DEVELOPMENT OF AN INTEGRATED POWDER BED FUSION ADDITIVE MANUFACTURING MONITORING SYSTEM: A CONCEPT

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ABSTRACT

As additive manufacturing is reaching maturity, the requirement for qualified parts has increased as additive manufacturing technologies is progressively being adopted into the aerospace and medical fields. For a part to be qualified, the quality of a manufactured part must be guaranteed. In order to guarantee the quality of parts manufactured using additive manufacturing technologies, extensive data must be collected during the manufacturing life cycle. This paper will focus on reviewing currently available additive manufacturing monitoring systems that could potentially be used for part qualification.

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1. INTRODUCTION

When additive manufacturing technologies was initially developed, it was mostly seen as a method to rapidly produce prototype models of conceptual products, hence the initial name of rapid prototyping [1]. However, as the technology matured, it has rapidly evolved to a technology that can be used to produce fully functional parts. With the integration of Additive Manufacturing (AM) into traditional manufacturing workflows, the requirement for adequate quality control of parts produced by AM systems have become vital [2] in the same way that quality control is important for parts manufactured using traditional manufacturing processes. These quality control measures are used to ensure that the part adheres to the predefined quality specifications.

Consequently, when manufacturing parts using AM technologies for aerospace and medical applications, these parts must be qualified before the part can be used for their intended purpose. This means that the machines and processes that are used for the manufacturing of these parts must be qualified according to specific industry standards. The goal of the qualification of parts can be described as the collection of data about a part or process that can prove that the said part or process will perform its designed function as expected [3]. This means that data must be collected of various parameters throughout the manufacturing process to ensure that the part was manufactured within specification. The use of in-situ AM monitoring systems has become one of the possible solutions that can be used to guarantee the final build quality of a part and provide valuable information about the process for qualification purposes [4]. This requires monitoring systems that can be used to record and analyse various parameters during the manufacturing process to monitor the outcome of the build and to ensure the part is manufactured according to specification. The data that is collected during the build process also forms part of the quality management framework around the AM platform. The data can also be used for part traceability, understanding the AM process and to make better informed decisions about part design and manufacturing [5].

Another important application for these monitoring systems is with the development of advanced control feedback systems, which can be used to increase the efficiency of the AM technology [6]. These integrated monitoring systems could be used to rectify problems during the manufacturing process using pre-defined remedial actions. It should also be noted that these actions should be developed to fit into the quality frameworks.

The proposed research study will be focused on identifying both experimental and commercially powder bed-based AM monitoring system. The reason for choosing powder bed-based AM technologies is because in 2018, the Wohlers Associates published in their annual report that nearly 45% of the industrial machines currently in operation at services providers where powder-bed based AM machines [7]. Thus, it would make logically sense to focus on this technology as it makes up the majority of the international market share. The study will also address the features and operation of the different monitoring systems as well as a few novel concepts for the detection of defects, specifically during the re-coating cycle.

2. POWDER BASED AM TECHNOLOGIES

Currently, there are three major groups of AM technologies available on the market. They are generally grouped according to the form of the bulk material used to manufacture the part namely a liquid, powder or solid sheet [8].

The first group of AM technologies makes use of a bulk material in the form of a liquid. Technologies that form part of this group consists of but is not limited to: Stereo Lithography (SLA), Fused Deposition Modelling (FDM), Digital Light Processing (DLP) and Continuous Digital Light Processing (CDLP).

The second group of technologies makes use of a bulk material in the form of a powder. However, there are two different methods that can be used to manufacture a part using a powder. The first method is called co-axial powder deposition. This method involves the feeding of powder through a nozzle into the path of a laser beam which then melts the powder particles onto a substrate.

The second method re-coats layers of powder onto a substrate which then forms a powder bed that contains the parts being manufactured. There are several technologies that makes use of a powder bed to manufacture parts. Some of these technologies include Selective Laser Sintering (SLS), Binder Jetting (BJ), Direct Metal Laser Sintering (DMLS) and Multi Jet Fusion (MJF). These types of machines contain a number of common basic machine components, most often it is only the powder fusion methods that differs between the different technologies.

