Material Dependent Thresholding for Dimensional X-ray Computed Tomography

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Abstract. Recently, the use of Computed Tomography for dimensional metrology has been emerging as a new application field. This new application domain calls for micron-level accuracy and traceability to the unit of length. Unfortunately, CT images inherently bear many artifacts, such as beam hardening and scattering noise. Moreover, the partial volume effect hinders accurate thresholding, which limits the achievable accuracy of CT dimensional metrology. Until now, the edge detection of single material workpieces in CT imaging commonly relies on the 50% iso-surface global thresholding method. In addition, advanced ‘local thresholding’ methods have been developed to reduce some artifacts and to improve CT model surface quality. Yet often, neither method can define the ‘exact’ edge, hence resulting in dimensional errors. This paper reports on material dependent thresholding. The position of the edge is shifted along the gray value histogram between the background (air) and material peaks, in order to check which value yields the most accurate dimensions, hence the most correct edge. The influences of material type on the exact edge location in the gray value histogram are presented. Application of this method on different materials has yielded consistent results.

1. Introduction

The use of X-ray Computed Tomography (CT) in the medical imaging field dates back to the early 1970’s, and since the 1980’s CT has become more and more popular for material analysis and non-destructive testing. Because of its capabilities to provide geometric information of inner and hidden structures of e.g. additive manufactured or assembled parts, CT has recently gained interest in the area of dimensional metrology. However, CT is inherently vulnerable to many influential factors. For example, the beam hardening effect, which arises due to the polychromatic character of the used X-ray spectrum, causes cupping and streak artifacts, and strongly affects the imaging quality. In addition, the partial volume effect, caused by a limited resolution, complicates the segmentation between material and background, which is crucial for accurate dimensional measurements.

In order to develop CT into a powerful tool for dimensional metrology, a number of attempts to quantify the achievable accuracy of CT measurements are found in literature. Clark suggests a simple but general rule for calculating the accuracy of an industrial micro-focus CT system, which is approximately 1/3 of the voxel size [1]. Carmignato et al. have developed a test specimen with shaft and hole structures to determine the threshold value and report the dimensional deviations to be within ±4μm for a voxel size of 9μm [2].

Suppes and Neuser claim that proper beam hardening correction and surface extraction methods reduce the deviations on diameters to less than 10% of the voxel size, whereas distance deviations can be lower than 1/50 of the voxel size [3]. All above results indicate a promising future for CT in the metrology field. However, most tests are done using workpieces with certain "easy" features, such as parallel planes, cylindrical shafts and holes, and spheres. Due to the large amount of influencing factors, including workpiece material characteristics, variable penetration depths, scattering noise, beam hardening, filter usage, resolution, magnification, X-ray power, etc., it remains a major challenge to directly transfer the measurement accuracy of such test objects to real industrial workpieces.

A very important choice one has to make when analyzing CT data is the thresholding method. Thresholding directly determines the extracted surface, hence strongly influences the measurement accuracy. Global thresholding methods use the information on gray value histograms to select a particular gray value as representation for the measurand's edge (Fig 1). In addition, many "advanced" local thresholding methods have been developed. Abutaleb et al. suggest a local thresholding method which depends on the joint (2D) entropy of a pixel neighbourhood [4, 5]. Similarly, White and Rohrer developed a method in which the pixel's gray value is compared with the average of the gray values in its neighbourhood [6]. This local thresholding method has been adapted by Niblack, using the local mean and standard deviation over a sliding window [7]. Many papers have claimed that using local thresholding methods can significantly improve the image quality of a CT 3D model as well as the measurement accuracy compared to global thresholding methods. Nevertheless, other authors state that no systematic improvements can be found between local and global thresholding methods with respect to the achievable accuracy (e.g. Kerckhofs [8]). Moreover, for multi-material measurands or when reconstruction artifacts are not negligible, most adaptive thresholding methods perform worse than global thresholding methods, since the former are more vulnerable to local variations originating from these artifacts [9].

