Although off-focal radiation production within X-ray tubes has been studied for medical X-ray imaging systems, its properties and its effects on dimensional measurements in industrial XCT systems have not been discussed prior to this research. The study comprises: evaluation of the geometrical properties of off-focal radiation through a theoretical and experimental study of two-dimensional projection images of the scanned objects, verification of these properties using computer simulations and evaluation of the impact of the secondary source on dimensional measurements using experimental and simulation approaches. In addition, ways to minimise the effects of off-focal radiation are discussed, and reference samples for characterising the properties of off-focal radiation are proposed.

Keywords	X-ray computed tomography, error, off-focal radiation, dimensional measurements
Taxonomy	Mechanical Engineering, Engineering, Industrial Engineering, Quality Engineering, Precision Engineering
Corresponding Author	wenjuan sun
Corresponding Author's Institution	National Physical Laboratory
Order of Authors	Nadia Flay, Stephen Brown, wenjuan sun, Thomas Blumensath, Rong Su
Suggested reviewers	Ian Sinclair

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Dr Wenjuan Sun
wenjuan.sun@npl.co.uk
Hampton Road
National Physical Laboratory
TW11 0LW
United Kingdom

20.04.2020

Dear editors:

I would like to submit an original research paper entitled "Effects of off-focal radiation on dimensional measurements in industrial cone-beam micro-focus X-ray computed tomography systems" for consideration by Precision Engineering.

X-ray computed tomography (XCT) is increasingly used in the field of dimensional metrology for industrial applications. However, sources contributing to errors in dimensional metrology is not well understood. In this paper, we studied the impact of off-focal radiation of X-ray sources. Off-focal radiation is a common issue of X-ray sources, but the impact on the dimensional metrology hasn't been investigated before. In this paper, authors have presented the latest research regarding the influence of off-focal radiation on dimensional measurements, development of reference samples to evaluate off-focal radiation and methods to minimise off-focal radiation. We feel that the scope of this paper suits Precision Engineering and sincerely hope the paper will be considered.

Thank you for your time and I look forward to your reply.

Regards,

Wenjuan Sun

Dear editors and reviewers,

Thank you for the excellent and constructive comments on our paper. We are grateful for the time and effort that has taken by you in providing the feedback. We have made changes according to your suggestions and hope the updated version addresses all your questions.

Two documents are included in the submission. One is the paper with replies to reviewers' comments, and the other document is the clean version of the paper.

Dear Reviewer 1:

Thank you very much for your thorough revision of our paper. Your comments are valuable to us. We have made changes according to your suggestions. Replies to your comments have been added after your original comments in the paper.

Dear Reviewer 2:

Thank you for your suggestions regarding references. We have added most of them into our paper.

Best regards,
Wenjuan

Effects of off-focal radiation on dimensional measurements in industrial cone-beam micro-focus X-ray computed tomography systems

Nadia Flay^{1,2}, Stephen Brown¹, Wenjuan Sun^{1*}, Thomas Blumensath², Rong Su³

¹National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK

²University of Southampton, Highfield Campus, Southampton, SO17 1BJ, UK

³Manufacturing Metrology Team, Faculty of Engineering, University of Nottingham, Nottingham, NG8 1BB, UK

*Contact of the corresponding author: wenjuan.sun@npl.co.uk

Abstract

A study of the secondary source phenomenon due to the presence of off-focal radiation in industrial micro-focus cone-beam X-ray computed tomography (XCT) systems and its influence on dimensional measurements is presented. Although off-focal radiation production within X-ray tubes has been studied for medical X-ray imaging systems, its properties and its effects on dimensional measurements in industrial XCT systems have not been discussed prior to this research. The study comprises: evaluation of the geometrical properties of off-focal radiation through a theoretical and experimental study of two-dimensional projection images of the scanned objects, verification of these properties using computer simulations and evaluation of the impact of the secondary source on dimensional measurements using experimental and simulation approaches. In addition, ways to minimise the effects of off-focal radiation are discussed, and reference samples for characterising the properties of off-focal radiation are proposed.

Keywords: X-ray computed tomography, off-focal radiation, dimensional metrology

1 Introduction

X-ray computed tomography (XCT) is the technique in which X-rays are employed to generate two-dimensional (2D) projection images (radiographs) that are used to compute a three-dimensional (3D) reconstruction of an object (Greek: *Tomos* 'slice, section', and *grapho* 'to write'). The technique was developed by Hounsfield and Cormack for medical use [1]. However, in recent years XCT has found a new niche in industrial applications, where the technology is increasingly used as a dimensional metrology tool [2-10].

XCT offers advantages over traditional tactile and optical coordinate measuring systems due to its ability to detect both outer and inner geometries of an object noninvasively. However, there is a lack of confidence in the measurements due to difficulties in determining the metrological characteristics of XCT systems for uncertainty evaluation [11]. At present, many influence factors affecting measurements using XCT are still poorly understood. Unlike tactile and optical coordinate measuring

systems, there are no internationally accepted standards for performance verification and calibration of XCT [12].

In XCT systems, the quality of X-ray sources plays a vital role. In common XCT systems, X-rays are produced by X-ray tubes. A typical Coolidge X-ray tube consists of a negatively charged cathode (filament) that is used as a source of electrons, a magnetic focusing coil used to focus the beam of electrons, and a positively charged metal target (anode) used to generate X-rays, all enclosed in vacuum [13]. Electrons are emitted from the hot filament and accelerated towards the anode, where they interact with the target. There are mainly two types of targets: transmission and reflection targets [12]. However, X-ray tubes with reflection targets (Figure 1) are more prevalent in industrial XCT systems due to the ability to tolerate higher temperatures and better durability.

Figure 1. Schema of an X-ray tube with a reflection target.

The interaction of the accelerated electrons with the target not only results in the emission of X-rays but also electrons that are scattered off the surface of the target. With a reflection target (Figure 1), these electrons are scattered back to the incident beam or the vicinity of the focal spot with all or most of the original energy preserved. They are often called the backscattered electrons [14-16].

The fraction of electrons backscattered depends on the atomic number of the target material. It has been shown that the increase in the angle between the incoming electron beam and the surface normal of the target increases the backscattering effect with a larger portion of the electrons "backscattered" in the forward directions [17]. These backbackscattered electrons may then interact with the X-ray tube housing components, resulting in the emission of off-focal X-rays and produce additional X-rays which result in off-focal radiation [18, 19]; this. The off-focal radiation is also known as 'secondary', 'extra-focal' or 'parasitic' radiation [18, 20, 21]. It is these re-emitted electrons, referred to as backscattered electrons (BSEs), which are the topic of this study.

. which Off-focal radiation is characterised as may cause a secondary shadows around the image of the projected object(s) and (Figure 2), where both the original projection images and the same images adjusted to highlight the ghosting are presented.. It may have a negative impact on reduces image contrast and can lead to unwanted ghost images artefact (ghosting) [22]., which is characterized as a secondary shadow around the image of the projected object(s) (. Figure 2); illustrates typical ghosting effects due to off-focal X-rays, where ghosting effects were shown as dark shadows around the objects in the projection images. Depending on the design of the XCT system,

Commented [1]: Makes me wonder if the term 'backscatter' is appropriate (compared to simply 'scatter') since, according to the new figure 4, it appears that the majority of electrons are scattered in the forward direction. I show from here on out how changing backscatter/ed does not negatively affect the discussion.

Commented [2R2]: Answer to reviewer's comments:
We share reviewer's concern. We have double checked references and "backscatter" is the terminology widely used. However, we have edited the content of this paragraph to make this clearer.

Commented [3]: Nonsensical sentence.

Commented [4R4]: Answer to reviewer's comments:
We have removed this sentence.