The third group of technologies make use of solid sheets of material that are bonded together using a roller and a special type of adhesive on the sheet material, high frequency welding or even a type of laser depending on the material type. Once the material has been fused together, the excess material is trimmed or removed using a tungsten carbide blade if the material used is paper or plastic and a high-power laser if metallic materials are used for the manufacturing of the part [9]. After each layer has been fused together and the excess material has been trimmed away, a new layer can be applied.

For the purposes of this study, only AM technologies that makes use of a powder bed such as Selective Laser Sintering (SLS), Binder Jetting (BJ), Direct Metal Laser Sintering (DMLS) and Multi jet Fusion (MJF) will be considered.

3. MONITORING OF POWDER BASED AM TECHNOLOGIES

3.1 Powder bed technology operation

In order to better understand the monitoring process for powder based technologies, it is necessary to briefly examine the powder bed based AM process. The diagram in Figure 1 displays all the basic components that powder bed based technologies have in common [10]. Although the diagram in Figure 1 shows the process for binder jetting, the only difference for SLS and DMLS technologies would be the powder fusion source. The fusion source is indicated with the letter (a) as illustrated in Figure 1. The rest of the components remain the same for all powder bed technologies.

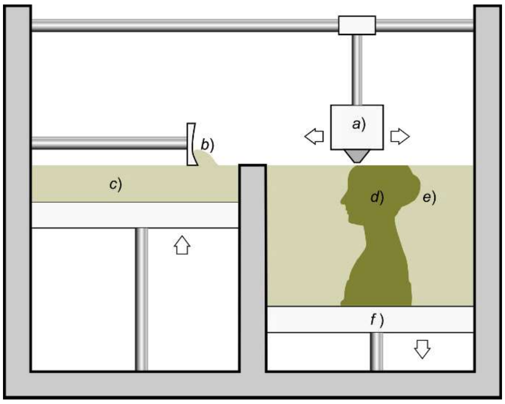

Figure 1 Powder bed Technology Components [10]

The manufacturing process starts when the build platform (f) is raised all the way to the top. Next, the powder feeder platform (c) is also raised by a predetermined amount. It is important to note that some types of machines makes use of a powder hopper in stead of a feeder platform, which would then not require this feeder platform raising step. The re-coater blade/scraper (b) then scrapes a new layer of powder over the build platform (f). Once the layer has been evenly spread over the entire build area, the binder head (a) moves over the build platform (f) and selectively sprays a binder solution over the powder to create the part geometry (d). The re-coating and binder spraying process is repeated until the entire part has been created. As the process is repeated for

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each layer of the part, a powder bed (e) is created by the surrounding unfused powder material. This then acts as a support for the part as the build progresses. Once the part has been completely manufactured, the part can be removed from the build platform and the excess powder removed from the manufactured part.

3.2 Monitoring of the powder bed.

The integration of AM technologies into the traditional manufacturing processes, has resulted in the increased demand for quality guaranteed parts. When parts are manufactured for applications such as the aerospace and medical sectors, very stringent quality assurance requirements must be met. These parts must undergo a qualification process in which a part is validated against specific ISO/ANSI/ASTM standards. Once these parts have successfully gone through this process, they will be referred to as qualified parts. The qualification process requires data to be collected throughout the manufacturing process, such as materials used, equipment used to manufacture the part, non-destructive testing of the part as well as the actual manufacturing process.

Apart from the gathering of data for the purpose of part qualification, there are often times errors that occur during the build process due to a number of circumstances. This can cause defective parts to be manufactured, as displayed in Figure 2. The part manufactured in Figure 2 will not pass the quality requirements as laid out in the qualification process due to the large defects present in the part structure.

Figure 2 Manufactured part with defects

In extreme cases, the entire build job may have to be scrapped completely due to the severity of the errors which indicate that the process parameters have deviated too far from the specifications and that the part has not been manufactured within qualification parameters [6]. This results in a major loss of raw materials, which becomes very costly. Thus, the data that is recorded using these additional cameras and sensors can also be used to detect the errors when they occur and with the appropriate feedback systems in place, can be used to either stop the build prematurely to prevent the further loss of costly raw materials, or appropriate remedial measures can be taken to repair the error that had occurred and allow the build to complete successfully. However, these remedial measures would also have to be in line with the quality management framework.