2. Comparison between Local Thresholding and Global Thresholding

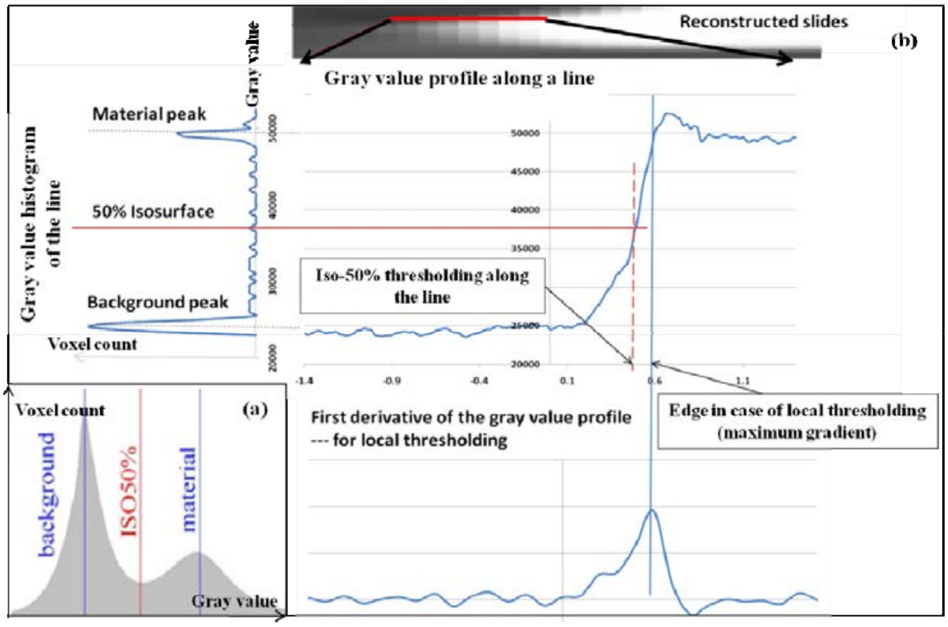


Figure 1. (a) 50% isosurface global thresholding method; (b): Working principle of the local thresholding method on a reconstructed slides

Until now, no single thresholding method has been demonstrated to be suitable for all situations. Within our research, two thresholding methods are frequently used: a “simple” global and a local adaptive method. The 50% isosurface global thresholding method defines the middle gray value between background and material peaks in the gray value histogram as material boundary (Fig 1a). The local adaptive method starts from a preliminary surface determined by the global thresholding algorithm. Subsequently, the algorithm searches perpendicularly to the preliminary surface within a predefined search zone at either side while looking for a sharp change in grey level denoting the edge (Fig 1b). Sub-voxel interpolation is used to improve the resolution. Generally speaking, local thresholding methods are more time consuming than global thresholding methods. In this section, both methods are compared using two criteria: the image quality of the 3D model and the accuracy of the dimensional measurements.

2.1 Image Quality

As mentioned previously, the local thresholding method re-interprets the boundary gray value differently depending on the surrounding voxels. Theoretically, the object surface determined by this procedure can be smoother than the surface determined by a global thresholding method, because local deviations due to beam hardening or other artifacts will be largely compensated for. This has been proven by the repeatability of feature fitting, distance and thickness measurements. If the CT scan has non-overwhelming artifacts, measuring the same distance 20 times on the isosurface leads to a variation of ca. 1μm on the distance of 35mm with the voxel resolution of 30μm; when applying the local adaptive thresholding method, the variation is not detectable. However, in many applications dealing with multi-material objects, non-negligible artifacts, or scans with low signal to noise ratio due to limited X-ray power, the local thresholding method further increases the noise instead of improving the image quality (Fig 2, 3).

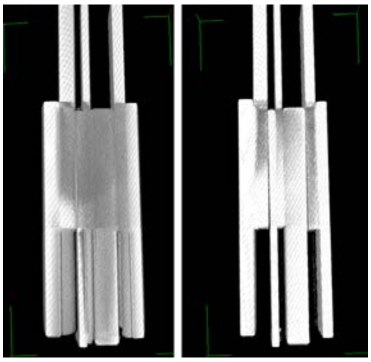


Figure 2. Ceramic (ZrO_2) gauge blocks (top) and steel gauge blocks (bottom) of various thicknesses scanned together. Left: local thresholding; Right: global thresholding.