‡The effects of off-focal radiation depend on the number of scattered electrons, the scattering direction, the distance from the target to the tube housing, the geometry and the material of the target and the housing, and the overall tube design [17, 23, 24]. The off-focal radiation due to to secondarybackscattered electrons has been studied in.

The sources of off-focal radiation in X-ray tubes with a rotating anode and the impact on imaging quality have been discussed in the literature [13, 18, 20] and off-focal radiation in an X-ray tube with a transmission target has been investigated in [19]. However, to the best of our knowledge, no literature concerning the impact of off-focal radiation on dimensional measurements in industrial cone-beam XCT has been identified prior to this study.

In this paper, we will study the effects of off-focal radiation through theoretical, experimental and simulation studies. The effects of off-focal radiation on 2D projection images and 3D reconstructed data will be shown. The influence on dimensional measurements of both single and multiple materials will be studied and methods to reduce the impact of off-focal radiation will be discussed.

2 Theoretical study of off-focal radiation

The study conducted at the National Physical Laboratory (NPL) used an industrial micro-focus cone-beam XCT system Nikon Metrology XT H 225 M, built specifically for metrological applications. In this XCT system, the tilt angle between the axis of the X-ray tube and the normal to the surface of the target is approximately 60° , for which approximately 65 % of the incoming electrons can be backscattered from a tungsten target [17, 20, 22]. No manufacturer's specification or instructions concerning the off-focal radiation are available for the X-ray tube used in the above system.

As there is very limited knowledge about the inner geometry of the X-ray tube housing, the location of the source of the off-focal radiation was estimated by comparing the size of features measured in the projection images due to the primary radiation and due to the off-focal radiation. The primary radiation source is a small spot with a diameter in the order of a few micrometres. The secondary source is expected to have an extended size as it is scattered from a larger area within the housing. The position may also deviate from the primary source.

Commented [5]: This is the first time I see the term 'secondary' being applied to describe electrons in this paper. Would it be more consistent to simply refer to them as 'scattered' electrons? Also, this sentence in its current low level of detail sits a bit oddly here. Consider removing or elaborating what this study exposes about off-focal radiation. Perhaps incorporate this sentence with the first few sentences of the next paragraph?

Commented [6R6]: Answer to reviewer's comments:
We have modified this. The term "secondary" is now introduced in the paragraph before.

Commented [7]: In this case it is no longer a 'point', which to me signifies and 'infinitesimally small point'.

Reply to reviewer's comments
We have modified this as suggested.

Commented [8]: Maybe this is a good place to introduce extended as follows:
"The secondary source is modelled as a radially symmetric spatial extension of the primary source, albeit displaced from the primary source along the XCT imaging axis."

Reply to reviewer's comments:
Thanks for suggestion. We have modified this sentence. However, as the shape of the secondary source depend on the shape of the housing material. In our case, it is circular (ring). We have modified this sentence to make it clearer.

Figure 2. The geometry of a magnified projection image produced by a secondary source.

Figure 2 shows a schematic representation of the formation of a 2D projection image of a scanned object acquired using a secondary source. d_0 is the size of the object, d_i is the size of the object at image plane due to the primary point source, f is the size of the secondary source, a is the source-to-object distance, $(a + b)$ is the source-to-detector distance. Assuming there is off-focal radiation, a' is the distance between the off-focal plane to the object, u is the width of the penumbra due to off-focal radiation and $d_{total} = (d_i + 2u)$ is the size of the object due to the off-focal radiation on the image plane.

For a point source, the geometric magnification m of a scanned object is

$$m = \frac{a + b}{a} = \frac{d_i}{d_0}. \quad (1)$$

The derivation of geometric magnification M due to a secondary source at the primary source plane is given in [25]. For a secondary source at the off-focal plane, the geometric magnification M' is:

$$M' = \frac{f}{d_0} (m' - 1) + m' = \frac{d_{total}}{d_0}, \quad (2)$$

where $m' = (a' + b) / a'$ is the point source magnification calculated at the off-focal plane. By measuring m and M' for two or more different d_0 , f and m' can be estimated by solving equation (2). Given m' and m allow us then to estimate a and a' .

3 Experimental evaluation of off-focal radiation on using projection images

Commented [9]: This is the first mention of the term 'extended'. Needs introduction.

Reply to reviewer's comments:
Have replaced this word with "secondary".

Commented [10]: I feel that this section should come before the section 2.1. It sheds light on why you model the secondary radiation the way you do.

Reply to reviewer's comment:
Thanks for the suggestion. As we quote equations 1 and 2 in section 3, we prefer to keep the current order of 2.1 and 2.2. However, we have made minor changes to the following sections to make the structure a bit clearer.

Commented [11]: "Effects of off-focal radiation on projection images" could be more straightforward.

Reply to reviewer's comment:
Thanks for suggestion. This section is to evaluate the off-focal radiation. The effects of off-focal radiation is covered in the following sections. We have modified the headings of the paper to make this a bit clearer.

In this section, the hypothesis of the off-focal radiation is studied based on 2D projection images. 2D projection images of different objects were acquired. For the steel spheres with a diameter of 0.79 mm, the secondary shadow due to off-focal radiation appeared as 'rings' around the spheres. For the larger spheres with a diameter of 2.36 mm, it is relatively noticeable that the secondary shadow is superimposed with the primary shadow, affecting the grey value of the bulk of the object material. The circular symmetry of the secondary shadows suggests that the secondary source is circular in shape and displaced from the primary source in the direction of the detector. The off-focal radiation is also non-uniform, indicated by the non-uniformity of the image shadow.

Figure 3. Illustrations of ghosting due to off-focal radiation. 2D projection images of steel spheres with the nominal diameters of (left) 0.79 mm and (right) 2.36 mm.

The position of the shadow in 2D projection images did not change when adjusting the position of the primary focal spot, which can be manipulated by altering the direction of the electron beam using the X-Y dedicated steering coils. This observation supports the hypothesis that the off-focal radiation originates from a fixed structure due to backscattered electrons hitting the material near the target a permanent feature inside the tube housing.

Based on both the theoretical and the experimental derivation, it is hypothesised that the off-focal radiation is emitted from the edge of the exit window in the target housing of about 4 mm in diameter, which is located approximately 6 mm from the primary focal spot towards the detector (Figure 4). The target housing is made of a tungsten/copper alloy, a material suitable for generating X-rays. The hatched area in Figure 4 is part of the target housing that surrounds X-rays as they exit the target assembly through the beryllium or aluminium window (shaded area). As the backscattered electrons interact with the target housing near the exit window, secondary X-ray radiation is produced. The geometry of the target housing is such that there is a greater area at the top of the housing, which results in more photons being generated at the upper portion of the housing comparing to the lower portion of the housing. Consequently, the secondary shadows are more pronounced in the lower portion of the projection image, hence explaining the non-uniformity.

Commented [12]: What results? Clarify.

Reply to reviewer's comment:
We have modified this sentence as suggested.

Commented [13]: This should have been introduced in the first reference to figure 2.

Reply to reviewer's comment:
This has been moved to earlier section as suggested.

Commented [14]: I would describe it as an "expanded albeit faint duplicate of the primary image".

Reply to reviewer's comment:
As there is clear separation between the primary and the secondary projection, it will be ambiguous if we use the word "expanded". However, we have modified this sentence, and removed the word "separate" as "ring" already indicate this.

Commented [15]: You could argue that this effect also occurs for the 0.79 mm diameter sphere, albeit not as noticeably.

Reply to reviewer's comment:
Thanks for suggestion. We keep the content as it is to make it easy for readers to understand.

Commented [16]: This would require specifying what X and Y refer to, which I don't think is important.

Reply to reviewer's comment:
We have modified the content as suggested.

Commented [17]: Elaborate.

Reply to reviewer's comment:
We have modified the content as suggested.

Figure 4. A schematic representation of the micro-focus X-ray target assembly.