This research study will review currently available experimental and commercial monitoring systems for powder-bed based AM technologies. In-situ monitoring systems has been explored by several researchers with the aim to solve specific problems during the manufacturing process. Some of the approaches required that additional cameras and sensors be integrated into the existing machine [6] [11] whereas others made use of the existing machine infrastructure [14].

Upon reviewing the studies performed by other researchers, several research focus areas were identified. Although most of the researchers only focused on a single area, each focus area is vital to the monitoring of powder bed type AM technologies. An area that has been extensively studied include the monitoring of the surface quality of the powder bed after re-coating and part geometry scanning operations. One of the reasons why this area can be considered a priority research area is due to the fact that defects that occur during the re-coating and scanning phase have some of the highest risk of causing total build failure, or as with some of the metal AM machines, even physical damage to the actual machine due to re-coater strikes etc.

This gives an indication that certain areas of the manufacturing process have a greater need for monitoring than others. It does not however mean that the other areas can be ignored, but that certain areas of the manufacturing process can have a greater impact on build success than others.

3.2.1 Defect Detection and Post Scan Analysis

One of the focus areas that has received a substantial amount of attention from researchers is the detection of defects on the powder bed surface after re-coating and also after the scanning cycle. This is not limited only to powder bed defects, but also include defects that may occur on the scanned part contour/geometry.

The study performed by Southon et. al [11], an in-process measurement and monitoring system was developed using a fringe projection 3D scanner as displayed in Figure 3. The aim of the study was to test the feasibility of using a fringe projection scanner to monitor the powder bed of an EOS P100 machine that manufactured parts with polyamide 12. The study focused on the ability of a fringe projection scanner to record defects that occurred on the powder bed during the printing process.

Figure 3 Fringe projection scanner [11]

Even though the fringe projection scanner was mounted outside the build area, the study proved that defects could be detected that varied from hundreds of micro meters in width, up to hundreds of milli meters in width. It also proved the capability to detect and quantify various effects such as part curling, re-coater blade striking the part (Figure 3) and even the consolidation of a single layer of the powder in the shape of the part geometry.

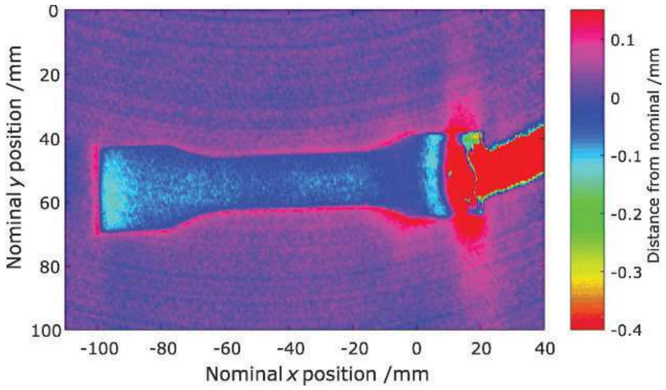

Figure 4 Re-coater Blade Strike [11]

In a study conducted by Li and Liu et. al [12], at the Huazhong University of Science and Technology, an in-situ monitoring system was proposed that also made use of fringe projection 3D scanning technologies. However, this study did not only focus on the scanning of the build area on the powder bed, but also scanned the entire powder bed post re-coating and post scanning to create a 3D surface topography map of the powder bed. This study scanned the powder bed using a custom-built fringe projection scanning setup. Two cameras were mounted over the powder bed at known distances, and a projector was used to project the fringe patterns over the build area as shown in Figure 5.

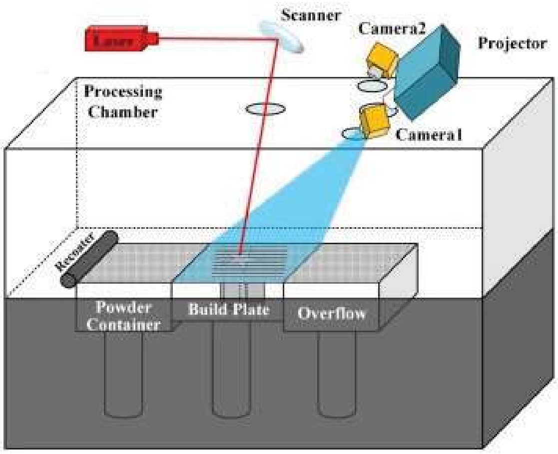

Figure 5 Camera setup for powder bed imaging [12]

These captured images were processed using an enhanced phase measuring profilometry (EPMP) method to create a 3D point cloud that can be used to monitor the 3D surface topography of the powder bed and the part fusion area. The output produced by the EPMP algorithm is displayed in Figure 6.