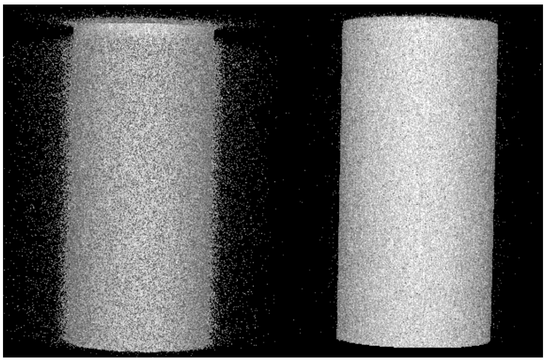


Figure 3. Aluminium cylinder. Left: local thresholding; Right: global thresholding.

2.2 Measurement Accuracy

In many cases, the local adaptive thresholding method leads to a better accuracy compared to the 50% isosurface global thresholding method. However, when shifting the isosurface to lower or higher gray values (Fig 1a), accuracy improvements can be detected as illustrated in Figure 4. Three stainless steel spheres (diameter: 2.5mm, 4mm, 6mm; guaranteed tolerance limits +/- 2 µm) are scanned together in one setup. The deviations on the diameters (measured value on the segmented CT-model minus the nominal dimension) are plotted as a function of the thresholding value. The figure shows that local thresholding gives more accurate results than 50% global thresholding. However, by adapting the gray value of the isosurface in the histogram, the measurement errors can be reduced down to ±3µm if the gray value of the isosurface is chosen at ca. 80% in the histogram. In this case, this is similar or even better than the results of local thresholding. The distance between the lines on Fig. 4 is, however, dependent on object, settings and machine characteristics.

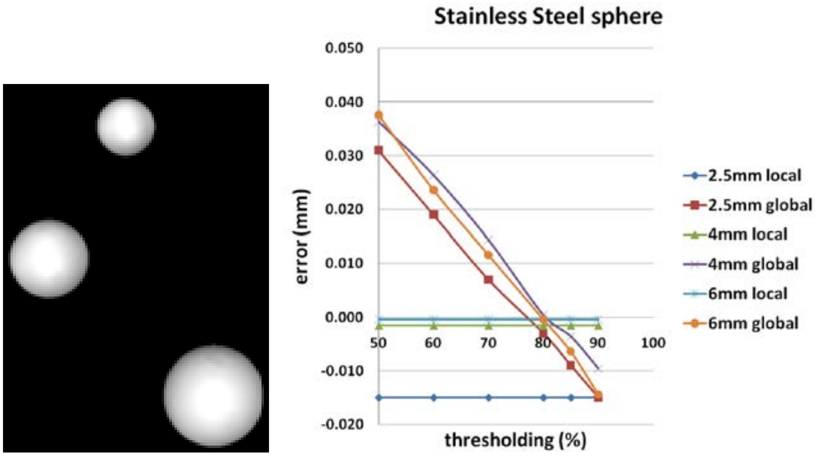


Figure 4. Comparison of the measurement results of local and global thresholding methods, 23µm voxel size

3. Investigation on the Material Dependent Global Thresholding Method

Figure 4 shows that the 50% isosurface makes the stainless steel spheres appear larger on the CT-model than their actual dimension. This section investigates whether this holds true for all materials and geometries.