To confirm the initial hypothesis about the size and location of the origin of the secondary source, several 2D projection images of a thin steel gauge of 8.95 mm in width and a thin silicon disk of 25.4 mm in diameter were examined (Figure 5). Using equations (1) and (2) and the properties of the XCT system, the theoretical sizes of the steel gauge at three different magnification positions and the silicon disk at one magnification setting produced by the primary and the secondary sources in the images were calculated. These theoretical values were then compared with the experimentally measured values of the images due to the primary and the secondary sources. A secondary source of 3.8 mm diameter located 6 mm in front of the primary focal spot was used in the calculations. Data presented in Table 1 shows that the experimentally measured values of the image sizes were in good agreement with the theoretical values.

Figure 5. Projection images of a steel gauge (a) and a silicon disk (b). In both images, the white dashed lines indicate image edges due to the primary source and the black dashed lines indicate those due to the secondary source.

Table 1. Summary of the experimentally measured and theoretically calculated image sizes of the steel gauge and the silicon disk produced by primary and secondary sources.

Magnification due to primary source	Measured image size due	Theoretical image size due	Measured image size due	Theoretical image size due
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		to primary source/ pixels	to primary source/ pixels	to secondary source/ pixels	to secondary source/ pixels
Steel gauge	7.0	314	317.0	430	429.7
Steel gauge	10.0	446	446.4	648	646.9
Steel gauge	13.8	622	620.6	923	926.3
Silicon disk	6.9	894	892.3	1029	1026.7

3.1 Development of a reference sample to evaluate non-uniformity

In addition to the spherical reference samples and the steel gauge, an object named 'the wheel' was designed and manufactured to investigate the radial non-uniformity of the off-focal radiation. This object consists of six crossed steel wires that are fixed inside of an aluminium cylinder (Figure 6 left). The diameter of the wires is 0.9 mm, and the inner diameter of the cylinder is 78 mm. The benefit of using the wheel reference sample is to allow the user to quickly identify the pattern of intensity non-uniformity due to the off-focal radiation. For example, the projection image of the wheel using the XCT system at NPL was more prominent in the lower portion of the projection image (Figure 6 right), confirming the hypothesis postulated in section 2.2.

Figure 6. Projection images of the wheel reference sample. Left. Original projection image of the wheel; Right. A magnified image of the wheel scanned at the same settings, with contrast adjusted for secondary image visibility.

4 Comparison between simulated and experimental 2D projection images

Having acquired numerical evidence to support the initial postulate regarding the size and the location of the off-focal radiation, a computer simulation study was conducted. Simulations of 2D projection images of spheres were performed in Matlab using the analytical ray-tracing method. All simulations were produced using a monochromatic X-ray attenuation model. The off-focal radiation was achieved by simulating a circular source of 3.8 mm diameter, displaced from the primary source by 6 mm along the X-ray beam axis in the positive direction towards the detector. The intensity of

Commented [18]: It is not clear which evidence you are referring to. Also, a simulation is numerical. This makes the use of 'numerical evidence' here not suitable. Are you referring to 'empirical evidence'?

Reply to reviewer's comment:

Agree to reviewer's comment and this sentence has been modified.

Commented [19]: It is not clear where the 'positive' direction is without a well-defined coordinate system.

Reply to reviewer's comment:

Agree to reviewer's comment and content is modified as suggested.

the simulated secondary source was set to 10 % of the primary intensity, which was in good agreement with experimental data.

Figure 7 shows a simulated projection image of an iron sphere 6.36 mm in diameter in the presence of the primary and the off-focal radiation. Adjusting the image contrast allows the effects of the off-focal radiation to be clearly visible. Ghosting can be seen surrounding the sphere, with further contrast adjustments exposing a 'dark core' inside the sphere, which is the projection image due to the primary radiation superimposed with the projection image due to the off-focal radiation. The simulated image is in close agreement with the real image of a steel sphere of 6.36 mm in diameter, acquired on the XCT system. Figure 8 shows the experimental image; the contrast is adjusted to show the ghosting and then the 'dark core'. The sizes of the images due to the primary source and the secondary source in both simulated and experimental images were calculated and are summarised in Table 2. The images were analysed using Matlab and ImageJ (an open-source image processing software developed by the National Institutes of Health, <http://imagej.nih.gov/>).

Figure 7. A simulated image of a steel sphere of 6.36 mm in diameter; a) original image; b) the same image with grey values adjusted for shadow visibility, here the white dashed line shows the image due to the primary source, and the grey dashed line shows the secondary shadow; c) the same image with grey values adjusted for the 'dark core' visibility, here the grey dashed line shows the 'dark core effect' due to the off-focal radiation.

Figure 8. An experimental image of a steel sphere of 6.36 mm in diameter; a) original projection image; b) the same image with grey values adjusted for shadow visibility, here the white dashed line shows the image due to the primary source, and the grey dashed line shows the secondary shadow; c) the same image with

grey values adjusted for the 'dark core' visibility, here the grey dashed line shows the 'dark core effect' due to the off-focal radiation.

Table 2. Diameters of images due to the primary and secondary sources in experimental and simulated images.

	Diameter of the sphere due to the primary source/ pixels	Diameter of the shadow due to the secondary source/ pixels	Diameter of the core due to the secondary source/ pixels
Experimental image	284	456	138
Simulated image	286	458	139

Although some degree of uncertainties existed due to the boundary definition in the image processing, the diameter values in the experimental and the simulated images are in good agreement. This observation further supports the initial postulate that in the XCT system used in this study, the off-focal X-rays are produced by the interaction of backscattered electrons with the exiting window of the tube housing with diameter and position as simulated. The investigations have shown clearly that the off-focal radiation affects the immediate background, edges, and internal portions of the projected object. The comparison also demonstrated the effectiveness of using the simulation approach to investigate the impact of off-focal radiation.

5 Effects of off-focal radiation on dimensional measurements

In this section, both simulation and experimental approaches were used to study the impact of the off-focal radiation on dimensional measurements. The experimental approach was considered to investigate the impact of the off-focal radiation on the single sphere and single material object. The simulation approach was used for more complicated cases where multiple spheres and multiple materials were considered.

In each simulation or experimental scan, Aa set of 3142 projection images were acquired of the scanned objects as they were rotated 360 ° on the sample stage. Tomographic reconstruction of the sphere objects was performed using Nikon CT Pro 3D software. The 3D volumes of the reconstructed objects were analysed using VGStudio MAX version 2.2. The iso-surfaces of the objects were identified by 'automatic' and 'advanced' surface determination techniques available in the VG Studio software. The 'automatic' technique, also known as ISO-50 % [7], identifies a surface by calculating the average between the mean grey value of the background and that of the material. In the 'advanced' technique, the surface is further refined by identifying the highest local grey value gradient within the specified number of search voxels from the ISO-50 surface. Subsequently, spheres were fitted to ISO-surfaces using a Gaussian least-squares fit with 1 000 sampling points. This enabled the calculation of sphere diameters and the range of the radial residuals to the fit, i.e. the apparent form error of the reconstructed spheres. The diameter and form error of the sphere and, where appropriate, the centre to centre length (distance between the centres of spheres) and bidirectional distances between spheres (bidirectional length measurement is created using the

Commented [20]: Was this a simulated or experimental scan?

Reply to reviewer's comment:

The first scan of a single sphere was based on experimental work. We have modified this in this section as well as the following sections to make it clearer.

Commented [21]: I don't think center-to-center distances qualify as uni- or bi-directional as they consider surfaces that are oriented in many directions.

Reply to reviewer's comment:

To avoid ambiguity, we have changed this wording and removed "uni-directional" in the content.

probing of two surfaces at two single points where the direction of the two surface normals is opposite [26, 27]) of the simulated volumetric data using the primary source only were compared to those using the combination of the primary and secondary sources.

