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NONDESTRUCTIVE MICRO-CT INSPECTION OF ADDITIVE PARTS: HOW TO BEAT THE BOTTLENECKS

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Abstract

Micro computed tomography (microCT) is widely in use for the inspection of additively manufactured parts. The main use of the technique is to detect unwanted voids inside the part. However, the ability to detect these kind of defects is strongly affected by image quality, which is often directly related to the scan time. Selecting fast scan settings (e.g. 5 minutes per part) can work for many situations where major flaws need to be identified (such as large unmelted cavities), but this may result in the missing of critical defects which are smaller, such as clustered metallurgical pores or chains of fine voids between layers or tracks caused lack of fusion . An important defect type which can be missed by fast scanning is small inclusions also. Possible ways of overcoming this problem are discussed. After scanning, image analysis requires computing power, time and skilled human interface for proper analysis. Reduction of the image analysis workflow is possible using semi-automated analyses and the data size can be reduced using simple methods, including removal of unwanted data outside the object, 8-bit data size and even .STL format outputs in some cases. In this paper all the above is discussed in relation to reducing the bottlenecks (problems causing delays in getting results and slowing the workflow) often associated with microCT.

Introduction

X-ray micro computed tomography (microCT) is an emerging technology used for the detailed 3D inspection and analysis of various materials. As a non-destructive imaging method, it finds application in various fields such as materials science [1], geosciences [2], industrial applications [3], dimensional metrology [4], food science [5], amongst various others. The use of this method in additive manufacturing (AM), and in laser powder bed fusion (LPBF) in particular, has been demonstrated widely, see for example [6-8]

The use of the technique has grown considerably over the last decade, as its availability has increased (especially with pay-per-use labs), and improvements in computing power and special softwares dedicated to analysis of CT datasets and image processing. In principle, this superior imaging technology can play a huge role in improving the quality of AM parts, by non-destructively identifying defective parts and also optimizing process parameters to eliminate build errors), this has been reviewed in detail recently [6]. Despite the huge potential of the technique, there are some major bottlenecks in typical tests conducted, which are not discussed in the literature. These bottlenecks and issues encountered are some of the reasons the technology is not yet more widely used, due to the perception of it being a slow process , relative to other more routine non-destructive test methods such as 2D digital radiography, ultrasonic and other techniques.

This perception of the complexity or time-consuming nature of microCT, and these underlying issues causing this perception, are the topic of this paper. We discuss in some detail the entire microCT workflow, from the perspective of a typical laboratory microCT facility used for such testing [9]. The major potential bottlenecks are identified and ways of minimizing their effect through some simple methods are discussed. Besides this perspective, quantitative analysis of a layered defect and larger porosity (largest pores approx. 0.6 mm) in two parts are demonstrated for varying image quality (scan times) and resolutions. This demonstrates why both image quality and resolution are important (i.e. it is important to have a good resolution and good image quality). This also demonstrates why witness specimens might be crucial to assess large parts by microCT, due to the inherent resolution limit on larger parts but not on the smaller witness specimen. An example of a typical layered defect in a large part is shown, and examples of non-internal (surface) defects are shown, with suggestions on simple reporting strategies. Finally, data reduction and reporting options are discussed. When these bottlenecks are minimized, the method becomes suitable as part of a routine additive manufacturing testing workflow, and becomes suitable for incorporation into automated inspection and reporting workflows for Industry 4.0.

Problem statement and background

The work reported here is relevant to typical laboratory microCT devices generically with capabilities as in [9], including a microfocus X-ray source up to 225 kV and best voxel resolution approximately 5 µm, with resolution scaling with geometrical magnification. Optimization of scan parameters is discussed in more detail in [10], especially different forms of artefacts that may be present and how to improve scan quality in general. The use of microCT in testing of powder bed fusion parts was reviewed recently [11] and Figure 1 shows a schematic of the microCT method. This paper is focused on Ti6Al4V due to its prevalence in biomedical and aerospace applications, especially in the powder bed fusion community, but all discussions are relevant to other metals and plastics and its applications.

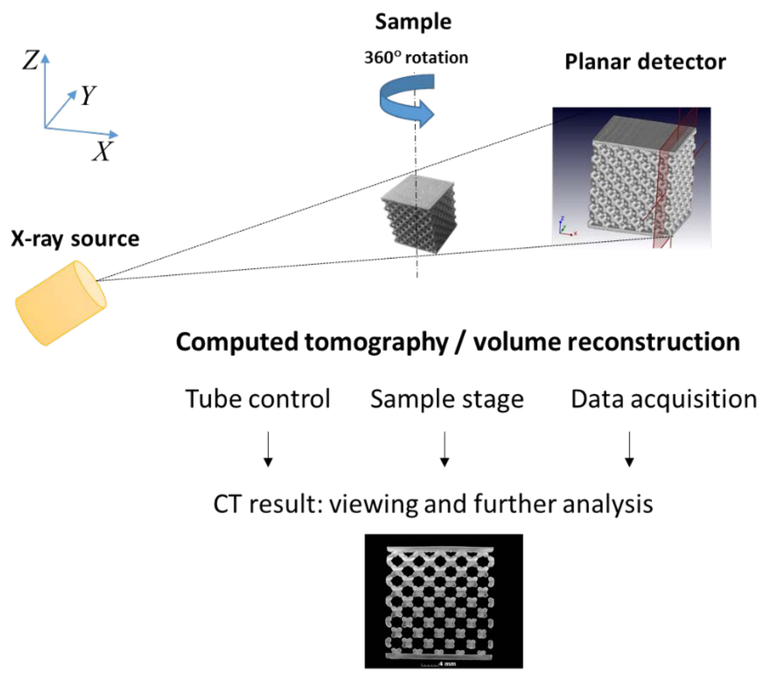


Figure 1: Schematic of the microCT technique.