3.1 Measurements of Steel or ZrO_2 Objects

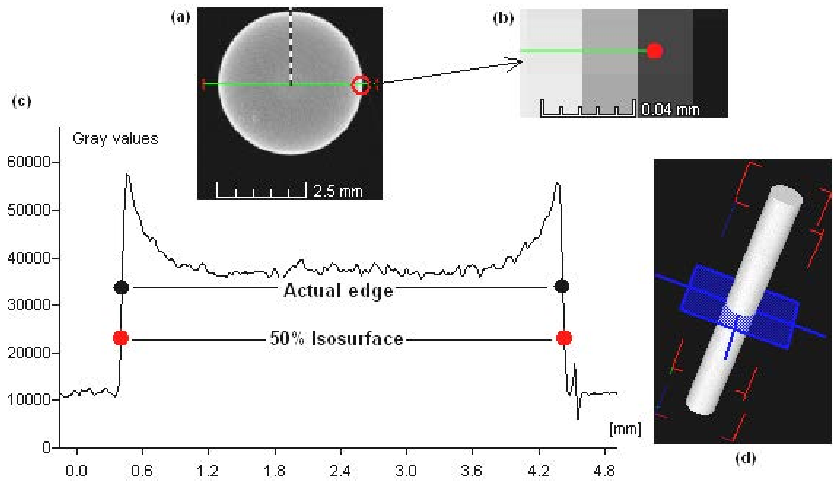


Figure 5. (a) Reconstructed slides of a stainless steel cylinder; (b) close-up of the edge. The red dot represents the position of the edge defined by the 50% isosurface; (c) gray value profile along the green line in “a”; (d) 3D model of the Ø4mm stainless steel cylinder after thresholding

Figure 5 shows results of a CT measurement of a stainless steel cylinder with diameter 4mm and guaranteed tolerance range of ±1µm. Due to severe beam hardening artifacts, steel is a rather “difficult” material for CT metrology. The voxels near the edge are characterized by much higher gray values than the voxels inside the object model. This is commonly referred to as the cupping effect (Fig 5c). As a consequence, the gray value of the surrounding air near the material edge is also raised significantly due to the non-zero voxel size and linear interpolation. When searching for the material edge around the 50% isosurface, the object model will appear larger than it is in reality. Figure 5c shows that the gray value of the "accurate" material edge (based on the nominal value of the cylinder diameter) is higher than the 50% value between material and background peaks; i.e., for steel, the gray value of the actual boundary is closer to the material peak. This is in accordance to Figure 4.

Zirconium dioxide (ZrO_2) is a ceramic material, used to manufacture accurate gauge blocks. The density of ZrO_2 is somewhat lower than for steel, but due to its larger molecule ZrO_2 actually attenuates X-rays more. Thus, ZrO_2 parts also suffer from severe beam hardening. Moreover, a lot of scattering and diffraction induced noise has been detected on CT scans of ZrO_2 gauge blocks due to their flat surfaces. Figure 6 shows the CT measurement results of six ZrO_2 gauge blocks with thicknesses ranging from 3mm to 8mm. Each gauge blocks is scanned separately under the same conditions (voltage, current, magnification etc). As can be expected, all measured thicknesses are larger than the real value when applying 50% global thresholding. Due to the scattering noise around the flat planes, the local thresholding method doesn't allow measuring. Since the gray value of the noise is mostly closer to the background peak than the real material edge, the surface quality improves when shifting the thresholding gray value towards the material peak. The "accurate" edge can be found around 100% (material peak in the histogram), at this level all deviations are within ±10μm.