5.1 Effects of off-focal radiation on the 3D scan of a single sphere

The effects of off-focal radiation on the reconstructed 3D volume of a 5 mm diameter steel sphere were studied experimentally. As expected, all 2D images were affected by the presence of the off-focal radiation (Figure 9). The diameter of the tomographically reconstructed sphere (Figure 10) was 4.993 mm, with a form error of 6.7 μm .

Figure 9. XCT projection images of a 5 mm steel sphere. a) An image of a steel sphere 5 mm in diameter; b) the same image with grey values adjusted for visualising the secondary shadow; c) the same image with grey values adjusted for visualising the 'dark core'.

Figure 10. Scan results of the 5 mm steel sphere sample. a) A 3D volume of the steel sphere; b) a 2D slice through the 3D volume with surfaces fitted to the outer boundary and the inner 'pseudo-boundary' inside the sphere; a profile through the centre of the 2D slice is marked in green; c) grey values along the profile line.

The analysis shows that the secondary shadow observed in the immediate background of the imaged sphere has little influence on the reconstruction of the sphere's outer surface. On the other hand, the presence of the dark core in the 2D images appears to have a significant effect inside the 3D volume, as it results in non-uniformity of reconstructed grey values (Figure 10b and Figure 10c). These observations confirm that the secondary source can have an adverse effect on the reconstructed 3D models and can lead to errors in reconstructed grey values.

5.2 Effects on measurements of multiple objects

The following acquisitions comprising iron spheres were simulated:

- 1) two spheres of 2 mm diameter with a 2 mm distance between their centres,
- 2) two spheres of 4 mm diameter with a 5 mm distance between their centres,
- 3) two spheres of 5 mm diameter with a 6 mm distance between their centres.

The simulations were performed once with only the primary source and again with both the primary and the secondary sources. The measurement results are summarised in Table 3.

Figure 11. Simulated projections of two iron spheres 4 mm in diameter with a 5 mm distance between their centres. a) A projection image using the primary and the secondary sources (the yellow arrow shows a centre to centre distance and the green arrow shows a bi-directional distance); b) A projection image with the grey values adjusted for shadow visibility; c) 2D cross-sectional view through the 3D reconstructed volume (the appearance of pseudo-objects inside the spheres is clearly visible); d) cross-sectional view through the 3D reconstructed volume using the primary source only; e) grey level profiles along the red line in c) and the blue line in d).

Figure 11a shows a 2D image of the two 4 mm diameter spheres, simulated using both the primary and the secondary sources. The effects of the off-focal radiation are clearly visible (Figure 11b). The analysis with and without the secondary source (Figure 11c and d, respectively) shows that although the presence of the off-focal radiation changes the grey level values of the background and the inside of the sphere (Figure 11e), the diameter, form error and centre to centre and bi-directional distance measurements appears to be largely unaffected. The results of the diameter and form error measurements of two-sphere objects are summarised in Table 3.

Table 3. A comparison of dimensional measurements performed on the reconstructions the two-sphere objects. The diameter, form error, centre to centre and bi-directional distances were measured for sphere surfaces determined using the advanced (Adv.) and automatic (ISO-50 %) surface determination techniques.

	Simulated spheres			Magnifi- cation	Voxel size/μm	Sphere1				Sphere2				Calculated distances/ mm			
	Diameter / mm	Centre to centre distance/ mm	Bi- directional distance/ mm			Diameter/m m		Form error/μm		Diameter/m m		Form error/μm		Centre to centre		Bi-directional	
						Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%
Primary source only	2.000	2.000	4.000	10	20.0	1.998	2.031	9.2	12.4	1.998	2.031	9.3	15.4	2.000	2.001	3.998	3.998
Primary and secondary sources	2.000	2.000	4.000	10	20.0	1.998	1.999	9.5	9.9	1.998	1.999	9.5	9.7	2.000	2.000	3.998	3.998
Primary source only	4.000	5.000	9.000	10	20.0	4.001	4.001	7.2	7.3	4.001	4.001	7.2	7.3	5.001	5.001	9.002	9.002
Primary and secondary sources	4.000	5.000	9.000	10	20.0	4.001	4.001	6.9	6.6	4.001	4.001	6.5	6.6	5.001	5.000	9.001	9.000
Primary source only	5.000	6.000	11.000	15	13.3	5.001	5.000	9.3	9.9	5.001	5.038	9.2	14.8	5.999	5.998	11.018	11.015
Primary and secondary sources	5.000	6.000	11.000	15	13.3	5.001	5.001	8.6	9.4	5.001	5.001	8.6	9.4	5.999	5.998	11.012	11.012

The preliminary results from the simulation of the two-sphere objects suggest that although the presence of off-focal radiation degrades the quality of 2D images, the effect on the measurement of simple single material objects such as spheres is insignificant.

5.3 Effects on measurements of multi-material objects

In order to investigate the effects of the off-focal radiation on the dimensional measurement of a simple multi-material object, the following acquisitions were simulated and analysed:

- 1) an iron sphere of 6 mm diameter using the primary source only;
- 2) the same object as in 1), using the combined primary and secondary sources;
- 3) an object with an outer iron sphere of 6 mm diameter and an inner aluminium sphere of 2.5 mm diameter using the primary source only;
- 4) the same object, as in 3), using the combined primary and secondary sources.

The results are summarised in Table 4.

Table 4. A comparison of 3D volumes of the iron (Fe) and aluminium (Al) spheres. The diameter and form error of spheres were measured for surfaces determined using the advanced (Adv.) and automatic (ISO-50 %) surface determination techniques.

	Simulated sphere diameter/mm	Diameter/mm		Form error/ μm	
		Adv.	ISO-50%	Adv.	ISO-50%
Primary source only:					
-sphere material Fe	6.000	6.000	6.000	14.035	14.268
Primary and secondary sources:					
-sphere material Fe	6.000	6.001	6.001	13.112	13.570
-pseudo-inner sphere		2.726		18.041	
Primary source only:					
-outer sphere material Fe	6.000	6.001	6.001	12.951	13.499
-inner sphere material Al	2.500	2.499		16.061	
Primary and secondary sources:					
-outer sphere material Fe	6.000	5.999	5.998	14.181	14.289
-inner sphere material Al	2.500	2.717		8.391	

As with the simulations of the two-sphere objects, the measurements of the diameter and form error of the iron sphere do not appear to be significantly affected by the secondary source. When analysing the diameter of the inner aluminium sphere, the situation is different. When the object with the outer (iron) and the inner (aluminium) spheres was simulated using the primary source only, the diameter of the inner sphere in the 3D reconstruction was calculated to be 2.499 mm. When this object was simulated using both the primary and the secondary sources, the inner sphere diameter was calculated to be 2.717 mm. The value of 2.717 mm is close to the value of 2.726 mm, which is the diameter of the pseudo-sphere identified inside the iron sphere that was simulated using the primary and the secondary sources of the single material sphere. The reason for such values becomes apparent when analysing the profiles through the 2D slices of the three reconstructed volumes (Figure 12): the presence of the off-focal radiation distorts the real boundary between iron and aluminium materials in the object (dashed grey line), resulting in the false boundary identification (solid grey line). This finding supports the proposition that off-focal radiation can increase measurement errors for complex multi-material objects.

Figure 12. Profiles taken through the centre of the 2D slices of 3D volumes reconstructed from image stacks of: an iron sphere of 6 mm diameter, simulated using both the primary and the secondary sources (green profile); an object with an outer iron sphere of 6 mm diameter and an inner aluminium sphere of 2.5 mm diameter, simulated using the primary source only (red profile); and the same object, simulated using the primary and the secondary sources (blue profile). The dashed grey line represents a position of the real iron/aluminium border, and the solid grey line represents a false iron/aluminium border.