The typical workflow for testing AM parts using microCT is depicted schematically in Figures 2-4, in stages from initial sample submission, through scanning and analysis, to the final stages of reporting and data handling. Bottlenecks are identified with red arrows and green arrows show at which point these problems initiate. This is a simplified representation and various permutations and issues might exist, but these are considered the most important steps in the microCT workflow.

Initial problem can be entitled "setting expectations and setup". When the parts are submitted for testing by microCT customer's expectations may be unrealistic due to lack of experience or lack of knowledge of the technique (Figure 2). The problem manifests later, when the scans need to be done, and the operator is not clear about the test requirements. In practice, the work is delayed at this step due to waiting for instructions, attempts to contact the submitter of the work, or the operator prioritizes other work which has more clear instructions. The miscommunication at this step might be due to impractical requirements or instructions such as "best possible resolution" when a very large part needs to be tested. The "best possible resolution" often requires excessive scan times which does not necessarily add value to the inspection task or detectability of defects, due to the potential for image artefacts at higher magnification. In fact, each new part it may require very specialized setup and optimization, in addition to scan time, which slows down the workflow. Often the submitter of the work might be under the impression that all types of analysis can be done from one scan – this also is not possible. It is crucially important to identify the exact requirements prior to accepting samples for scanning, as this determines the scan setup and type of scan done, which in turn affects the time spent and hence cost involved. Once the instructions are clear on the goal of the scan, the next potential bottleneck is in the setup and optimization of the scan. Each scan requires generally a custom setup and optimization which takes some time. Inexperienced operators might take longer at this step, or might select incorrect settings or sample orientations. Additionally, some unexpected problems might arise, such as the sample being too dense to scan, or unexpected dense inclusions causing image artefacts will require rescanning with different beam filtration. One possible solution to this issue is to make fast scout scans prior to the actual scan, to ensure no artefacts are present, with the scout scan simply being used to assess the scan setup.

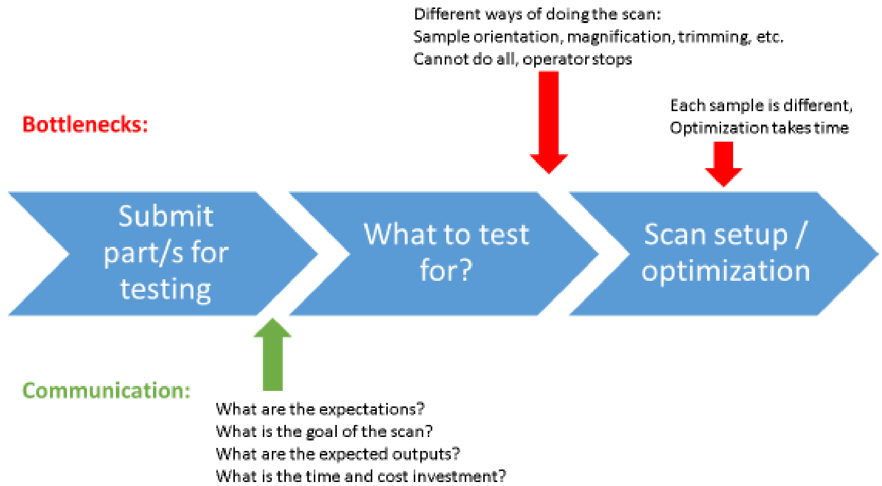


Figure 2: Workflow prior to scanning, with bottlenecks identified in red. Communication at early stage minimized these bottlenecks.

Once a setup is completed, the next phase is actual scanning and analysis (Figure 3). The actual scanning might lead to bottlenecks if the system is unstable or causes failed scans. For example, when a system fails near the end of a 1 hour scan, not only does the system need to be fixed and checked by the operator, but the scan must be set up properly and repeated entirely from the start in most cases. This causes unexpected delays of at least 1-4 hours depending on the source of the problem. At this point, despite attempts to optimize the scan, the final scan might be of poor quality, possibly due to sample movement (improper fixing, thermal expansion, etc.). This requires rescanning, and can only be diagnosed after reconstruction of the data. The reconstruction step itself is usually fast, but some systems might require more manual input than others which might make this an additional bottleneck. Generally, reconstruction also requires significant computing hardware to speed up the process (with optimized hardware this is 30 – 90 seconds, but with aging computers and basic software this might be 30-60 minutes).

The final step in this phase is image analysis. This is the largest bottleneck at present in all microCT analysis, not only in AM. In most cases this process involves initially viewing the data in slices and making some form of image segmentation to separate material from background air and from internal porosity or inclusions, sometimes with additional analysis functions calculating the porosity per cent and distribution. Any image analysis of large data is time-consuming, more so when computing power is not available and when the software is not optimized for the purpose. Usually this process is also strongly dependent on user interaction, which causes a bottleneck when the basic functions are not sufficient but custom methods need to be devised. Often the planned analysis does not work, which requires a back and forth process of segmentation and analysis until the result is acceptable. This time investment is difficult to plan and might sometimes be insufficient depending on the required analysis (e.g. pores visible but too small to accurately quantify, edges of part visible but accurate surface determination fails due to grey value differences across the part).

