3-in-1 X-ray Computed Tomography

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Abstract
For over 30 years, X-ray Computed Tomography (CT) has been used for Non-Destructive Testing (NDT) of manufactured components for validation of internal integrity [1]. More recently the first X-ray CT systems dedicated to dimensional metrology applications have reached the market. Since then, the field of dimensional X-ray CT has gained much interest, especially for inspection of Additively Manufactured (AM) components [2]. This novel manufacturing route has brought new challenges for inspection due to internal or inaccessible features and unique surface characteristics. Recent research has demonstrated the feasibility for surface metrology with commercially available micro-CT systems [3] [4]. The potential for performing dimensional, integrity and surface analysis within a single process has made X-ray CT highly desirable for AM inspection. Further innovation is required however, in order to produce a commercial hardware and software that can complete the complex workflow required for 3-in-1 inspection.

Keywords: X-ray, Computed Tomography, Surface Metrology, NDT Inspection, Additive Manufacturing

1 Introduction
The 3-in-1 X-ray CT project has developed the capability to perform dimensional, integrity and surface inspection within a single system and workflow. The goal of the project was to demonstrate improved efficiency gained over the current Additive Manufacturing workflow. In order to achieve this, developments to existing commercial hardware and software were required. Firstly, the X-ray source has been redesigned to reduce image noise caused by non-uniformity of the source spectrum. Region Of Interest (ROI) scanning has also been implemented to enable the acquisition of higher resolution data such that small scale surface features can be resolved without being constrained by the physical component size. A methodology for extracting surface texture parameters from the CT data has been integrated into a specialised voxel analysis software to allow semi-automated, repeatable surface measurements that are consistent with current ISO standards. A number of additional tools have been developed to allow the CT data to be fully interrogated; removing the need for additional inspection stages within the manufacturing process.

2 Industrial Use Case
The initial driver for this project was the challenge presented by the need to inspect additively manufactured heat exchangers (Figure 1). No ‘off-the-shelf’ solution currently exists for characterising the internal surface texture; critical to the performance of the component. X-ray CT is currently used for integrity inspection and a structured light system for dimensional inspection of external features. The ability to perform dimensional, integrity and surface inspection with a single system would therefore be highly beneficial for the current production process. It has the potential to reduce inspection time and remove the need for additional inspection equipment, therefore reducing costs, cycle times and potential increasing workable floorspace.

Figure 1: Hotbox heat exchanger, image courtesy of HiETA Technologies.
The current production route for the hotbox heat exchanger is given in Figure 3. After the build has finished, the part must undergo post processing, inspection and functional testing before it can be passed. X-ray CT is currently used to validate the internal integrity and check for trapped powder. A single X-ray CT scan will capture millions of data points over the entire CT volume allowing external and internal surfaces information to be extracted. There exists the potential therefore to extract dimensional and surface data from this, provided the data is of sufficient quality and resolution. If this can be achieved, a number of other process can be removed from the production chain, as shown in Figure 3.

2.1 X-ray CT Scans

A number of test components were built from AlSi10Mg and Inconel 625 (Figure 2); representing the best and worst case for common heat exchanger materials in terms of X-ray penetration. Each of these different type of component were scanned at the Manufacturing Technology Centre using two Nikon XTEK systems; the XT H 225 ST and the XT H 450 LC for the aluminium based alloy and nickel based alloy respectively. The scan parameters used are given in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Al Hotbox</th>
<th>Inconel Hotbox</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>XT H 225 ST</td>
<td>XT H 450 LC</td>
</tr>
<tr>
<td>Voltage</td>
<td>192 kV</td>
<td>350 kV</td>
</tr>
<tr>
<td>Current</td>
<td>85 µA</td>
<td>160 µA</td>
</tr>
<tr>
<td>Filtration</td>
<td>1 mm Al</td>
<td>4 mm Cu</td>
</tr>
<tr>
<td>Voxel Size</td>
<td>67 µm</td>
<td>72 µm</td>
</tr>
<tr>
<td>Scan Time</td>
<td>3540 s</td>
<td>7000 s</td>
</tr>
</tbody>
</table>

Table 1: X-ray CT parameters used for scans of Inconel 625 and aluminium hotbox samples provided by HiETA Technologies.