6 Possible correction methods

There are a number of methods that can minimise the intensity of off-focal radiation and its effects. One common solution is the hardware method in which additional collimators (often made of lead) are installed in the path of the X-ray beam, to stop off-focal radiation from penetrating the object [28]. This method is particularly widespread in medical XCT, as it not only improves the image quality but most importantly reduces exposure to radiation. The presence of such collimators is often required by the health and safety standards [4]. However, the reduction of radiation is a drawback to industrial XCT. Furthermore, the presence of the collimator also limits the field of view, which can negatively affect the system's scanning versatility. Users should consider whether the use of additional collimating devices is beneficial for a given scanning task.

Figure 13 demonstrates the improvement of measurements using the hardware method. A 2D image of an object made with four crossed metal wires has been imaged without and with a collimator. Figure 13a is the projection image without a collimator, and Figure 13b shows the same object scanned at the same settings but with an added tungsten aperture of 3 mm diameter and 4 mm thickness placed in front of the exiting window. It is clear that the effects of off-focal radiation were reduced; as expected, the overall brightness of the image scanned with the aperture was also reduced (Figure 13c).

Figure 13. Hardware correction of off-focal radiation using a collimator. a) An image of the object made with four crossed metal wires; b) an image of the same object with the same settings scanned using a collimator (a tungsten aperture of 3 mm diameter and 4 mm thickness); c) a comparison of the profiles taken through one of the wires in the image without collimator (red) and with collimator (blue).

One considerable disadvantage of the hardware method for XCT systems used in dimensional metrology is the reduction of the field of view, which can adversely affect the versatility of the system.

Another method is the software correction method [29], where the error due to the off-focal radiation is estimated by convoluting the projection image with the secondary source. This is based on the assumption that each 2D image is a combination of the images due to the primary and the secondary sources. The aim is to eliminate the image due to the secondary source from each 2D image [6]. Although the software correction of individual 2D projection images can reduce the effects of off-focal radiation, this method has a number of limitations. In order to remove the effect completely, the exact position, size and shape of the secondary source needs to be known. As shown in this study, a reasonable estimate of the secondary source size and position can be achieved, but some degree of approximation is always present. The intensities of the images due to the secondary source is also estimated depending on a number of factors. Precise knowledge of these factors is

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essential to eliminate the effects of off-focal radiation using the software correction method, but often impossible to obtain. The software correction method can reduce the effect, but cannot eliminate the error entirely [29]. Due to the reasons mentioned above, the software correction method is, therefore, not robust and will not be considered further.

A third method of reducing the effect of off-focal radiation is through adjusting the design of the X-ray tube and the tube housing in particular. Since the off-focal radiation is generated by the interaction of backscattered electrons with the housing material, it is proposed to shield the inner part of the housing close to the exiting window with a soft material, such as aluminium. Aluminium is often a material of choice in electron shielding [30]. Since the number of backscattered electrons increases rapidly with the increased angle between the incoming electron beam and the target material, it is also possible to reduce backscatter by changing the tilt angle.

7 Conclusions

In this paper, off-focal radiation in an industrial X-ray tube has been investigated, and the effects on dimensional ~~metrology~~ measurements have been studied. A secondary source that causes off-focal radiation may be generated in an X-ray tube due to scattering of electrons in the target housing. The position, size and shape of the secondary source can be estimated from projections of simple reference objects. The secondary source can result in noticeable shadowing effects and grey value variations in the tomographic reconstruction of a single material object. For multi-material objects, image artefacts due to off-focal radiation have been shown to influence dimensional measurements.

Based on the findings of this study, it is recommended that the evaluation of the properties of the off-focal radiation, such as its location, size, shape and intensity, is included as a part of the overall qualification procedure of the X-ray tube. Further research should include the investigation of the effects of off-focal radiation on dimensional measurements of multi-material objects of complex geometries. Several ways to minimise the off-focal radiation were discussed, although none of these methods is ideal. Further study should be conducted to investigate the correction methods.

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Commented [23]: 'metrology' is first and foremost 'the science of measurement' and should not be used to substitute 'measurement(s)'

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Highlights of the paper below:

- off-focal radiation in industrial micro-focus cone-beam X-ray computed tomography systems
- influence of off-focal radiation on dimensional measurements
- reference samples to evaluate off-focal radiation
- minimisation of off-focal radiation

Effects of off-focal radiation on dimensional measurements in industrial cone-beam micro-focus X-ray computed tomography systems

Nadia Flay^{1,2}, Stephen Brown¹, Wenjuan Sun^{1*}, Thomas Blumensath², Rong Su³

¹National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK

²University of Southampton, Highfield Campus, Southampton, SO17 1BJ, UK

³Manufacturing Metrology Team, Faculty of Engineering, University of Nottingham, Nottingham, NG8 1BB, UK

*Contact of the corresponding author: wenjuan.sun@npl.co.uk

Abstract

A study of the secondary source phenomenon due to the presence of off-focal radiation in industrial micro-focus cone-beam X-ray computed tomography (XCT) systems and its influence on dimensional measurements is presented. Although off-focal radiation production within X-ray tubes has been studied for medical X-ray imaging systems, its properties and its effects on dimensional measurements in industrial XCT systems have not been discussed prior to this research. The study comprises: evaluation of the geometrical properties of off-focal radiation through a theoretical and experimental study of two-dimensional projection images of the scanned objects, verification of these properties using computer simulations and evaluation of the impact of the secondary source on dimensional measurements using experimental and simulation approaches. In addition, ways to minimise the effects of off-focal radiation are discussed, and reference samples for characterising the properties of off-focal radiation are proposed.

Keywords: X-ray computed tomography, off-focal radiation, dimensional metrology

1 Introduction

X-ray computed tomography (XCT) is the technique in which X-rays are employed to generate two-dimensional (2D) projection images (radiographs) that are used to compute a three-dimensional (3D) reconstruction of an object (Greek: *Tomos* 'slice, section', and *grapho* 'to write'). The technique was developed by Hounsfield and Cormack for medical use [1]. However, in recent years XCT has found a new niche in industrial applications, where the technology is increasingly used as a dimensional metrology tool [2-10].

XCT offers advantages over traditional tactile and optical coordinate measuring systems due to its ability to detect both outer and inner geometries of an object noninvasively. However, there is a lack of confidence in the measurements due to difficulties in determining the metrological characteristics of XCT systems for uncertainty evaluation [11]. At present, many influence factors affecting measurements using XCT are still poorly understood. Unlike tactile and optical coordinate measuring

systems, there are no internationally accepted standards for performance verification and calibration of XCT [12].

In XCT systems, the quality of X-ray sources plays a vital role. In common XCT systems, X-rays are produced by X-ray tubes. A typical Coolidge X-ray tube consists of a negatively charged cathode (filament) that is used as a source of electrons, a magnetic focusing coil used to focus the beam of electrons, and a positively charged metal target (anode) used to generate X-rays, all enclosed in vacuum [13]. Electrons are emitted from the hot filament and accelerated towards the anode, where they interact with the target. There are mainly two types of targets: transmission and reflection targets [12]. However, X-ray tubes with reflection targets (Figure 1) are more prevalent in industrial XCT systems due to the ability to tolerate higher temperatures and better durability.

Figure 1. Schema of an X-ray tube with a reflection target.

The interaction of the accelerated electrons with the target not only results in the emission of X-rays but also electrons that are scattered off the surface of the target. With a reflection target (Figure 1), these electrons are scattered back to the incident beam or the vicinity of the focal spot with all or most of the original energy preserved. They are often called the backscattered electrons [14-16].

The fraction of electrons backscattered depends on the atomic number of the target material. It has been shown that the increase in the angle between the incoming electron beam and the surface normal of the target increases the backscattering effect [17]. The backscattered electrons may interact with the X-ray tube housing components, resulting in the emission of off-focal X-rays [18, 19]; this off-focal radiation is also known as 'secondary', 'extra-focal' or 'parasitic' radiation [18, 20, 21].