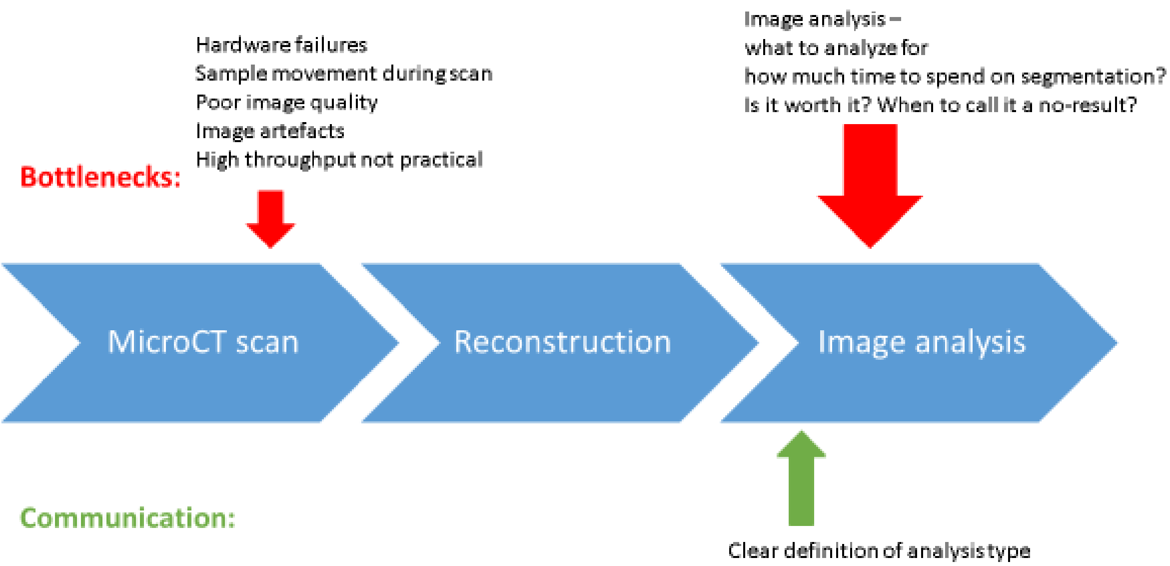


Figure 3: Scanning and analysis steps – bottlenecks during scanning and major bottleneck usually in analysis step. Clear definition and prior communication of analysis methodology smooths out this problem.

Finally, once the analysis is complete, this needs to be reported in an efficient manner (Figure 4). The data itself is large and requires not only disk space but generally good computing power to visualize and inspect the results. Therefore, simpler reporting methods must be used. Due to the many different permutations of reporting the results (slice images from different angles, videos, STL files, porosity values, porosity data spreadsheets, *etc.*), this often causes a bottleneck, as the operator or instrument scientist performing the analysis is unsure of the best way to present this to the client. Often the analysis is complete but the client waits weeks to receive the data (*e.g. via* shipment of hard drive) and then has trouble opening the analyzed data set, which is not a scientific issue but a practical one. This bottleneck can be eased by using standard reporting outputs available in commercial software packages, with some further simplified viewing options for quick self-assessment by the client. Finally, once the results are reported, the full data typically needs to be saved and shared with the client. This is not trivial as a single scan data set is typically 20 Gb and includes all acquired X-ray images, reconstructed volume data set and associated analysis files. When the data was de-noised this additionally increases the data set size as each de-noised volume data has its own raw data set. Clearly, for ease of use this process needs to be streamlined, especially for data transfer purposes. The method to do this is to align the part with the axes and crop unnecessary air voxels from around the part, possibly downscale the data to 8-bit if this is acceptable, then save the downscaled and cropped image stack. This will easily compress a 20 Gb data set to below 1 Gb, with some further compression possible using standard file compression formats. The raw X-ray images are discarded in this workflow. Ideally this final step can be automated.

