Evaluation of internal defects in additive manufactured metallic network structures by Computed Tomography

Lars Pejryd¹

¹Örebro University, School of Science and Technology. SE 701 82 Örebro, Sweden, e-mail: lars.pejryd@oru.se

Abstract
The ability to manufacture complex internal features is one of the distinct differentiators of Additive Manufacturing (AM) as compared to other manufacturing methods for metal components. This manufacturing process provide designers with new opportunities in the design, such as e.g. networks and curved and non round cooling channels. To fully take advantage of metal AM in industrial use, robust methods for the detection of potential internal defects is however needed. A method that holds the promise of being one of the few tools for non-destructive evaluation (NDE) of internal features and defects is X-ray computed tomography (CT). The applicability and limitations of CT, especially for defect determination in products with complex internal structures is however not fully understood. In this work, parts with different sizes of controlled internal defects in the form of slots of varying width, 0,1 – 0,4 mm was manufactured by AM, using Selective Laser melting (SLM). The parts were produced in both titanium and aluminium alloys and both with internal networks and as solid pieces. For both of the designed types of samples, containing the pre designed defects, the ability to detect the defects by industrial computed tomography (CT) was evaluated. The evaluation of defects using CT data can be done by a trained operator. For solid components this can be done with some assistance of analysis modes that are available in commercial software. For components with complex internal structures, the result is more operator dependent and more work is needed to develop methods for CT inspection that can enable automation of the inspection process and/or to assist a trained operator.

Keywords: Selective laser melting, aluminium, titanium, computed tomography

1 Introduction
Additive Manufacturing (AM) is a, especially for metallic components, relatively new manufacturing technology that may give designers new freedoms in design, adding complexity that have not been possible before to components, resulting in a potential to create new or improved functionality in products. This complexity has e.g. been defined by Gibson et al. [1] as consisting of shape complexity, material complexity, hierarchical complexity and functional complexity. Although this complexity advantage may give an advantage for AM compared to existing manufacturing methods, the AM process is however often considered as more expensive than other manufacturing methods [2], stressing the importance of increased functionality of the products. Successful application of AM is therefore often resulting in abstract and complex shapes in order to obtain product advantages that can cope with the added cost. This may result in components with several complex internal features included into the product. To utilise the advantages of AM to its full capacity, there is a need in industry for robust methods to secure both product verification and/or quality assurance. In general, several technologies for both assurance of dimensional accuracy, such as CMM, and of micro structural integrity, e.g. Ultra sonic inspection and Eddy Current, are present for metallic components. The capabilities of these methods, especially for investigation of components with rough surfaces and internal features such as networks, that may be present in AM components, are however limited [3]. A method with the potential for covering both the metrological needs as well as the material integrity inspection needs is Computed Tomography (CT).

Regarding quality assurance for the material integrity of AM parts there are two main questions, the microstructure of the material and the porosity/inclusions. The most common use of CT is based on absorption contrast, thus investigating the difference in density of constituents in materials. This makes the method quite suitable for investigations of porosity in AM components. The AM processes are primarily powdermetallurgical processes and thus the question of porosity in the final product is of high importance. Although CT have developed considerably during the last ten years [4] there are still not much of industrial standards that can be used to secure the methodology of inspection and analysis or the detectability limits for different AM component geometries. A study was therefore initiated to evaluate the potential for detecting controlled defect-like features in different AM component simulators with different internal structures using industrial CT. In this paper, the results from CT of AM titanium samples, both solid and networks are reported and discussed in relation to results from AM processing of aluminium using the same process. The aluminium CT results were earlier compared to Ultra sonic inspection and Eddy Current investigations [3].

2 Experimental
In this work, test samples of titanium (Ti6Al4V) and aluminium (AlSi10Mg) with different sizes of internal defects in the form of slots of varying width, 0,1 – 0,4mm were designed and manufactured by selective laser melting (SLM), Figure 1. The type of defect chosen was done so partly to mimic potential flaws that could be the result of to wide hatching distance and/or in the transition region between contour line printing parameters and hatching parameters. The dimensions (width) were chosen based on earlier experimental atemts of manufacturing of internal defects, as spheres, where it was found that for titanium the limits of the manufacturing process may lie slightly below 0,25 mm. The hypothesis was therefore that for the smaller slots, the defects
may either be totally closed or partially sintered and thus they could provide a possibility to detect areas of higher porosity than the surrounding material even if the intended slot was not manufactured completely as designed. The test samples were manufactured in two different configurations for each material. One configuration with an internal network structure (Figure 2) and one which was solid (apart from the slots, Figure 1). The aluminium samples were only analysed by CT in the as printed condition while the titanium samples were analysed both in as printed conditions and one set of samples were treated in a hot isostatic pressure (HIP) process and subsequently analysed by CT. To facilitate calibration of the CT measurement results, three external half spheres were added on the upper surface of the part (relative to the build direction). By external measurements of these half spheres the center to center distance could be determined and used as a reference for the measurement when using the CT data.