Off-focal radiation may cause secondary shadows around the image of the projected object(s) and reduces image contrast and can lead to ghost images [22]. The effects of off-focal radiation depend on the number of scattered electrons, the scattering direction, the distance from the target to the tube housing, the geometry and the material of the target and the housing, and the overall tube design [17, 23, 24].

The sources of off-focal radiation in X-ray tubes with a rotating anode and the impact on imaging quality have been discussed in the literature [13, 18, 20] and off-focal radiation in an X-ray tube with a transmission target has been investigated in [19]. However, to the best of our knowledge, no

literature concerning the impact of off-focal radiation on dimensional measurements in industrial cone-beam XCT has been identified prior to this study.

In this paper, we will study the effects of off-focal radiation through theoretical, experimental and simulation studies. The effects of off-focal radiation on 2D projection images and 3D reconstructed data will be shown. The influence on dimensional measurements of both single and multiple materials will be studied and methods to reduce the impact of off-focal radiation will be discussed.

2 Theoretical study of off-focal radiation

The study conducted at the National Physical Laboratory (NPL) used an industrial micro-focus cone-beam XCT system Nikon Metrology XT H 225 M, built specifically for metrological applications. In this XCT system, the tilt angle between the axis of the X-ray tube and the normal to the surface of the target is approximately 60° , for which approximately 65 % of the incoming electrons can be backscattered from a tungsten target [17, 20, 22]. No manufacturer's specification or instructions concerning the off-focal radiation are available for the X-ray tube used in the above system.

As there is very limited knowledge about the inner geometry of the X-ray tube housing, the location of the source of the off-focal radiation was estimated by comparing the size of features measured in the projection images due to the primary radiation and due to the off-focal radiation. The primary radiation source is a small spot with a diameter in the order of a few micrometres. The secondary source is expected to have an extended size as it is scattered from a larger area within the housing. The position may also deviate from the primary source.

Figure 2. The geometry of a magnified projection image produced by a secondary source.

Figure 2 shows a schematic representation of the formation of a 2D projection image of a scanned object acquired using a secondary source. d_0 is the size of the object, d_i is the size of the object at image plane due to the primary point source, f is the size of the secondary source, a is the

source-to-object distance, $(a + b)$ is the source-to-detector distance. Assuming there is off-focal radiation, a' is the distance between the off-focal plane to the object, u is the width of the penumbra due to off-focal radiation and $d_{total} = (d_l + 2u)$ is the size of the object due to the off-focal radiation on the image plane.

For a point source, the geometric magnification m of a scanned object is

$$m = \frac{a + b}{a} = \frac{d_l}{d_0}. \quad (1)$$

The derivation of geometric magnification M due to a secondary source at the primary source plane is given in [25]. For a secondary source at the off-focal plane, the geometric magnification M' is:

$$M' = \frac{f}{d_0} (m' - 1) + m' = \frac{d_{total}}{d_0}, \quad (2)$$

where $m' = (a' + b) / a'$ is the point source magnification calculated at the off-focal plane. By measuring m and M' for two or more different d_0 , f and m' can be estimated by solving equation (2). Given m' and m allow us then to estimate a and a' .

3 Experimental evaluation of off-focal radiation

In this section, the hypothesis of the off-focal radiation is studied based on 2D projection images. 2D projection images of different objects were acquired. For the steel spheres with a diameter of 0.79 mm, the secondary shadow due to off-focal radiation appeared as 'rings' around the spheres. For the larger spheres with a diameter of 2.36 mm, it is relatively noticeable that the secondary shadow is superimposed with the primary shadow, affecting the grey value of the bulk of the object material. The circular symmetry of the secondary shadows suggests that the secondary source is circular in shape and displaced from the primary source in the direction of the detector. The off-focal radiation is also non-uniform, indicated by the non-uniformity of the image shadow.

Figure 3. Illustrations of ghosting due to off-focal radiation. 2D projection images of steel spheres with the nominal diameters of (left) 0.79 mm and (right) 2.36 mm.

The position of the shadow in 2D projection images did not change when adjusting the position of the primary focal spot, which can be manipulated by altering the direction of the electron beam using dedicated steering coils. This observation supports the hypothesis that the off-focal radiation originates from a fixed structure inside the tube housing.

Based on both the theoretical and the experimental derivation, it is hypothesised that the off-focal radiation is emitted from the edge of the exit window in the target housing of about 4 mm in diameter, which is located approximately 6 mm from the primary focal spot towards the detector (Figure 4). The target housing is made of a tungsten/copper alloy, a material suitable for generating X-rays. The hatched area in Figure 4 is part of the target housing that surrounds X-rays as they exit the target assembly through the beryllium or aluminium window (shaded area). As the backscattered electrons interact with the target housing near the exit window, secondary X-ray radiation is produced. The geometry of the target housing is such that there is a greater area at the top of the housing, which results in more photons being generated at the upper portion of the housing comparing to the lower portion of the housing. Consequently, the secondary shadows are more pronounced in the lower portion of the projection image, hence explaining the non-uniformity.

Figure 4. A schematic representation of the micro-focus X-ray target assembly.

To confirm the initial hypothesis about the size and location of the origin of the secondary source, several 2D projection images of a thin steel gauge of 8.95 mm in width and a thin silicon disk of 25.4 mm in diameter were examined (Figure 5). Using equations (1) and (2) and the properties of the XCT system, the theoretical sizes of the steel gauge at three different magnification positions and the silicon disk at one magnification setting produced by the primary and the secondary sources in the images were calculated. These theoretical values were then compared with the experimentally measured values of the images due to the primary and the secondary sources. A secondary source of 3.8 mm diameter located 6 mm in front of the primary focal spot was used in the calculations. Data presented in Table 1 shows that the experimentally measured values of the image sizes were in good agreement with the theoretical values.

a)

b)

Figure 5. Projection images of a steel gauge (a) and a silicon disk (b). In both images, the white dashed lines indicate image edges due to the primary source and the black dashed lines indicate those due to the secondary source.

Table 1. Summary of the experimentally measured and theoretically calculated image sizes of the steel gauge and the silicon disk produced by primary and secondary sources.

	Magnification due to primary source	Measured image size due to primary source/ pixels	Theoretical image size due to primary source/ pixels	Measured image size due to secondary source/ pixels	Theoretical image size due to secondary source/ pixels
Steel gauge	7.0	314	317.0	430	429.7
Steel gauge	10.0	446	446.4	648	646.9
Steel gauge	13.8	622	620.6	923	926.3
Silicon disk	6.9	894	892.3	1029	1026.7

3.1 Development of a reference sample to evaluate non-uniformity

In addition to the spherical reference samples and the steel gauge, an object named ‘the wheel’ was designed and manufactured to investigate the radial non-uniformity of the off-focal radiation. This object consists of six crossed steel wires that are fixed inside of an aluminium cylinder (Figure 6 left). The diameter of the wires is 0.9 mm, and the inner diameter of the cylinder is 78 mm. The benefit of using the wheel reference sample is to allow the user to quickly identify the pattern of intensity non-uniformity due to the off-focal radiation. For example, the projection image of the wheel using the XCT system at NPL was more prominent in the lower portion of the projection image (Figure 6 right), confirming the hypothesis postulated in section 2.2.

Figure 6. Projection images of the wheel reference sample. Left. Original projection image of the wheel; Right. A magnified image of the wheel scanned at the same settings, with contrast adjusted for secondary image visibility.

4 Comparison between simulated and experimental 2D projection images

To support the initial postulate regarding the size and the location of the off-focal radiation, a computer simulation study was conducted. Simulations of 2D projection images of spheres were performed in Matlab using the analytical ray-tracing method. All simulations were produced using a monochromatic X-ray attenuation model. The off-focal radiation was achieved by simulating a circular source of 3.8 mm diameter, displaced from the primary source by 6 mm along the X-ray beam axis towards the detector. The intensity of the simulated secondary source was set to 10 % of the primary intensity, which was in good agreement with experimental data.