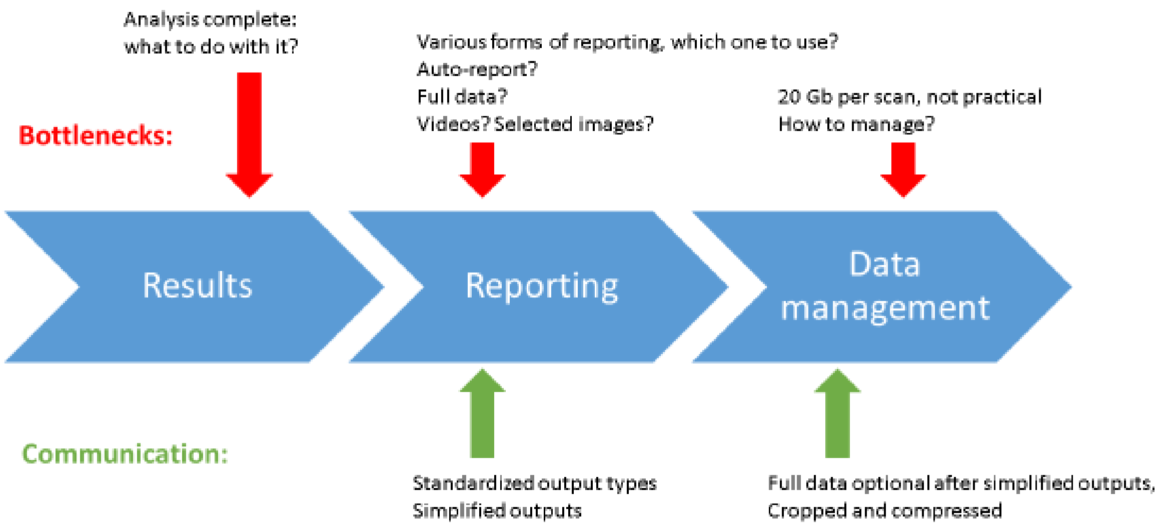


Figure 4: Final steps in the process – bottleneck in reporting and data handling and transfer, these can be simplified using standardized output types, with simplified reporting and data for fast communication and full data moved later.

Solutions

Despite the many issues highlighted above, the solutions to all the above bottlenecks are in standardization at every step. Submitting parts of standard geometry is possible when the analysis workflow is optimized. For example, a 10 mm cube can be scanned using pre-defined parameters and a near automatic image analysis workflow requiring minimal user input. The small size allows high scan quality, high resolution allowing detection of small pores and other detail, and therefore a simplified image analysis workflow. For this type of sample, three standardized analysis workflows based on the same scan allow accurate and simple quantification of porosity [12], physical density [13] and surface roughness [14] of selected surfaces. This allows a streamlined workflow for optimizing additive manufacturing process parameters, while also checking for major flaws that may be present.

Furthermore, despite AM producing complex parts, some form of standardization is possible for parts in different size categories. For smaller parts <100 mm, a standardized workflow was described in [15]. Since the resolution scales with part size, typical complex parts cannot be inspected reliably for critical porosities which may be very small and possibly in layered or clustered form. For this purpose, one partial solution is to produce a witness specimen, *i.e.* a cylindrical rod built next to the complex part of interest. This rod can be analyzed at high resolution by microCT using a standardized and automated workflow, and if critical-type defects are detected, the same is expected in the complex part (as these kinds of defects originate from deformations or delamination during manufacturing, uneven powder spreading across the build platform, or due to system instability, powder handling or other issues affecting all parts in the build at the time). The complex part itself can also be subject to microCT since it may also contain larger unexpected defects, which can be detected despite the poorer resolution. The pass/fail decision still rests with the user, but standardized outputs allow better informed decisions to be made and compared over long periods of testing similar parts, potentially using different CT systems.

Included in this standardization requirement is the method of reporting and handling of noisy data or data with artefacts, and streamlining the workflow, the data format and data handling in general. All the above standardization is already possible with existing hardware and software and requires only implementation. The series of examples below attempt to demonstrate methods to ease the bottlenecks and allow simpler workflow supporting the incorporation of microCT into Industry 4.0.

Examples

Scan image quality and resolution

In this demonstration, we use two laser based LPBF samples scanned together: a 10 mm cube containing porosity sub-surface and a 15 mm diameter rod containing a layered defect. As the resolution gets poor, all pores are more difficult to observe clearly and no quantitative analysis is possible (Figure 5).

However, when fast scan settings are used (5 minutes) even at higher resolution of 25 µm, artefacts are obscuring the presence of the defects and the data is too noisy for a successful analysis, as shown in Figure 6a. Using best resolution and quality, good analysis of the porosity is achieved using a 3D analysis algorithm which successfully detects all defects, and the layered defect is clearly identified (Figure 6b, c).

(a) (b)

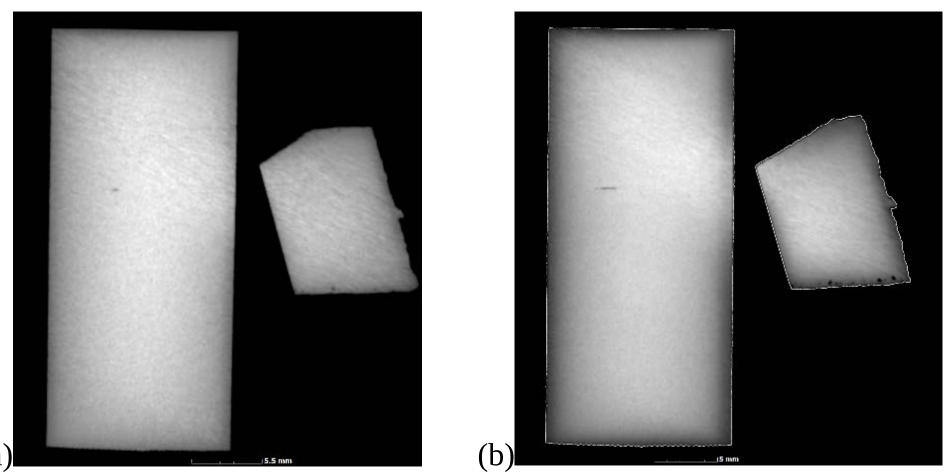
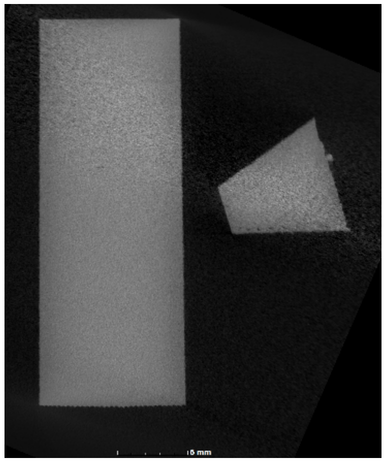
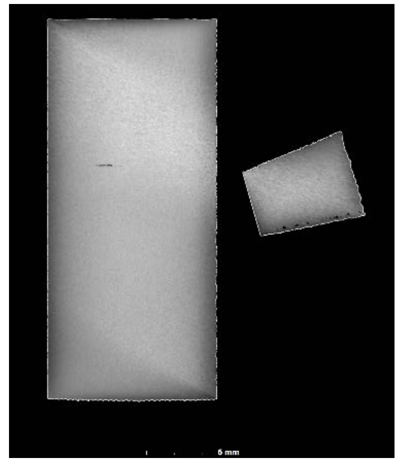