The CT analysis was performed using a Nikon industrial CT system with a 225 kV X-ray micro focus source, without physical filtering applied to the X-rays and consisting of scans with 1500 projections. The scanning parameters used in this work resulted in a voxel size (i.e. the dimension of the volumetric pixel unit) of about (80 µm)$^3$ for scans of the complete samples and down to (27 µm)$^3$ for scans of only parts of the samples (at higher magnification). A filtered back-projection algorithm was used to reconstruct the investigated 3-D volume based on the X-ray projections obtained. To separate the metallic material and the pores (air) and determine the interfaces in the reconstructed volume, the commercial software (WGstudio Max) was used by applying thresholding using adaptive surface determination methods. The resulting data was then used to determine the geometry and dimensions of the defects produced. To evaluate the presence and size of non-melted areas in the form of slots, two types of approaches, defect determination and actual/nominal comparison, were used.

3 Results and Discussion

Solid samples
For the solid samples in the as printed condition, both titanium and aluminium (Figure 3), it was possible to detect all of the defects/slots that were designed to be included in the sample. The slots were shown to contain un-melted powder and porosity between powder particles. For the wider slots, this is clearly shown as regions of lower density than the surrounding solid material. Due to the higher density of titanium as opposed to aluminium, higher energies for creating the X-rays that could penetrate the sample was needed. This may result in higher risk for artefacts in the resulting CT volume. This can sometimes be
a problem in the inspection work looking for defects in e.g. the form of pores. Given he size of the intended defects in this study, however the use of higher energies did not pose any particular problems. To analyse the defects some different procedures was evaluated. By using the “Void” mode and the algorithm “VGDefx” in the software (VGStudio Max) it was possible to identify the complete defect volumes of the pre-defined slots. This includes both the volumes of higher and lesser density of the larger slot. These slots were found to contain volumes of both high degree of unmelted powders and volumes with less or no unmelted powder. This is clearly seen (for aluminium) in Figure 3, to the left, where the larger (or wider) slots both show black (empty) and grey (partially filled but not solidified) areas. The analysis mode “actual/nominal” was also attempted. In this mode, the reconstructed CT volume is compared to the as designed CAD file, in this case with the CAD file without the designed slots. The mode is however not designed to analyse internal defects, and no clear measurement values of the internal defects/slots could be obtained by this method.

![Figure 3: CT cross section of the SLM aluminium sample (solid configuration) with slots of varying dimensions. From left to right going from large to small width (0.4 – 0.1 mm). The virtual cut is perpendicular to the build direction.](image)

For the titanium sample that was subjected to HIPing (Figure 4), not surprisingly, all of the slots from the fabrication of the sample were closed as an effect of the heating and pressurising during the HIPing process. Since the voxel size (i.e. the dimension of the volumetric pixel unit) for the scans of the whole samples were about (80µm)³ all porosity smaller than at least some (150µm³) is is not detectable. This means that whether the HIPing can actually close all porosity, in addition to the pre-designed slots, or not, could not be determined. The HIPing procedure was also found to cause some dimensional distortion of the sample. This is partly due to the release of thermally induced stresses from the manufacturing process and maybe also to the closing of the internal slots, who were not homogenous in density before the HIP processing, as discussed above.

### Network samples
For the samples with internal network, Figures 5 & 6, the evaluation of the CT results was not as straight forward as for the solid sample. Since the “defects” that should be identified are in most cases open “voids” connected to the inner surface of the network structure instead of “pores”, the mode “defect determination” in the software VGStudio MAX does not apply. These defects are by the software seen as a part of the network structure (just another internal surface) and is therefore not identified as a defect. The slots present in the samples were instead identified by visual evaluation of the CT information. Although it was quite easy to identify slots in the part of the sample were the design resulted in wider slots, the identification of defects using this procedure is operator dependant. This is especially marked for the narrower slots. The mode “actual/nominal”, were the CAD file of the designed object is compared to the CT data, can give some help in identifying defects. No usable numbers for measurement of the defect sizes could however be obtained using this mode. Further method development may therefore be of value to reduce the influence of operator skill in the identification and measurement of defects in complicated structures that may be the result of additive manufacturing.