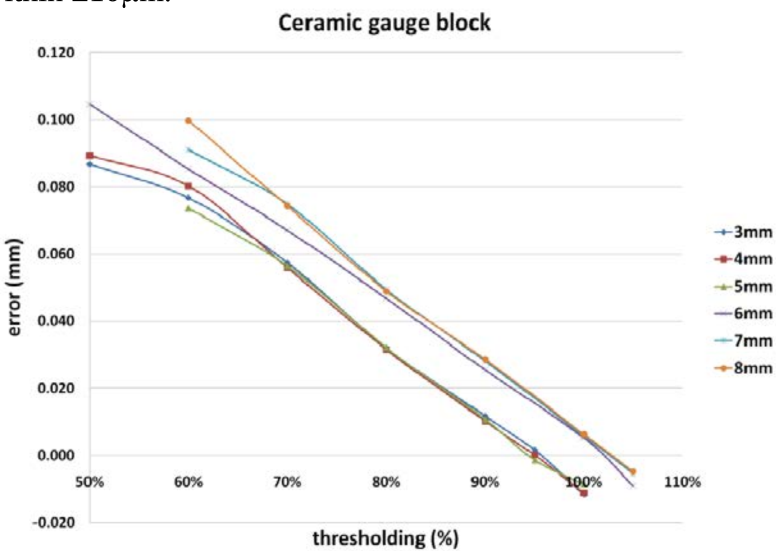


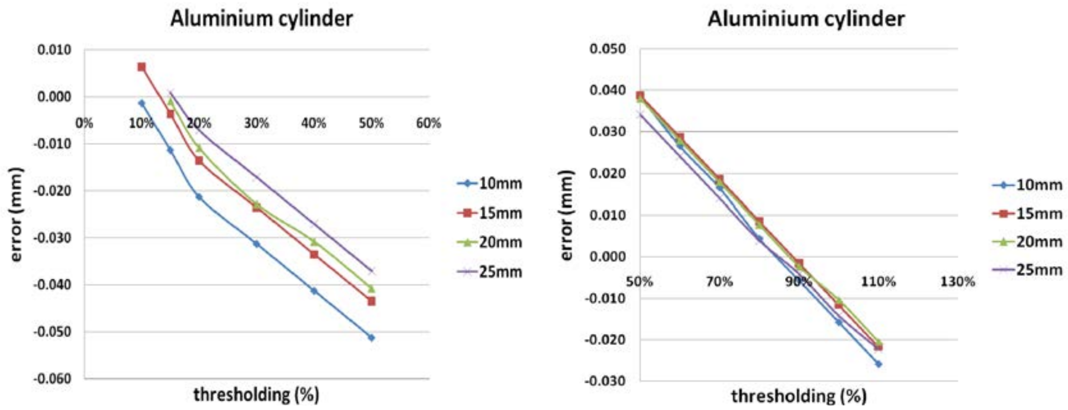
Figure 6. CT measurements of 6 ceramic gauge blocks, voxel size is 21μm

3.2 Measurements of Aluminium Objects

Since the X-ray attenuation of aluminium is significantly lower than that of steel, aluminium parts suffer less beam hardening artifacts if appropriate settings are chosen. Hence, the gray value of the voxels around the boundary is raised significantly less (compare Fig 8c to Fig 5c). The actual edge location of aluminium workpieces is thus very different from that of steel.

Four aluminium cylinders with diameters ranging from 10mm to 25mm and accuracies below 10 microns were measured with the same machine settings: X-ray voltage current, magnification etc., but on different CT machines which were equipped with a similar 225kV source but different detectors: Varian 2520 (Fig 7a) which detects X-ray energies from 40 keV- 150 keV and Perkin Elmer 1621 (Fig 7b) which is suitable for X-ray energies from 20 keV- 450. Whereas the former yields little beam hardening (Fig 7a), the latter yields more severe beam hardening (Fig 7b).

As shown in Figure 7a, in contrast to the conclusions for steel, all cylinders appear smaller than their real dimensions when applying the 50% isosurface thresholding method. In order to search for the accurate edge, the gray value of the isosurface has been shifted towards the background peak in the histogram. All curves converge at around 15%, where the errors for all cylinders are within ±10μm.



(a) **(b)**

Figure 7. CT measurement of 4 Aluminium cylinders: (a) without obvious beamhardening; and (b) with obvious beamhardening; Voxel size is 23μm

Figure 8 shows the gray value profile of a line which crosses a reconstructed slide of a cylinder. It is obvious that the actual material edge is located within the first voxel where the gray value starts to increase rapidly. For the other three aluminium cylinders, similar results have been found.

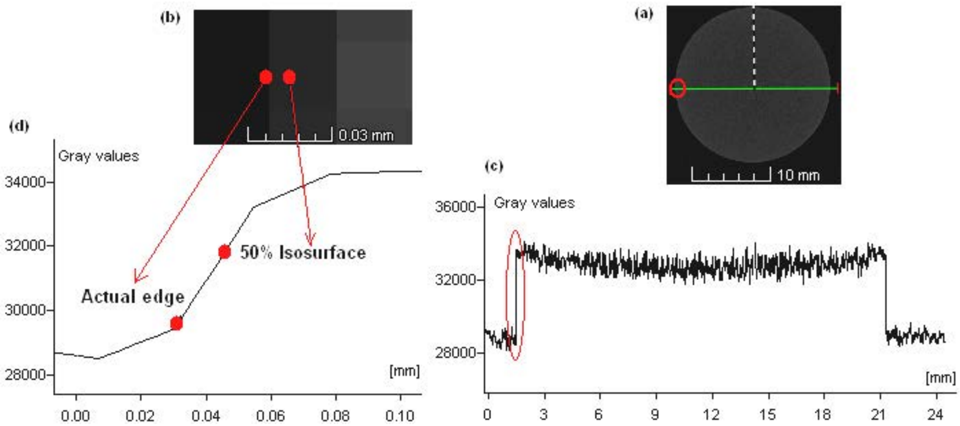


Figure 8. (a) Reconstructed slides of an aluminium cylinder measured without obvious beam hardening; (b) Close-up of the edge. The red dot on the right side represents the location of the edge defined by the 50% isosurface; (c) Gray value profile along green line in (a); (d) Close-up of the boundary transition in (c)