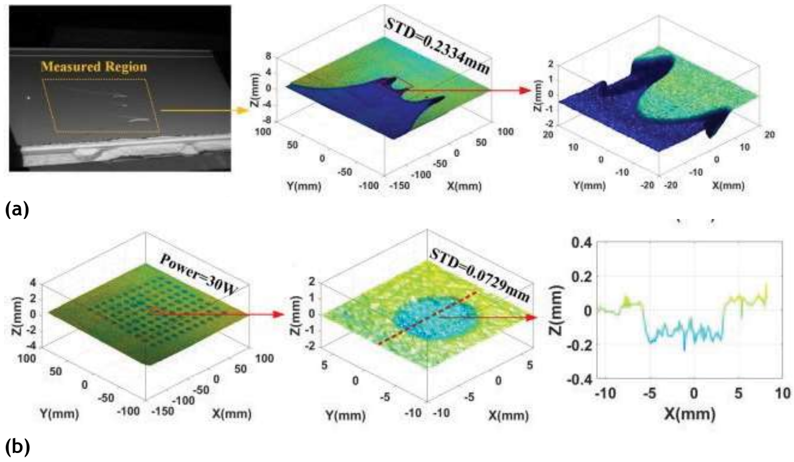

Figure 6 3D Surface Topography and 3D part contours [12]

The series of images shown in Figure 6a display the 3D topography representation of the powder bed, and clearly shows when a defect had occurred during the re-coating process. The second series of images in Figure 6b shows the fusion area topography of the entire powder bed after the scanning process is competed as well as the fusion area of the individual parts. Once the build was completed, the scanned 3D contours could be stacked to create a digital twin of the parts in the build. The digital twin could then be compared to the CAD model to ensure that the parts were within specification even before they are removed from the powder bed as displayed in Figure 7. This means that dimensional inaccuracies could be detected without even the need for physical measurement.

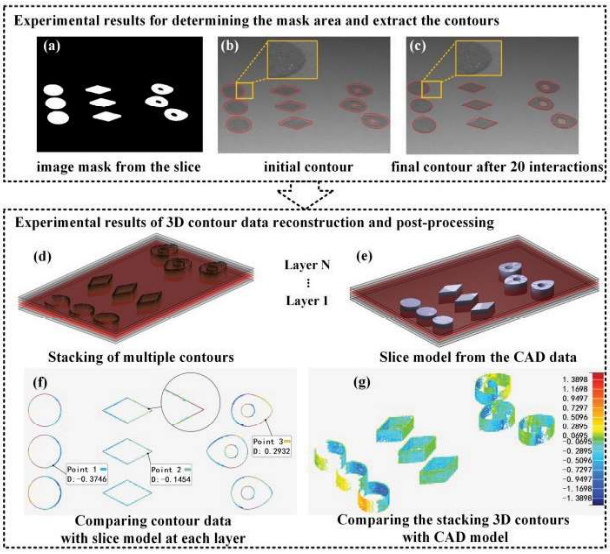

Figure 7 Comparison of Contour data to CAD model [12]

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In another study conducted by Abdelrahman et. al [13], a “flaw detection” system was developed using a DSLR cameras and several flash units and chamber lights placed in strategic locations inside the build chamber to capture images using a variety of illumination angles. The layout of the system is displayed in Figure 8.

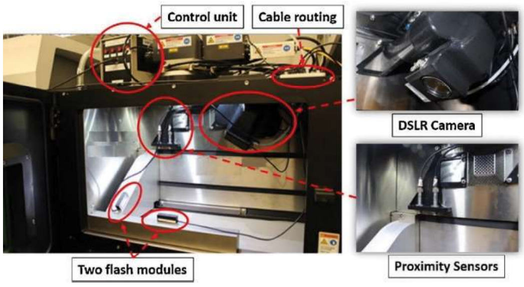


Figure 8 Camera and Lighting setup [13]

The system was designed to capture images of the powder bed after each re-coating cycle and also after each scanning operation was completed. The system was not integrated into the machine control system, but rather used proximity switches on the re-coater blade to trigger the image capturing process. Once the images were captured using each one of the 5 lighting angles, a specific region of interest was cropped out of the main image and these cropped images had a light normalization algorithm applied to them to enhance the features on the captured images. Each image was then segmented using a level set method to isolate only the part area that is of interest, and a shape-to-image registration technique is used to map the contours of manufactured part to the specific layer of the STL file as shown in Figure 9.