Figure 5: Porosity and layer defect analysis, variation of resolution: 100 µm (a) and 60 µm (b).

(a) 

(b) 

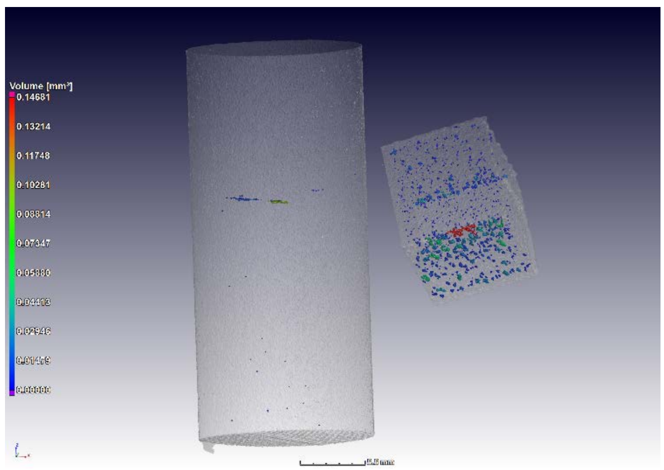
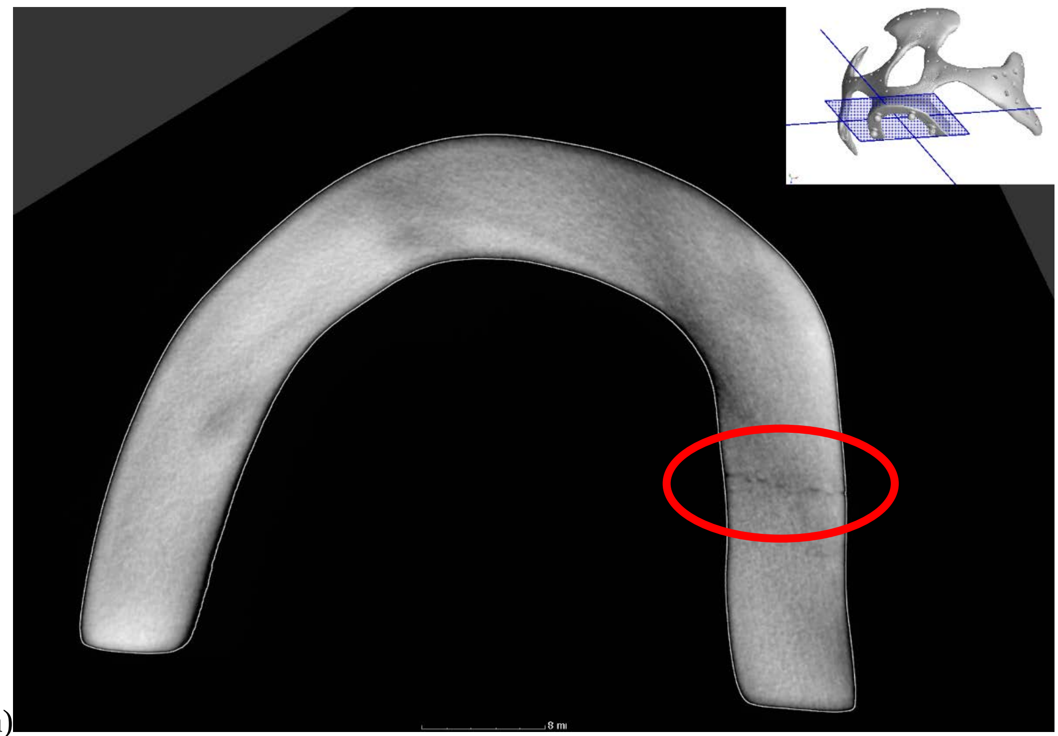
(c) 