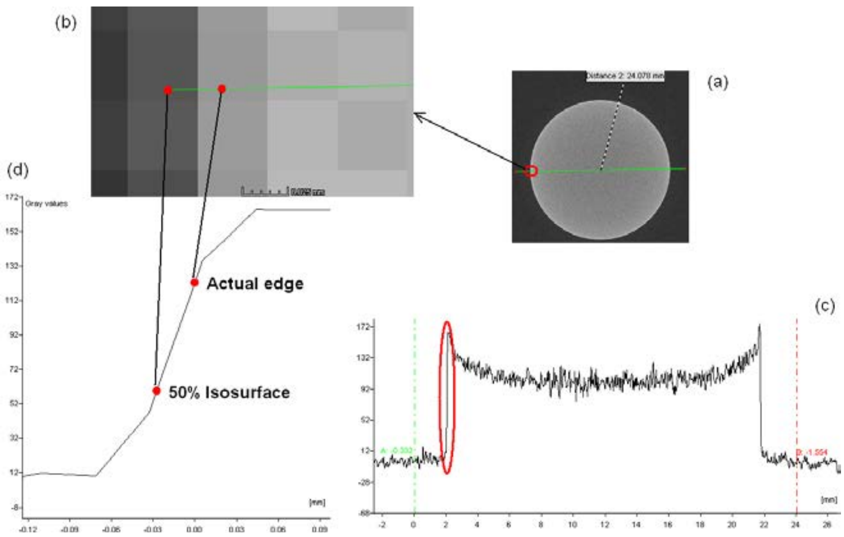


Figure 9. (a) Reconstructed slides of an aluminium cylinder measured with obvious beam hardening; (b) Close-up of the edge; (c) Gray value profile along green line in (a); (d) The boundary transition in (c)

However, if aluminium parts are scanned using lower x-ray powers or detectors with higher sensitivity for low energy photons, obvious cupping effect can also be found (Fig 9). One notices that in this case, the actual material edge location is similar to that of steel (Fig 7b).

3.3 Simultaneous Measurements of Steel and Aluminium Objects

The previous sections leads to the hypothesis that, in the presence of severe beam hardening, the accurate edge location is closer to the material peak in the histogram, whereas in absence of cupping effects the accurate edge is closer to the background peak. This section discusses whether this hypothesis can be confirmed when analysing measurements featuring both steel and aluminium objects simultaneously in a single setup. Similar to the situation in Figure 7, the measurements of Figure 10 and Figure 11 have also been performed on different machines. One is equipped with the Perkin Elmer 1621 detector (Fig 10), the other one with the Varian 2520 detector (Fig 11).

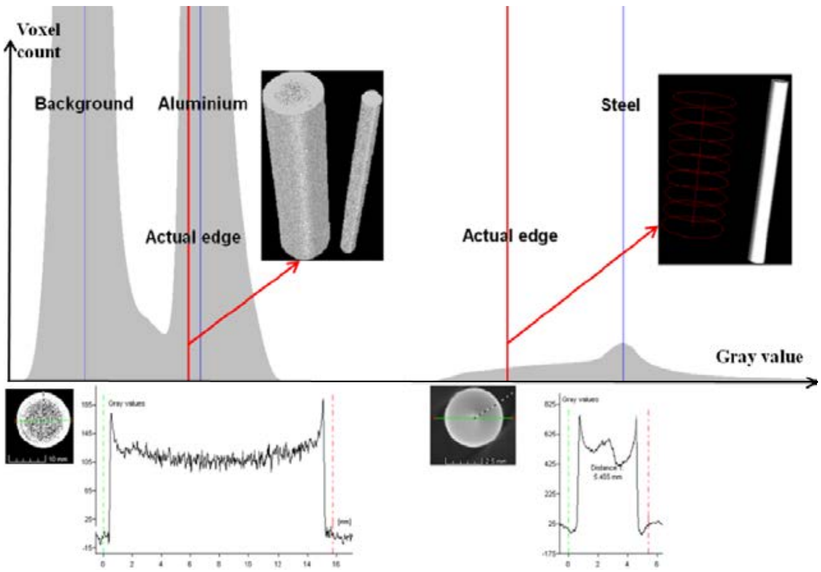


Figure 10. Aluminium (left) and steel (right) parts scanned together; both have severe beamhardening artifacts