The CT images obtained for each of the two samples were analysed to assess the quality. The data acquired from the aluminium hotbox contained minimal image artefacts and had a high signal-to-noise ratio, most probably due to the relatively low X-ray absorption properties of aluminium. The Inconel data set was of poorer quality with a lower signal-to-noise ratio and significant cupping and streak artefacts visible. This could be attributed to the higher X-ray absorption properties of the alloy materials; inducing significant beam hardening and requiring a higher X-ray acceleration voltage to achieve sufficient part penetration. At higher source energies, the fraction of Compton scattered X-rays increases, leading to further degradation of the image signal. For this reason it was decided that the 3-in-1 system would focus on low energy applications, that require no more than 225 kV of source acceleration. The aluminium dataset was therefore used for the development and testing of the software tools in Section 4.
Figure 3: A suggested production route for the hotbox heat exchanger which implements the 3-in-1 X-ray CT system, allowing the majority of the inspection stages to be completed in a single process.
3 Hardware Development

Nikon XTEK currently manufacture a Metrology CT system, the MCT225 (Figure 4) which has been developed for dimensional measurement applications by providing increased accuracy and repeatability of data collection. The next generation of this system has been adapted to make it more suitable for surface measurement tasks. This has been achieved through a number of improvements in the existing hardware and acquisition capability of the system. The main developments have focussed on redesign of the X-ray source which will, in principle, lead to improved image quality. Simulation results predicted that the new design will reduce the so called heel effect; variation of the source spectrum across the imaging field. Other developments include scatter correction methods and implementing ROI scanning in order to achieve high resolution images of localised regions of the sample.

![Figure 4: MCT225 metrology X-ray CT system from Nikon.](image)

3.1 Heel Effect

The heel effect is a phenomenon associated with reflection-type X-ray tubes; it is described as the spatial variation in the X-ray source spectrum caused by the geometry of the X-ray target. Variations in the X-ray path length through the target material will lead to differences in the observed spectrum over the vertical cone angle as illustrated in Figure 5. The heel effect can lead to variations in the source intensity over the detector field. Non-uniform source intensity is routinely dealt with through the use of shading or flat-field corrections. These corrections will reduce the sensitivity of the detector however, and as such, it is beneficial to begin with a more uniform source to reduce the reliance on flat-field corrections or the use of hardware filters.

![Figure 5: Illustration of the heel effect in an X-ray reflection tube.](image)

The new source design has changed the configuration of the target such that the variation in X-ray path lengths are reduced - lessening the heel effect. Experimental trials were performed to validate the new design. The X-ray spectrum was characterised
at four different cone angles at the position of the detector for both the existing source and the improved source design. The result of these experiments are given in Figure 6. It can be seen that the variation in the X-ray spectrum across the four angular sections has been reduced by the new source design - confirming the effectiveness of this new design.

Figure 6: X-ray spectrum measurements in four vertically spaced sections at the detector. a) Heel effect is present when using the conventional source design as seen by variation of source spectrum in the different sections. b) Heel effect is reduced using the new source design as noted by the similarity of the source spectrum across the four sections. Images courtesy of Nikon Metrology.

4 Software Development

Recent research into the use of X-ray CT for extraction of areal surface measurements [3] [4] has highlighted the feasibility of this technique for such applications. The processes for generating surface texture parameters in-line with existing ISO standards have been integrated into Simpleware ScanIP, a commercial voxel analysis software, which has the ability to automate many of the manual processes. A geometry distortion compensation model based on previous research [5] has also been integrated into this software to detect and measure deviations from the nominal part geometry which can be used to generate a corrected AM build file. The analysis software will also implement a number of other tools to enable a semi-automated workflow to minimise operator influence. These include a localised, sub-voxel surface correction in order to extract the fine surface detail. Additional software tools have enabled automatic registration of two data sets and extraction of dimensional measurements.

4.1 Local Surface Correction

Initial findings in the 3-in-1 project revealed that a local surface determination with sub-voxel interpolation was necessary to adequately represent the surface texture. Global threshold-based surface determination is often more susceptible to the presence of image artefacts and noise; leading to the detection of false edges in the data [6]. Since the existing workflow relied on a global surface determination, a local surface correction algorithm was developed to allow the surface to adapt to the local variation in grayscale. The corrected surface determination was trialled on the CT images taken of the aluminium hotbox detailed in Section 2. An example of the global and locally corrected surface determinations are shown in (Figure 7). It was found that the corrected surface was less prone to detection of false edges due to image artefacts in the CT data.

4.2 Surface Measurement

There has been recent interest in using industrial micro-focus X-ray CT as a tool for performing surface measurement tasks, especially on AM components due to the ability to measure internal of inaccessible features. Previous work demonstrated this capability and defined a workflow for extracting the desired surface texture parameters from X-ray CT data [3] [4]. This workflow required performing a large number of manual steps to achieve the desired result, as outlined in Figure 8. One of the main aims of this project was to implement software tools to enable better automation of this workflow - reducing the effort required and allowing less experienced users to follow these procedures repeatability and in-line with current ISO standards (ISO 25178-2 [7]).