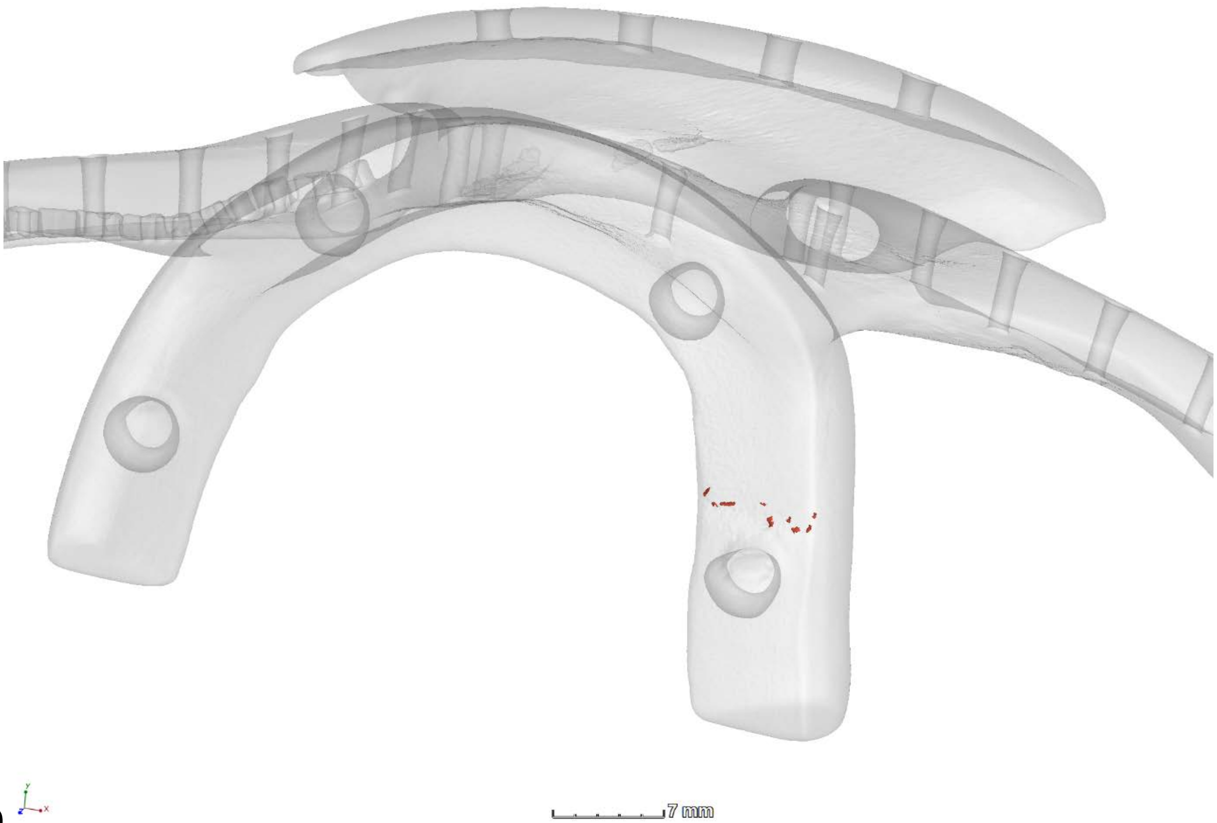
Figure 6: Porosity analysis at 25 µm resolution – variation of image quality (scan time) – fast scanning obscures all defects (a); high quality scan settings clearly identify defects on slice images (b) and allows full defect analysis in 3D samples (c).

Visualization of defects despite artefacts

When a part is large or complex shaped, various artefacts can affect the scan results. These image artefacts refer to brightness differences which are not related to the part density or integrity, but due to a lack of X-ray penetration of the part in some directions, or a beam hardening artefact due to polychromatic X-ray beam absorption. Various other artefacts may be present when a part is too large, or when it is too X-ray dense, or when the scan is either not done properly or something went wrong during the scan. None of these are necessarily seen in the data output, making it possible to miss important defects which can be obscured by these image artefacts. The only way to diagnose this is currently to view the CT slice images, unprocessed, and establish a level of confidence in the image quality and lack of artefacts. Image quality can be quantified using a measurement of signal and noise levels in the scan data, as demonstrated in [16]. While most artefacts are easily detectable and identified by users, this requires access to the slice images for the user, and is not an automated process yet.

Furthermore, in case of artefacts, automated analysis is not possible, making quantitative analysis and data reporting difficult. Major flaws might be identified but how can one quantify this? This results in possible bottlenecks as the reporting method is not clear. The method proposed to overcome this problem is to manually inspect each slice image, from 3 orthogonal axes. When a potential indication is identified, a digital marker is saved in the data. This may be reported in the form of a slice video/s, for simple and easy viewing, and simple transfer of results. To demonstrate this, an example is used from [11], demonstrating the CT slice image with its variations in grey values and the defect line most likely caused by uneven powder spreading. This defect is clearly seen in Figure 7(a) in a slice image, but an automated analysis does not work as the brightness variations across the part is too high. For this case a manual image segmentation is necessary to highlight the location and 3D distribution as shown in Figure 7(b).

(a)




(b)

Figure 7: Analysis of defect in a large laser based PBF part, with slice image showing variation in greyscale (a) and manual segmentation showing location and orientation of defect (b).

Non-porosity defects

A further complication is where a part is submitted for integrity testing and it shows no internal porosity, but surface defects and warping, which are two common problems in additive manufacturing. Warping is easily analyzed by performing a CAD variance analysis, and individual annotations show local deviation (warping values) or 3D colour coded deviations as shown in Figure 8. Surface defects are more difficult to highlight, but can be highlighted by a process of image analysis: a closing and smoothing function is applied to the surface data and this is compared to the actual part, showing strong variations at sharp discontinuities, this is also shown in Figure 8. This type of analysis is reported first using videos and images, and later in analyzed data sets for further in-depth viewing.

