Optimization of surface determination to improve the accuracy of detecting unfused powder in AM Aluminium component

Ahmed Tawfik¹, Liam Blunt¹, Christopher Dawson¹, Radu Racasan¹, Desi Bacheva², Paul Bills¹

EPSRC Future Advanced Metrology Hub, University of Huddersfield¹, Huddersfield, United Kingdom,
Ahmed.Tawfik@hud.ac.uk

HiETA Technologies Ltd ² Bristol & Bath Science Park Dirac Crescent Emersons Green Bristol BS16 7FR
desibacheva@hieta.biz

Abstract

Additive manufacturing (AM) is quickly being recognized as a core technology for producing complex and customized components, so the need for well understood non-destructive testing is more urgent than ever. The mechanical properties of cast components are well studied and non-destructive testing is well established by various methods like XCT and ultrasound. On the other hand, there are big challenges for NDT with regard to additive manufactured components as the pores are different in nature from those found in cast alternatives. In additive manufactured components, the pores could be hollow, filled with partially fused powder or unfused powder. Furthermore, porosity could be due lack of fusion of un-melted powder (low laser energy) or balling up effect (too high laser energy). There is also the possibility of unfused powder within the internal architecture of complex components. In such cases XCT becomes an essential detection tool.

This paper presents the design of an Aluminum (AlSi10Mg) AM artefact / sample with built-in unfused and semi fused powder features. Several defects with different shapes and dimensions were created. Two 1mm cylinder defects were placed inside an 8mm aluminium cylinder artefact. The first defect was located 200µm from the outside envelope of the surface and the second defect was located centrally 1mm from the top surface of the artefact. The built-in defects were used as markers to identify the determined powder grey value. A Nikon XTH 225 (Nikon Metrology, Tring) industrial XCT was used to analyze the pores/ defects’ location and volume. This threshold was utilized to ascertain the optimum ISO value for surface determination. Data processing, surface determination process and defect analysis was carried out using VG Studio Max 3.1 (Volume Graphics, Heidelberg). The artefact was then sectioned to confirm the actual location and dimensions of the designed defects using an Alicona G4 (Alicona, Graz) focus variation instrument. The results of the scans were determined using two different surface determination strategies. The results obtained from each of the defect analysis were compared to the designed value and the focus variation.

The focus of the study is on providing best practice for selecting inspection parameters, optimizing ISO value for porosity detection and identifying unfused and semi fused powder in AM SLM component.

Keywords: Additive manufacturing, Surface determination, Porosity analysis, Unfused powder, Non-destructive testing, AlSi10Mg

Introduction

Additive manufacturing (AM) is the process in which powder or wire is sintered to build parts layer by layer. AM is a relatively new approach to manufacturing and offers great potential over subtractive machining, in terms of weight reduction, design optimization and the creation of complex components with internal and external features that would be impossible with conventional machining [1-2]. The possible weight savings through use of AM design optimization will help to achieve carbon footprint reduction by reducing fuel consumption in aerospace and automotive applications. Furthermore, the amount of material waste in the AM process can be much lower than in subtractive manufacturing [3] especially when considering powder recycling. Several metallic materials are currently used in AM, ranging from Inconel to Aluminum [4-7].

At the moment one of the main reasons stopping AM from becoming more widely used in many industries is inconsistent fatigue performance. This issue is due to the existence of internal defects as a by product of the manufacturing process. These internal defects can reduce the fatigue life of mechanical components dramatically [8]. Also, it has been found that subsurface porosity can lead to crack initiation hot spots which vastly decrease the fatigue life of any AM mechanical components [9-14].