Figure 7 shows a simulated projection image of an iron sphere 6.36 mm in diameter in the presence of the primary and the off-focal radiation. Adjusting the image contrast allows the effects of the off-focal radiation to be clearly visible. Ghosting can be seen surrounding the sphere, with further contrast adjustments exposing a 'dark core' inside the sphere, which is the projection image due to the primary radiation superimposed with the projection image due to the off-focal radiation. The simulated image is in close agreement with the real image of a steel sphere of 6.36 mm in diameter, acquired on the XCT system. Figure 8 shows the experimental image; the contrast is adjusted to show the ghosting and then the 'dark core'. The sizes of the images due to the primary source and the secondary source in both simulated and experimental images were calculated and are summarised in Table 2. The images were analysed using Matlab and ImageJ (an open-source image processing software developed by the National Institutes of Health, <http://imagej.nih.gov/>).

Figure 7. A simulated image of a steel sphere of 6.36 mm in diameter; a) original image; b) the same image with grey values adjusted for shadow visibility, here the white dashed line shows the image due to the primary source, and the grey dashed line shows the secondary shadow; c) the same image with grey values adjusted for the 'dark core' visibility, here the grey dashed line shows the 'dark core effect' due to the off-focal radiation.

Figure 8. An experimental image of a steel sphere of 6.36 mm in diameter; a) original projection image; b) the same image with grey values adjusted for shadow visibility, here the white dashed line shows the image due to the primary source, and the grey dashed line shows the secondary shadow; c) the same image with grey values adjusted for the 'dark core' visibility, here the grey dashed line shows the 'dark core effect' due to the off-focal radiation.

Table 2. Diameters of images due to the primary and secondary sources in experimental and simulated images.

	Diameter of the sphere due to the primary source/ pixels	Diameter of the shadow due to the secondary source/ pixels	Diameter of the core due to the secondary source/ pixels
Experimental image	284	456	138
Simulated image	286	458	139

Although some degree of uncertainties existed due to the boundary definition in the image processing, the diameter values in the experimental and the simulated images are in good agreement. This observation further supports the initial postulate that in the XCT system used in this study, the off-focal X-rays are produced by the interaction of backscattered electrons with the exiting window of the tube housing with diameter and position as simulated. The investigations have shown clearly that the off-focal radiation affects the immediate background, edges, and internal portions of the projected object. The comparison also demonstrated the effectiveness of using the simulation approach to investigate the impact of off-focal radiation.

5 Effects of off-focal radiation on dimensional measurements

In this section, both simulation and experimental approaches were used to study the impact of the off-focal radiation on dimensional measurements. The experimental approach was considered to investigate the impact of the off-focal radiation on the single sphere and single material object. The simulation approach was used for more complicated cases where multiple spheres and multiple materials were considered.

In each simulation or experimental scan, a set of 3142 projection images were acquired of the scanned objects as they were rotated 360 ° on the sample stage. Tomographic reconstruction of the sphere objects was performed using Nikon CT Pro 3D software. The 3D volumes of the reconstructed objects were analysed using VGStudio MAX version 2.2. The iso-surfaces of the objects were identified by 'automatic' and 'advanced' surface determination techniques available in the VG Studio software. The 'automatic' technique, also known as ISO-50 % [7], identifies a surface by calculating the average between the mean grey value of the background and that of the material. In the 'advanced' technique, the surface is further refined by identifying the highest local grey value gradient within the specified number of search voxels from the ISO-50 surface. Subsequently, spheres were fitted to ISO-surfaces using a Gaussian least-squares fit with 1 000 sampling points. This enabled the calculation of sphere diameters and the range of the radial residuals to the fit, i.e. the apparent form error of the reconstructed spheres. The diameter and form error of the sphere and, where appropriate, the centre to centre length (distance between the centres of spheres) and bidirectional distances between spheres (bidirectional length measurement is created using the probing of two surfaces at two single points where the direction of the two surface normals is opposite [26, 27]) of the simulated volumetric data using the primary source only were compared to those using the combination of the primary and secondary sources.

5.1 Effects of off-focal radiation on the 3D scan of a single sphere

The effects of off-focal radiation on the reconstructed 3D volume of a 5 mm diameter steel sphere were studied experimentally. As expected, all 2D images were affected by the presence of the off-focal radiation (Figure 9). The diameter of the tomographically reconstructed sphere (Figure 10) was 4.993 mm, with a form error of 6.7 µm.

Figure 9. XCT projection images of a 5 mm steel sphere. a) An image of a steel sphere 5 mm in diameter; b) the same image with grey values adjusted for visualising the secondary shadow; c) the same image with grey values adjusted for visualising the 'dark core'.

Figure 10. Scan results of the 5 mm steel sphere sample. a) A 3D volume of the steel sphere; b) a 2D slice through the 3D volume with surfaces fitted to the outer boundary and the inner 'pseudo-boundary' inside the sphere; a profile through the centre of the 2D slice is marked in green; c) grey values along the profile line.

The analysis shows that the secondary shadow observed in the immediate background of the imaged sphere has little influence on the reconstruction of the sphere's outer surface. On the other hand, the presence of the dark core in the 2D images appears to have a significant effect inside the 3D volume, as it results in non-uniformity of reconstructed grey values (Figure 10b and Figure 10c). These observations confirm that the secondary source can have an adverse effect on the reconstructed 3D models and can lead to errors in reconstructed grey values.

5.2 Effects on measurements of multiple objects

The following acquisitions comprising iron spheres were simulated:

- 1) two spheres of 2 mm diameter with a 2 mm distance between their centres,
- 2) two spheres of 4 mm diameter with a 5 mm distance between their centres,

3) two spheres of 5 mm diameter with a 6 mm distance between their centres.

The simulations were performed once with only the primary source and again with both the primary and the secondary sources. The measurement results are summarised in Table 3.

Figure 11. Simulated projections of two iron spheres 4 mm in diameter with a 5 mm distance between their centres. a) A projection image using the primary and the secondary sources (the yellow arrow shows a centre to centre distance and the green arrow shows a bi-directional distance); b) A projection image with the grey values adjusted for shadow visibility; c) 2D cross-sectional view through the 3D reconstructed volume (the appearance of pseudo-objects inside the spheres is clearly visible); d) cross-sectional view through the 3D reconstructed volume using the primary source only; e) grey level profiles along the red line in c) and the blue line in d).

Figure 11a shows a 2D image of the two 4 mm diameter spheres, simulated using both the primary and the secondary sources. The effects of the off-focal radiation are clearly visible (Figure 11b). The analysis with and without the secondary source (Figure 11c and d, respectively) shows that although the presence of the off-focal radiation changes the grey level values of the background and the inside of the sphere (Figure 11e), the diameter, form error and centre to centre and bi-directional

distance measurements appears to be largely unaffected. The results of the diameter and form error measurements of two-sphere objects are summarised in Table 3.

Table 3. A comparison of dimensional measurements performed on the reconstructions the two-sphere objects. The diameter, form error, centre to centre and bi-directional distances were measured for sphere surfaces determined using the advanced (Adv.) and automatic (ISO-50 %) surface determination techniques.