Figure 9 shows that microCT scans can easily identify the presence of inclusions or impurities in the AM parts as shown in (a) and partially melted powder material left on the surface or inside parts of a complex shape, when it is difficult to evacuate the powder during post-processing (b).

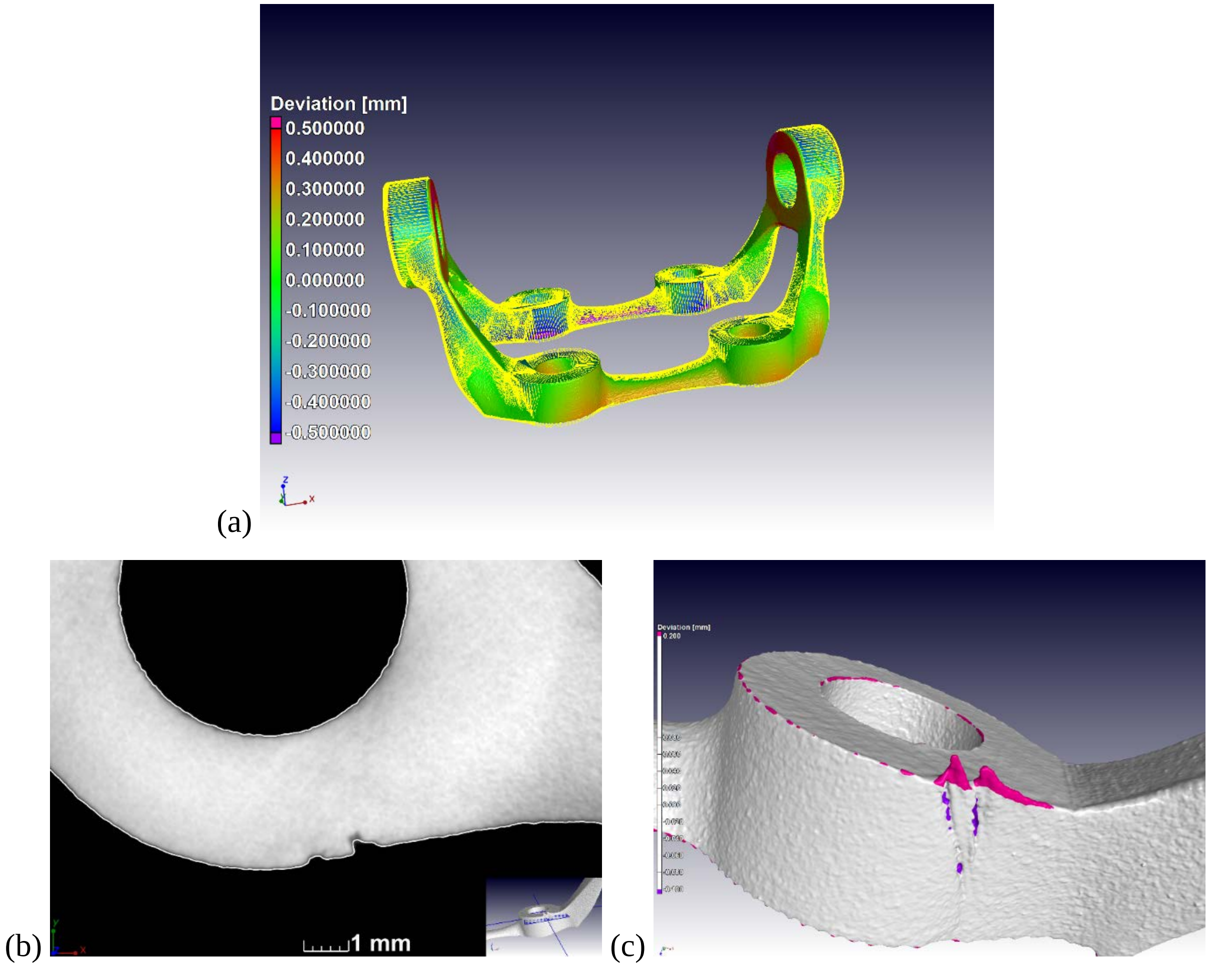


Figure 8: CAD variance analysis shows some warping (a) and surface defects - shown in slice image (b) and in 3D using colour coding (c) on sharp edges and notches.

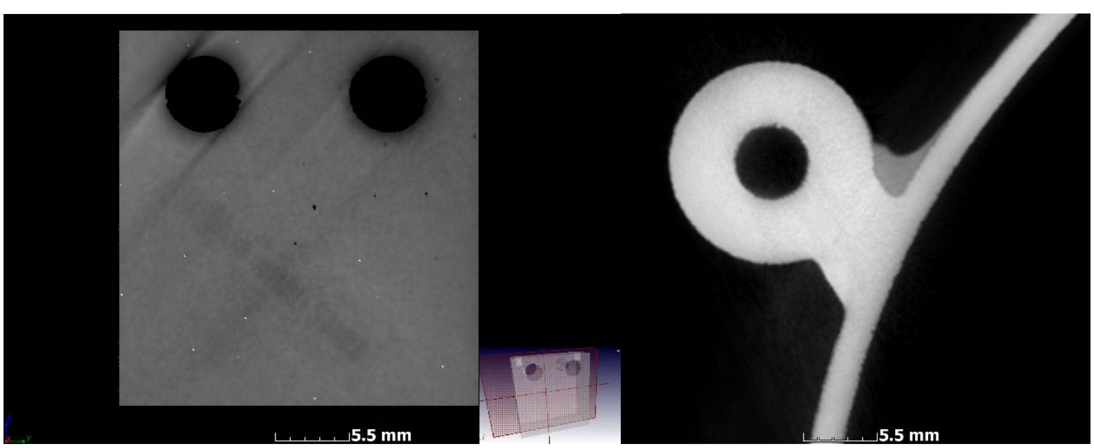


Figure 9: Slice images show impurities in AM part (a) and powder that is trapped in corner of complex part, partially attached making its removal difficult (b).