X-ray computed tomography (XCT) is widely used for measuring and non-destructive testing of AM components, this is due to the difficulty in measuring complex outer and inner geometry using conventional measurement techniques normally through methods such as CMM which can be time consuming and still require a large amount of post processing to determine full geometries. Furthermore, the ability of AM to build internal structures within components and consequent possible existence of internal defects requires an inspection method that can acquire internal dimensions and volumes. While XCT looks promising with various different technologies available, one of the main obstacles that stops XCT from being accepted is the level of subjectivity within the process allied to a lack of verification; the only way to verify internal features is by sectioning the part thus the process becomes destructive, losing time and costs. The challenges in inspecting
(AM) components are quite different than cast ones and unfused powder detection is one of the biggest issues, as the powder size used in sintering the (AM) component can be smaller than 20 µm. Detecting small pores/defects of such a size requires the use of high magnification and bespoke XCT settings.

The XCT results can be presented in the form of histogram which is plotting the number of voxels versus gray value. In the case of single materials, the histogram will contain two peaks: one peak will represent the air and the other will represent the material as shown in figure . A single threshold (ISO) grey value in the grayscale between the two peaks represents the edge of the material. The automated algorithm commonly used and cited in the engineering applications is ISO 50% surface determination [15]. ISO 50% shown in figure 1 automatically positions the threshold within equal distance between the maximum values of the two peaks of the histogram.

![Figure 1 Histogram image for single material.](image1)

![Figure 2 a Iso50% surface](image2a)

![Figure 2 b Local iterative surface determination](image2b)

There is no specific scientific explanation for selecting ISO 50%, furthermore implementing an inappropriate ISO value could erroneously classify some material as air and vice versa. This will result in a failure to correctly detect the edge of the component [16]. An earlier study carried out at K.U. Leuven showed that ISO 50% will result in dimensional shrinkage for aluminum and elongation for steel and Zro2. The study recommended utilizing ISO values 35-45% and 80-90% for aluminum and steel respectively [17]. Another study was carried out by Townsend et al [18]. looking at the impact of surface determination on the surface extraction of a Rubert 50 plate, the author scanned the plate with 12.9µm voxel size and compared four different surface determination strategies; three global and one local.

The first method used was a manual one where the global surface determination was set by the user optimizing the surface location, explained in details in VGStudio MAX 3.2 [19]. The second method was the standard ISO 50% surface determination method as explained previously. The third method was based on Otsu method [20] used in ITK [21], this method identifies two clusters in the grey value histogram minimizing the sum of the within-class differences between the background and scanned materials. The final method used was local iterative surface determination, examples of this method are shown in figure 2 [18]. This method enhances sub voxel detection by finding the max gradient in grey value and successfully differentiating between the edge of the material and air. The results of this investigation proved that all the global surface determination methods are achieving similar results.

XCT settings have an important influence on the obtained results, but what makes the process subjective is the accuracy in identifying the grey value threshold for measuring the enclosed internal features and defects. The grey value of the enclosed internal surfaces is different than those exposed to the outer surface. This difference is primarily due to the difference in X-ray path length between the outer edge and the center section of the component. The challenges in inspecting (AM) components are quite different to those which are conventionally cast. In these cases, the detection of unfused powder has been highlighted as a critical issue. The powder size used in the AM process can be smaller than 20 µm making detection difficult. Detecting small pores/defects of such a size requires the use of high magnification and bespoke XCT settings. It was also noted in an early investigation carried out by the author that the unfused powder particles’ grey value is closer to the fully fused material value [22].

**Methodology**

In this experiment a Nikon XTH225 industrial XCT was used to characterize a AlSi10Mg alloy 10 mm diameter artefact shown in figure 3 built using a Renishaw AM250 Selective laser melting (SLM). The sample contains several internal features designed to represent pores / defects, varying in size from 50µm to 1mm, and located between 150µm and 5mm from the outside surface of the component. The features were designed as geometric features (spheres, cylinders, prisms and helical prisms). This study will focus on the four cylinders located in the middle of the artefact shown in figure 3. The cylinders designed diameter is 1mm and length is 500µm, the cylinders are spaced 2mm from the center of each other. The distance from the outer edge of the part to the closest cylinder edge is 500µm.
The AlSi10Mg alloy powder used in this study had been recycled 7 times. Figure 4 shows an SEM image of the powder used and in which contamination is notable. The AM build parameters are shown in table 1, the part was located on the top right edge of the build plate and the argon flow in this build chamber is from left to right.