In this investigation, the network samples were designed as “an open structure” with external openings to allow the the un-melted powder to be easily removed after the build. This allows for that unmelted powder, in slots that are wide enough and in connection to the open parts of the network structure, can easily be removed from the structure after the build. The component will therefore not contain powder in these areas after the build resulting in a larger contrast between the solid parts of the sample and the intended defects as compared to the solid sample case, where some of the un-melted powder remains in the slots.
In contrast to the solid samples, the narrower slots in the network samples were fully or semi closed. For the aluminium sample, this is seen for when the width of the slots (as designed) are in the range of 0.11 – 0.14 mm. In the case of titanium this is even more marked. Here this effect is seen for slots designed to be up to 0.28 mm. This closure of the designed slots is due to partial or full melting of the intended openings. The reason for this is most likely an effect of excess heat around the melt zone due to reduced heat conduction in the network structures as compared to the solid structures (more material to act as a heat sink). Titanium also have a lower heat conductivity than aluminium resulting in that this effect of solidifying of the narrowest slots is even more marked in the titanium case (Figure 6) than in the aluminium case. This effect is also in agreement with results from additive manufacturing using SLM shown earlier [4].

Figure 5: CT image (virtual cross section) of a SLM aluminium (top) and titanium (bottom) as printed sample. Here, From left to right the designed slot widths are going from small to large (0.1 – 0.4 mm). Note the lighter grey areas indicating the existence of remaining powder from the SLM process in the titanium sample.

Figure 6. SLM titanium sample with internal network. Small slots (a) are more closed than larger slots (b).

For the SLM titanium that was HIPed, Figures 7 & 8, it is clear, but not unexpected, that the slots in a network structure were not closed by the HIP process in contrast to what happens in the solid sample. Since the HIP process rely on transferring the pressure to the component by gas pressure, it can not be expected that open porosity, such as the slots in a network structure, will be closed during processing. Only closed porosity can be “healed” by HIPing. However, if the gas that is entrapped within the pores is not dissolvable in the alloy (as e.g. noble gases) the pores will basically only be smaller but they will not “heal” completely.

The importance of removal of excess powder from network structures before additional heat treatment processes, such as HIPing, is evident from the Figures 7 & 8. In the case where this is not done correctly, the result may be as shown. Thus the structure will contain sintered or semi sintered remains of excess powder that will be very hard to remove. Although the density in these areas are not to the full extent of the solid material, the material of these regions are much more strongly bonded to the rest of the structure than after the AM process itself. This may influence the behaviour of a component in use in different ways depending on the design intent of the component in question.
General comments
A question that is often raised when discussing the application of CT in industrial contexts is the question of resolution. This is especially stressed when discussing porosity and defect determination. The detection of defects by the use of CT is highly dependent on the resolution in the CT system used. The resolution is also depending on both the material studied, density and dimensions, and the magnification, resulting in the voxel size and thus the resolution that can be obtained. By studying internal defect in Ti6Al4V parts built using electron beam melting (EBM) methods, Tammas-Williams et al. [6] found that using high magnification CT (2µm voxel size) can give results of porosity comparable to microscopy investigations. This level of resolution may however be hard to obtain in industrial CT systems and on many sizes of components. It normally requires samples of small dimensions, such as 1-2 mm. Tammas-Williams et al. [6] also performed CT scans resulting in voxel sizes of 10µm and concluded that in such a case it is not possible to detect pores smaller than 25µm. Most likely this may be considered as the low end of the detectability range for most current industrial CT systems. Work by Wits et al. [7] using voxel sizes of 9 µm have shown that CT underestimate the total volume of porosity as compared to microscopy methods although the trend of porosity between the different samples in their investigation was similar. In addition, the effect of CT magnification on the level of detail which can be distinguished in the surface morphology of AM surfaces have e.g. been studied by Zekavat et al. [8]. The resolution of the CT equipment and sample sizes used in this case was not high enough to resolve pores below sizes of at least (60µm)³. The extent of pore closure of small pores by th HIP process could thus not be determined. The intentionally manufactured defects with sizes down to 100µm could however be detected.

4 Conclusions
This work shows that industrial computed tomography (CT) can be a powerful tool in quality assurance of additively manufactured (AM) metallic components. Several difficulties do however exist based on geometrical configuration of the AM component in question.

For components without complex internal structures such as networks, the CT analysis can be done by a trained operator using visual inspection employing the mode Void and the algorithm VGDefx in software such as VGStudio Max. The detectability is mainly depending on the resolution of the CT system used, including the material type and component thickness.

For components with complex internal structures, such as networks and for topology optimised structures, at least for the types of defects studied in this work, the result is more operator dependant. In order to enable automation of the inspection process and/or to assist a trained operator, more work is needed to develop methods for CT inspection.
Additional result of this work is that the heat balance of the SLM process is sensitive to the geometry of the surrounding of the actual build site. The networks, being thinner and less material than the solid structure, seem to concentrate more heat around the build site while the solid structure act more strongly as a heat sink during the build. This may be needed to take into account in the design process for AM components.

Acknowledgements
The financial support from the VINNOVA program Production2030, through Grant 2014-05148, is gratefully acknowledged. The manufacturing of the test samples by Lasertech AB and the acquisition of the CT data by Bofors Test Center AB is also greatly appreciated.

References