Data reduction workflow

The above examples show typical analyses for additive manufactured parts and simplifications to report these. Finally, the analyzed data set needs to be reported and transferred as well, which currently causes a bottleneck due to file sizes (Figure 10). Some simple methods for reducing this size are implemented ideally prior to the analysis. This involves firstly an alignment relative to the coordinate axes of analysis, then a cropping of the region of analysis, removing unnecessary air voxels.

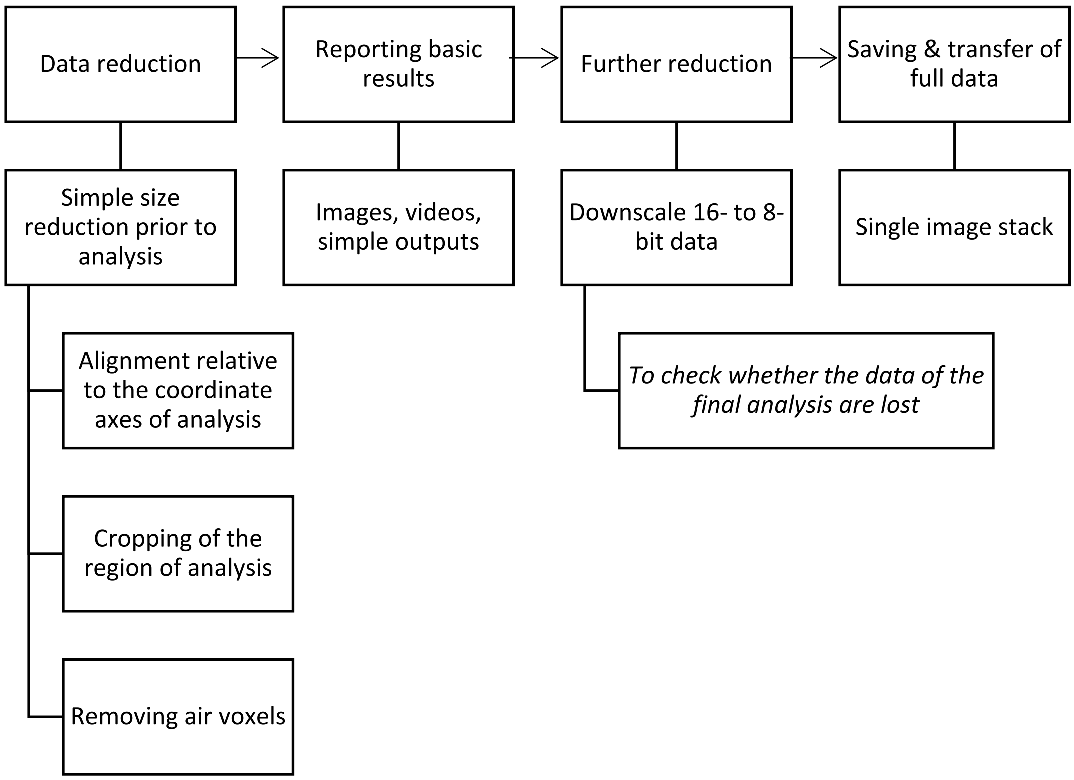


Figure 10. Data reduction workflow.

A more advanced method which removes more air voxels involves using the surface data and image dilation to select all voxels of the object and a set number of layers of voxels from around it. In this way especially complex objects have much exterior air voxels removed from the selection. The next step is de-noising of data and at this point the data can be downscaled from typical 16-bit to 8-bit. However, 8-bit data might affect some types of analysis, therefore the choice of downscaling from 16 to 8 bit depends on the data reduction requirement vs the criticality of the analysis. Finally, the data is saved with only a single image stack which has been cropped and this is ready for transmission to the client or for long term storage. A typical medium-resolution microCT data size is reduced from 4 Gb for the scan data in 16-bit to 300 Mb for the cropped data in 8-bit data, when using only a single image stack and discarding unnecessary raw data.

Conclusions

Some of the bottlenecks in microCT were highlighted and it was shown that all of these issues can be streamlined using a combination of standardized methodologies for each of the steps involved in scanning, processing and reporting of microCT results. Automated workflows are necessary to incorporate microCT into Industry 4.0 systems, allowing automated reporting of results and accept/reject criteria assessment. Currently it is not possible to automate the entire workflow, but by minimizing human input, potential bias is minimized and the workflow is streamlined. Due to the large data format of microCT output, various quick outputs were demonstrated and data reduction techniques discussed. These reductions and compression of data are crucial to the future uptake of microCT into Industry 4.0 workflows, especially for simple but complete result reporting. Future growth areas will likely be in cloud-based storage and analysis, and improvement of standardized workflows, especially with optimized algorithms searching for specific defect types relevant to additive manufacturing– e.g. layered defects or cracks.

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