**Table 1 3D printing build parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>200w</td>
</tr>
<tr>
<td>Laser focus</td>
<td>0mm</td>
</tr>
<tr>
<td>Laser speed</td>
<td>0.55m/s</td>
</tr>
<tr>
<td>Point distance</td>
<td>80µm</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>25µm</td>
</tr>
<tr>
<td>Exposure time</td>
<td>140µs</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1400</td>
</tr>
</tbody>
</table>

The part file was converted to STL and the model was prepared with QuantAM software [23], the software was used to add the appropriate support structures, view the part slicing and orientation. Figure 6 (a) shows slicing of 4 cylinders. After the build the sample was then XCT scanned (26µm voxel size) to create a volume file of the entire part. The XCT scanning parameters were optimized by reducing gain and fine-tuning the histogram by minimizing beam filters and reducing filament current to ensure that measurement noise is minimized, without compromising X-ray beam penetration. Figure 5 shows a CT image of the actual sample.
The data obtained was analyzed using Volume Graphics VGStudio Max 3.1 to accurately quantify the unfused powder volume and determine the gray value threshold. The diameter and depth of each defect was evaluated by using geometry measurements tools in the software. To determine the adequate ISO threshold three different methods were employed: manually selecting background and material, selecting automatic ISO 50%; and manually identifying grey values of the pores/defects. To confirm the XCT results the part was sectioned by CNC machine and the features was measured with Alicona G4 focus variation microscope, the location of the defects was compared to the design and XCT results.

**Results**

The part was scanned with XCT then sectioned using a turning CNC machine, to ensure that the location for slicing and XCT dimensional measurement was coincident, the center of the 4 cylinders was selected as the optimum point. The location of the area of interest was designed to be 14.40 mm from the base of the part. While sectioning the location for the area of interest was 14.38mm, 20µm less than the designed location. Figure 6 (c) shows top view of the section area of interest. After sectioning, the cylinders in the area of interest were measured with the Alicona, the cylinders are numbered 1 to 5 from left to right. (location of cylinder 5 is shown in figure 6 (a)).

It was evident from the XCT results and the high magnification microscope images that the 5 cylinders contained semi-fused powder. The presence of the semi-fused powder meant that any attempt to measure the cylinders depth was unsuccessful. Furthermore, the presence of the semi fused powder changed the geometry of the cylinders such that in order to measure the length and width of the cylinders the longest distance was chosen. Whilst comparing the geometry of the 5 cylinders it was found that cylinder 1 and 5 (closest to the edge) are the most affected by the presence of the semi-fused powder. Cylinder 4 is the best manufactured when compared to the other 4 cylinders. The length and width results obtained from the Alicona measurement and XCT with different surface determination strategies are compared in figure 7.

The threshold value of the two surface determination strategies, namely; manually selecting background and material, and selecting automatic ISO 50% was identical. The gray value of the unfused powder was subsequently manually identified and then the obtained value was selected as the threshold surface gray value shown in figure 7 graph as (custom SD). Optimizing this threshold value enabled the detection of the overall contour of the pore and the gaps between the unfused powder particles. In terms of the dimensional comparison the
length and width values were constantly lower than the designed values the only exception was the width for cylinder 1 and 5 which were 2% larger than the designed width. The length comparison shows that the custom threshold results are closer to those obtained from the Alicona. Comparing custom ISO to the Alicona results, the difference in cylinder 1 is 0.5%, 0.9% for cylinder 2, 0.3% for cylinder 3 and cylinder 4 is 0.2%. The difference in value between Alicona and ISO50% for cylinder 1 is 9% and cylinder 2 is 7%, for cylinder 3 and 4 are 7.8% and 5.1% respectively.