Initial testing of the new software tools was performed on high resolution CT data of a sample AM surface made from Ti6Al4V. The workflow outlined in Figure 8 was followed in Simpleware ScanIP O-2018.12 with additional surface measurement plug-ins
Figure 7: Comparison of the newly implemented local surface correction against a global threshold surface. Image courtesy of Synopsys.

**Manual Workflow**

1. Surface Determination
2. Generate Surface STL or PLY
3. Trim Data
4. Convert STL to PLY as Required
5. Align Surfaces
6. Perform Deviation Analysis as Required
7. Cropping
8. Clean Mesh
9. Convert to Height Map
10. Further Cropping as Required
11. Filter per ISO 25178-3
12. Generate Parameter Data per ISO 25178-2

**Semi-Automated Workflow**

1. Surface Determination
2. Generate Surface STL or PLY
3. Select Region of Interest
4. Calculate Surface Parameters per ISO 25178-2

Figure 8: An outline of the original workflow followed in [3]. Extracting the surface deviation parameters from XCT data required many manual processing steps.
developed by the University of Huddersfield. The CT image was acquired on a Nikon MCT225 system. The CT data was read in as a 16-bit TIFF stack. A global threshold value was selected using the Otsu thresholding method. The local surface correction tool was then applied. Although these two steps were automatic, some manual image processing was required to remove some of the background noise. A region of interest was then manually selected and the surface parameters extracted. The selection of the region of interest was repeated several times, as such, variation in the surface parameters was expected as the measurements relate to slightly different areas. The average measurement results are given in Table 2 with the reference values shown for comparison.

<table>
<thead>
<tr>
<th>Surface Parameter</th>
<th>Description</th>
<th>ScanIP Measurement with Surface Correction</th>
<th>Reference Value</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetical Mean Height ($S_a$)</td>
<td>The difference in height of each point compared to the arithmetical mean of the surface.</td>
<td>24.565 µm</td>
<td>25.505 µm</td>
<td>-0.94 µm</td>
</tr>
<tr>
<td>Root Mean Square Deviation ($S_q$)</td>
<td>$S_q$ represents the root mean square value of ordinate values within the definition area. It is equivalent to the standard deviation of heights.</td>
<td>31.329 µm</td>
<td>32.528 µm</td>
<td>-1.199 µm</td>
</tr>
<tr>
<td>Skewness ($S_{sk}$)</td>
<td>$S_{sk}$ values represent the degree of bias of the roughness shape.</td>
<td>0.109</td>
<td>0.203</td>
<td>-0.094</td>
</tr>
<tr>
<td>Kurtosis ($S_{ku}$)</td>
<td>$S_{ku}$ value is a measure of the sharpness of the roughness profile.</td>
<td>3.532</td>
<td>3.641</td>
<td>-0.109</td>
</tr>
</tbody>
</table>

Table 2: Surface measurement parameters obtained in Simpleware ScanIP software of AM surface sample using the plug-in provided by the University of Huddersfield.

The local surface correction was then compared against the original surface as obtained using the global threshold method. Each of the two surfaces were measured seven times; selecting a slightly different region of the surface each time. The results are shown in Figure 9. It is apparent that the average deviation from the reference value is reduced when using the surface correction tool. The measurement variation is also reduced upon when using the local correction.

Figure 9: Comparison of repeated measurements obtained using the global surface determination and locally corrected surface determination using the Simpleware ScanIP software and surface measurement plug-in.
5 Conclusions

A number of software tools have been developed as part of the 3-in-1 project. These tools have helped to enable a more automatic workflow for extraction of surface measurement parameters from X-ray CT data within a standard voxel analysis package. This paper has summarised the results obtained during the project to date. However, further development work is required to test and validate the surface measurement tools before they can be made commercially available. The surface measurement parameters obtained from ScanIP were found to be in good agreement with the reference values obtained by conventional methods. Although a large number of influences still exist when performing surface measurement with X-ray CT, this new workflow minimises the influence of the user by reducing the number of manual processing steps involved. This influence could be further reduced by more robust methods of selecting the measurement region. With the use of fiducial markers it should be possible to repeatedly select the same region of interest as made by the reference measurement which should further reduce the surface measurement variation.

Further implementations are still required before the complete 3-in-1 workflow can be realised. The other aspect of performing surface measurements with micro-focus X-ray CT is the acquisition of suitable data. For surface measurement, a high magnification ROI scan is typically required to achieve sufficient resolution on large components. The project aims to address this issue by implementing ROI scanning and automatic image registration so that high resolution regions can be aligned with a lower resolution scan. The quality of the data will also be improved once development of the hardware is complete and the new source design has been implemented.

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References