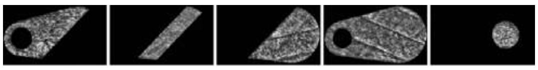
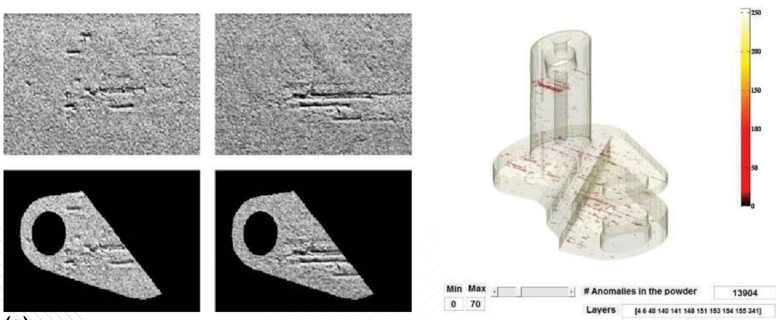


Figure 9 STL Layer image segmentation [13]

Once the part outline had been segmented out of the image, the images could be individually analysed to identify any defects that may be present either after the re-coating or scanning process. The images in Figure 10a shows re-coating defects that occurred over the part area which can potentially affect the part integrity. A 3D model was also constructed as shown in Figure 10b that shows on which layers of the part re-coating errors had occurred.



(a) (b)

Figure 10 Re-coating errors and re-coating error 3D model [13]

The images that were captured once the part geometry scanning has completed also followed the same segmentation process. However, the final processing of the images was different for the post re-coating and post-scanning images. For the post scanning images, a method was proposed that could be used to detect potential defects based upon the variations in the image intensity due to the differences in the lighting conditions of a part that contained a defect. This defect detection method also assumed that a defect could only be classified as a defect if it spans more than one layer. If an anomaly were detected on a single layer but not on the subsequent layer, it was not regarded as a defect. Once defects had been detected over the part area, they were highlighted as displayed in Figure 11.

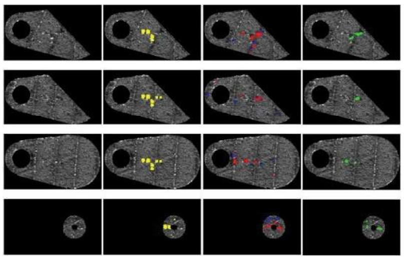


Figure 11 Detected Part Fusion Defects [13]

All these images with the defects present were then stored, and as with the re-coating defects, a 3D model was generated of the part as shown in Figure 12 showing the different layers where defects had occurred on the part without the need of a CT scan.

Figure 12 3D CT Model with defects indicated [13]

The recorded defect data could then be further corroborated by an actual CT scan to verify the presence of possible defects inside the part as well as any porosity that may have formed during the manufacturing process.

3.2.2 Defect Classification

Although several researchers had focused on the detection of defects that may occur on the powder bed, only a single group of researchers at the time of publication had focused on the classification of defects.

In the study conducted by Scime and Beuth [14], a novel method was proposed for the classification of defects using images captured with a computer vision camera mounted inside the machine and processed using image processing and machine learning algorithms. The individual layer images were captured using the EOSTATE hardware and software package, and the images were processed externally after the build job had completed. Since the camera was mounted at an angle and the images weren't properly illuminated and had to be brightened and warped to correct the image perspective using a series of image processing techniques. Even though the lighting conditions where not ideal, they could easily be corrected for in software since the lighting conditions remain consistent throughout the build. The view of the powder bed after processing is displayed in Figure 13.