Simulated spheres				Magnifi- cation	Voxel size/ μm	Sphere1				Sphere2				Calculated distances/ mm			
	Diameter / mm	Centre to centre distance/ mm	Bi- directional distance/ mm			Diameter/m m		Form error/ μm		Diameter/m m		Form error/ μm		Centre to centre		Bi-directional	
						Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%	Adv.	ISO- 50%
Primary source only	2.000	2.000	4.000	10	20.0	1.998	2.031	9.2	12.4	1.998	2.031	9.3	15.4	2.000	2.001	3.998	3.998
Primary and secondary sources	2.000	2.000	4.000	10	20.0	1.998	1.999	9.5	9.9	1.998	1.999	9.5	9.7	2.000	2.000	3.998	3.998
Primary source only	4.000	5.000	9.000	10	20.0	4.001	4.001	7.2	7.3	4.001	4.001	7.2	7.3	5.001	5.001	9.002	9.002
Primary and secondary sources	4.000	5.000	9.000	10	20.0	4.001	4.001	6.9	6.6	4.001	4.001	6.5	6.6	5.001	5.000	9.001	9.000
Primary source only	5.000	6.000	11.000	15	13.3	5.001	5.000	9.3	9.9	5.001	5.038	9.2	14.8	5.999	5.998	11.018	11.015
Primary and secondary sources	5.000	6.000	11.000	15	13.3	5.001	5.001	8.6	9.4	5.001	5.001	8.6	9.4	5.999	5.998	11.012	11.012

The preliminary results from the simulation of the two-sphere objects suggest that although the presence of off-focal radiation degrades the quality of 2D images, the effect on the measurement of simple single material objects such as spheres is insignificant.

5.3 Effects on measurements of multi-material objects

In order to investigate the effects of the off-focal radiation on the dimensional measurement of a simple multi-material object, the following acquisitions were simulated and analysed:

- 1) an iron sphere of 6 mm diameter using the primary source only;
- 2) the same object as in 1), using the combined primary and secondary sources;
- 3) an object with an outer iron sphere of 6 mm diameter and an inner aluminium sphere of 2.5 mm diameter using the primary source only;
- 4) the same object, as in 3), using the combined primary and secondary sources.

The results are summarised in Table 4.

Table 4. A comparison of 3D volumes of the iron (Fe) and aluminium (Al) spheres. The diameter and form error of spheres were measured for surfaces determined using the advanced (Adv.) and automatic (ISO-50 %) surface determination techniques.

	Simulated sphere diameter/mm	Diameter/mm		Form error/ μm	
		Adv.	ISO-50%	Adv.	ISO-50%
Primary source only:					
-sphere material Fe	6.000	6.000	6.000	14.035	14.268
Primary and secondary sources:					
-sphere material Fe	6.000	6.001	6.001	13.112	13.570
-pseudo-inner sphere		2.726		18.041	
Primary source only:					
-outer sphere material Fe	6.000	6.001	6.001	12.951	13.499
-inner sphere material Al	2.500	2.499		16.061	
Primary and secondary sources:					
-outer sphere material Fe	6.000	5.999	5.998	14.181	14.289
-inner sphere material Al	2.500	2.717		8.391	

As with the simulations of the two-sphere objects, the measurements of the diameter and form error of the iron sphere do not appear to be significantly affected by the secondary source. When analysing the diameter of the inner aluminium sphere, the situation is different. When the object with the outer (iron) and the inner (aluminium) spheres was simulated using the primary source only, the diameter of the inner sphere in the 3D reconstruction was calculated to be 2.499 mm. When this object was simulated using both the primary and the secondary sources, the inner sphere diameter was calculated to be 2.717 mm. The value of 2.717 mm is close to the value of 2.726 mm, which is the diameter of the pseudo-sphere identified inside the iron sphere that was simulated using the primary and the secondary sources of the single material sphere. The reason for such values becomes apparent when analysing the profiles through the 2D slices of the three reconstructed volumes (Figure 12): the presence of the off-focal radiation distorts the real boundary between iron and aluminium materials in the object (dashed grey line), resulting in the false boundary identification (solid grey line). This finding supports the proposition that off-focal radiation can increase measurement errors for complex multi-material objects.

Figure 12. Profiles taken through the centre of the 2D slices of 3D volumes reconstructed from image stacks of: an iron sphere of 6 mm diameter, simulated using both the primary and the secondary sources (green profile); an object with an outer iron sphere of 6 mm diameter and an inner aluminium sphere of 2.5 mm diameter, simulated using the primary source only (red profile); and the same object, simulated using the primary and the secondary sources (blue profile). The dashed grey line represents a position of the real iron/aluminium border, and the solid grey line represents a false iron/aluminium border.

6 Possible correction methods

There are a number of methods that can minimise the intensity of off-focal radiation and its effects. One common solution is the hardware method in which additional collimators (often made of lead) are installed in the path of the X-ray beam, to stop off-focal radiation from penetrating the object [28]. This method is particularly widespread in medical XCT, as it not only improves the image quality but most importantly reduces exposure to radiation. The presence of such collimators is often required by the health and safety standards [4]. However, the reduction of radiation is a drawback to industrial XCT. Furthermore, the presence of the collimator also limits the field of view, which can negatively affect the system's scanning versatility. Users should consider whether the use of additional collimating devices is beneficial for a given scanning task.

Figure 13 demonstrates the improvement of measurements using the hardware method. A 2D image of an object made with four crossed metal wires has been imaged without and with a collimator. Figure 13a is the projection image without a collimator, and Figure 13b shows the same object scanned at the same settings but with an added tungsten aperture of 3 mm diameter and 4 mm thickness placed in front of the exiting window. It is clear that the effects of off-focal radiation were reduced; as expected, the overall brightness of the image scanned with the aperture was also reduced (Figure 13c).

Figure 13. Hardware correction of off-focal radiation using a collimator. a) An image of the object made with four crossed metal wires; b) an image of the same object with the same settings scanned using a collimator (a tungsten aperture of 3 mm diameter and 4 mm thickness); c) a comparison of the profiles taken through one of the wires in the image without collimator (red) and with collimator (blue).

Another method is the software correction method [29], where the error due to the off-focal radiation is estimated by convoluting the projection image with the secondary source. This is based on the assumption that each 2D image is a combination of the images due to the primary and the secondary sources. The aim is to eliminate the image due to the secondary source from each 2D image [6]. Although the software correction of individual 2D projection images can reduce the effects of off-focal radiation, this method has a number of limitations. In order to remove the effect completely, the exact position, size and shape of the secondary source needs to be known. As shown in this study, a reasonable estimate of the secondary source size and position can be achieved, but some degree of approximation is always present. The intensities of the images due to the secondary source is also estimated depending on a number of factors. Precise knowledge of these factors is essential to eliminate the effects of off-focal radiation using the software correction method, but often impossible to obtain. The software correction method can reduce the effect, but cannot

eliminate the error entirely [29]. Due to the reasons mentioned above, the software correction method is, therefore, not robust and will not be considered further.

A third method of reducing the effect of off-focal radiation is through adjusting the design of the X-ray tube and the tube housing in particular. Since the off-focal radiation is generated by the interaction of backscattered electrons with the housing material, it is proposed to shield the inner part of the housing close to the exiting window with a soft material, such as aluminium. Aluminium is often a material of choice in electron shielding [30]. Since the number of backscattered electrons increases rapidly with the increased angle between the incoming electron beam and the target material, it is also possible to reduce backscatter by changing the tilt angle.

7 Conclusions

In this paper, off-focal radiation in an industrial X-ray tube has been investigated, and the effects on dimensional measurements have been studied. A secondary source that causes off-focal radiation may be generated in an X-ray tube due to scattering of electrons in the target housing. The position, size and shape of the secondary source can be estimated from projections of simple reference objects. The secondary source can result in noticeable shadowing effects and grey value variations in the tomographic reconstruction of a single material object. For multi-material objects, image artefacts due to off-focal radiation have been shown to influence dimensional measurements.

Based on the findings of this study, it is recommended that the evaluation of the properties of the off-focal radiation, such as its location, size, shape and intensity, is included as a part of the overall qualification procedure of the X-ray tube. Further research should include the investigation of the effects of off-focal radiation on dimensional measurements of multi-material objects of complex geometries. Several ways to minimise the off-focal radiation were discussed, although none of these methods is ideal. Further study should be conducted to investigate the correction methods.

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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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