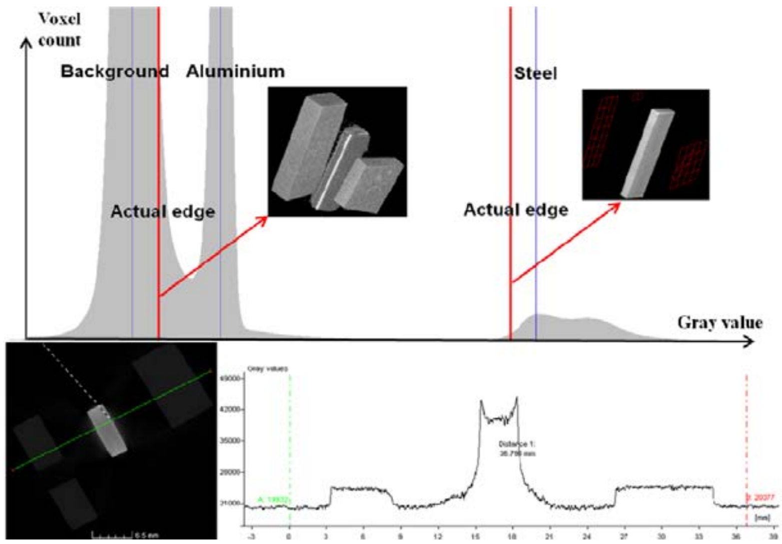


Figure 11. Aluminium and steel (middle) parts scanned together; only steel has severe beamhardening artifacts

Figure 10 demonstrates obvious cupping effects on both steel and aluminium parts. When identifying the gray values corresponding to the correct edge, both material edges are located close to their respective material peaks. In addition, when applying the global thresholding method using the aluminium edge as the isosurface, the aluminium workpiece can be measured accurately whereas the surface of the steel workpiece is surrounded with large amounts of noise. Applying local thresholding even increases the noise. On the other hand, when thresholding with the gray value characteristic for the steel edge, the aluminium workpiece totally disappears and the surface of the steel workpiece becomes smooth and accurate. For the measurement shown in Figure 11, only the steel is characterized by obvious cupping effects, whereas the aluminium does not. When searching for the correct edge of the aluminium part, the segmentation grey value needs to be shifted to the left side, i.e. closer to the background peak in the histogram. This confirms the hypothesis stated in Section 3.2. The grey value characterizing the steel part remains close to the steel peak in the histogram.

4. Conclusion and Discussion

Many local thresholding methods have been developed to improve the image quality and the accuracy of CT metrology. However, local thresholding methods are very vulnerable to yet non-removable artifacts and in many cases are not proven to be more accurate than global thresholding. On the other hand, although 50% isosurface is in most cases inaccurate, the accuracy can be significantly improved by shifting the thresholding value; for all experiments mentioned in this paper, thresholding regions can be found where all errors fall within 10μm. Furthermore, the paper demonstrates that the accurate edge location is largely material dependent and even beam hardening dependent. Under the presence of severe beam hardening, the actual edge stays closer to the material peak. If less attenuating materials are scanned with equipment and settings resulting in non-obvious beamhardening artifacts, the actual edge is often found in the voxels where rapid increasing of the gray values starts. This is also applicable for multi-material cases. Although the single isosurface thresholding method cannot create nice 3D models for multi-material objects, it does provide a way to accurately measure components of different materials separately. Further research is necessary to confirm the current findings and to implement them into useful algorithms for segmentation. In addition, local and global thresholding methods could be combined by first using global thresholding to locate the edge depending on material type and beam hardening level, and subsequently applying local thresholding to improve the image quality.

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