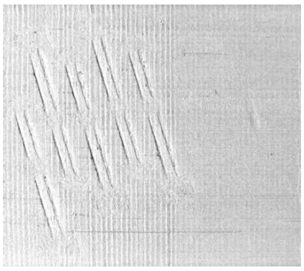


Figure 13 Improved Powder bed image [14]

However, before images of actual builds could be processed, a series of training images had to be selected for the machine learning algorithm. For this, powder bed images with the following defects present had to be acquired: re-coater hopping, re-coater streaking, debris on the powder bed, super elevation, part failure and incomplete spreading (also known as re-coater short feeding). Examples of the defects used by the authors is shown in Figure 14. The defect images where of a fixed size and did not include the entire powder bed image, only the portion of the image that contained the defect were used.

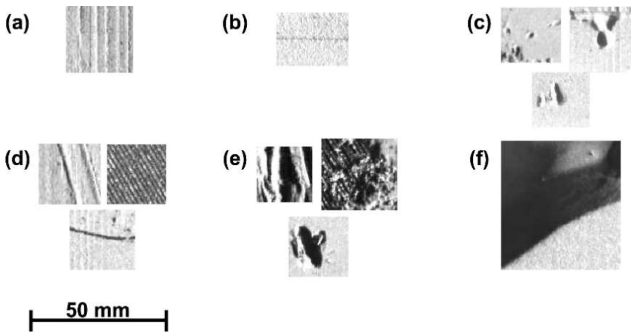


Figure 14 Powder bed defect types [14]

A total of 2402 images were used in the training database. The images also had to be manually sorted and tagged for the training purposes. Each of these training images were then processed by a specially developed algorithm that used various image processing techniques and machine learning algorithms in order to create a type of "finger print" for each type of defect. Each defect was then compiled into a dictionary against which future images of defects could be compared to. Anomaly free images were also added to the dictionary to simplify the dictionary searching process and prevent false positives. Since a large portion of a build should contain no defects, the no-defect images were classified as a type of defect to prevent pristine areas of the powder bed as being classified as a defect. Once the algorithms have processed all of the training images, images from actual build jobs can then be analysed. The entire powder bed image is broken up into patches and each patch is reviewed individually. Each image patch captured of the build is reviewed by the algorithms to create a unique fingerprint again. However, once a finger print had been created, it was compared against the fingerprints inside the dictionary and a percentage value that indicates a similarity value was generated. Based on the highest percentage value recorded for a specific type defect, the defect will then be classified as that type of defect. Once the build has been completed, a heat map of the build can be created which would indicate which areas of the build had defects as well as how many defects of a specific type had occurred in a specific area as shown in Figure 15.

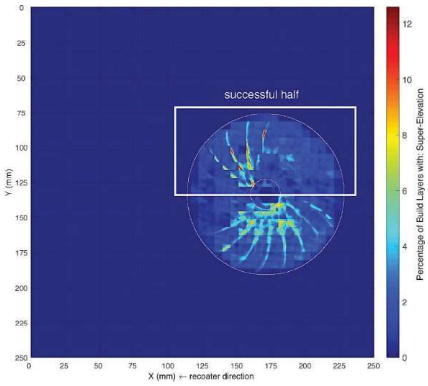


Figure 15 Heatmap of Super Elevation Defects [14]

3.2.3 Commercially Available Systems

Since this study considered monitoring systems that can be used to monitor build jobs, it is necessary to also consider commercially available systems. At the time of publication there were 3 commercially available monitoring system. These systems are Electro Optical Systems EOSTATE monitoring package, Concept Laser's QM package and Materialise Inspector.

- **EOSTATE**

The EOS EOSTATE monitoring suite is a modular hardware and software package that can be used to capture all production and quality data in real time [15]. This monitoring suite consists of four modules that can be used to monitor a variety of parameters. These modules include: EOSTATE ExposureOT, EOSTATE Meltpool, EOSTATE Powderbed and EOSTATE System. These four modules give the EOSTATE monitoring suite the capability to monitor the melt pool, the energy density applied to each area of the part geometry, the surface quality of the powder bed after each re-coating operation and the recording of all internal and external machine parameters. It should be noted that the EOSTATE monitoring suite can only be used on the EOS M series and can not be used on third party hardware or on polymers and other types of materials.