Similarly, for the width comparison the custom threshold and the Alicona results, the difference in cylinder 1 is 1.8%, cylinder 2 0.5%, cylinder 3 4.5%, cylinder 4 and 5 are 0.9% and 1% respectively, whilst the differences between the Alicona and ISO 50% results for cylinder 1 and 2 are 6% and 4.1% respectively. For cylinder 3 the difference is 11.4%, cylinder 4 and 5 1.6% and 5.4% respectively.

The internal features were all affected by the melt pool dimensions, any designed feature under 150µm width or depth could not be resolved in the build. All the features that are located 200µm or less from the surface were not encapsulated and therefore appeared as holes. When analysing the geometric features it was found that the largest errors were in the spherical features with the prismatic features resolving more accurately. The voxel size used was found to be insufficient to resolve the individual unfused powder particles but in the case of the semi-fused particles it was evident that the semi fused particles were joining together in the areas closer to the melt pool creating bigger irregular particles, those particles grey value is very close to the solidified material which makes it more difficult to threshold and quantify.

**Discussion**

Utilizing the ISO 50% approach is widely cited as the generally accepted method for XCT surface determination for single material components. This experiment proved that the grey values of pores and powder defects of additive manufactured components are such that they require a different, more bespoke approach to be adopted. This study presents a generalized approach to determine the threshold level in AM produced components by manually defining the maximum gray value of the pore.

The results comparison proves that ISO50% successfully detected the pores filled with air but failed in detecting the individual contours of the unfused powder. The custom ISO threshold detected the cavities between the powder particles, it was also noted that for this study the gray value threshold was 60.9, which corresponds to ISO 63.2%. The values for the threshold can vary while scanning the same part due to scanning parameters selected by the operator, furthermore scanning different shapes and dimensions of the same material will always result in different grey value the threshold of the unfused powder will always be more than 50%. The grey value of the external background (air) for this investigation proved to be different than the background found inside the feature, the highest value for background was found inside the mid cylinder and lowest was inside cylinder 1 and 5.

![Figure 8 (a) powder contamination (b) semi fused powder (c) small semi fused powder](image)

The grey value of materials is directly related to the density of the material, this difference in grey value can be used to detected contamination within AM build as shown in figure 8 with brighter particles representing contamination. These particles have a grey value of 135 which was double the grey value of the background solidified particles. Figure 8 b shows an area of cylinder 5 with internal semi fused particles, these particles are bigger than those found in other cylinders. The grey value of the smaller particles (figure 5c) was found to be much smaller than bigger irregular particles, therefore it is much easier to threshold and detect smaller particles. The structural integrity of semi- and un-fused powder parts is considerably less than fully dense counterparts but with the presence of semi fused particles is it harder to accurately detect those particles.
Conclusion
The study demonstrated that it is possible to design a built-in defects artefact that contain unfused powder and semi fused powder. The artefact also showed some of the limitations of the SLM process in resolving small internal geometry features due to the melt pool/spot size. The results of this study also confirm that ISO50% is not the appropriate threshold for porosity analysis and for detecting unfused powder. The study has shown that to identify individual powder particles the exact grey value must be used. The values obtained from optimized surface determination proved to be closer to the alicona results than those obtained from standard ISO50%. The grey value of the unfused powder tends to be closer the material peak in the histogram. Visual inspection should be used to accurately identify the required threshold for surface determination. Optimization of surface determination can enhance the capability of non-destructive inspection to detect unfused or semi fused powder. It was also noted that the surface threshold values required for accurate porosity detection is different than that needed for outer surface profile measuring. The threshold for surface determination is dependent on the material, material thickness and scanning parameters. Therefore, scanning the same part with two different parameters will result in different ISO values.

Acknowledgements
The authors acknowledge the machining work done by Holtex Ltd, thanks to Aaron Holt for his assistance.
References