- **Concept Laser QM**

Concept Laser is a subsidiary company of General Electric Additive and has created their own hardware and software package called the Concept Laser Quality Management system that can be used to monitor various parameters of their own patented metal laser melting process called the Laser Cusing which is also their registered trademark [16]. This Quality Management system is modular in design and has various modules that can be used depending on the type of build being run and the data needed. There is a total of 10 modules available in the monitoring system. Some off the Concept Laser QM modules have been evaluated by scientists at NASA for their effectiveness as an in-situ research and evaluation tool [17]. It should be noted that the Concept Laser QM system can only be used on the OEM Concept Laser hardware and can not be used on third party hardware.

- **Materialise Inspector**

Materialise is a company that develops several software packages for AM such as the Materialise Magics software that can be used to stack 3D cad models inside a build envelope in preparation for a build [18]. The company also created an AM monitoring package that can be used to monitor build jobs and identify any possible errors that may have occurred. Materialise Inspector is a software tool that can be used to analyse data that is recorded throughout the manufacturing process from the preparation of the 3D model to the finished part in order to improve and guarantee the quality of the part. Some of the capabilities of Materialise Inspector include a slice viewer that can be used to analyse different build parameters such as vector with thickness, laser scanning strategies for multiple optics and a platform display with a scan or grid view. The other capabilities that Materialise Inspector has is post build image analysis of the images that are captured with a camera inside the main build envelope as well as big data analysis tools for in depth build analysis.

4. CONCLUSION

In this paper a series of studies were reviewed that focused on monitoring of powder bed type AM technologies. The studies that were reviewed focused on the detection of defects that occur on the powder bed. The defects often occur either during the re-coating cycle or after the powder material has been fused together. The information in Table 1 summarizes the potential advantages and disadvantages of the reviewed systems in this paper.

Table 1 System Advantages and Disadvantages

Researcher	Type of system	Advantages	Disadvantages
Southon et. Al [11]	Defect Detection	Detect small powder bed defects.	Can only monitor a small build area. Requires large amounts of computing power. Requires specialized scanner. Limited to polymer AM.
Li and Liu et. al [12]	Defect Detection	Detect powder bed defects. Detect part fusion defects	Requires large amounts of computing power. Requires specialized scanning equipment. Limited to metal AM.
Abdelrahman et. al [13]	Defect Detection	Detect powder bed defects. Detect part fusion defects	Requires specialized cameras and lighting. Limited to metal AM.
Scime and Beuth [14]	Defect Detection and Classification	Detect powder bed defects. Classification of powder bed defects	Requires large amounts of computing power. Limited to metal AM.
EOS GmbH [15]	Defect Detection	Detect powder bed defects	Limited to OEM hardware.
Concept Laser GmbH [16]	Defect Detection	Detect powder bed defects	Limited to OEM hardware. Limited to metal AM.
Materialise NV [18]	Defect Detection	Detect part fusion defects.	Limited to metal AM

After considering the disadvantages listed in Table 1, several common disadvantages could be highlighted, namely:

- Commercially available systems except Materialise Inspector is limited to OEM hardware only.
- All the systems focused on a single type of powder.
- All the studies except one focused only on defect detection.
- The defect classification study must be validated and tested for false positives/false negatives.
- No closed loop feedback into the machine control system

These disadvantages are areas in which future research could be focused on. Although a large amount of work has been done with regards to the monitoring of powder-bed based AM technologies, a lot still needs to be done.

Lastly, an important part of a monitoring system that has at the time of writing has not been addressed in depth by any of the researchers is the closed loop feedback from such a monitoring system into the machine control system. This capability would enable a machine to automatically take the appropriate corrective measures if an when a defect occurs without any human intervention required. This type of system would require specific defect information from a system such as developed by Scime and Beuth in order to make an appropriate decision as to how to deal with a specific type of defect. However, this corrective actions would have to be taken in line with specific manufacture standards to ensure that the quality of the part is still up to standard and can be guaranteed.

This study forms part of the main author's PhD study and will be used to identify possible gaps in existing literature for the proposal of the author's study. The overall aim of this PhD study would be the development of a modular type of AM monitoring system that can be used to monitor the build process of powder-bed based AM systems to potentially address quality requirements and improve the efficiency of powder-bed based AM processes. This system will then incorporate several of the methods used previously by other researchers as discussed in this paper.

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