

DETECTING DEFECTS DURING POWDER DEPOSITION IN ADDITIVE MANUFACTURING

ABSTRACT

Additive manufacturing applications, in areas such as aerospace and medicine, are limited due to the lack of process stability and quality management [1]. In particular, geometrical inaccuracies and the presence of mechanical defects hinder repeatability of the process. To break into industries with very high quality standards, an important issue to be addressed is in-situ quality control during a build [2, 3]. The work which will be presented here is focused on image based process monitoring of the powder bed after the deposition of a new powder layer. We will also discuss the effects these might have on consolidating the powder with the rest of the part. Preliminary results will be shown of defects identified after a new powder layer has been deposited.

1. INTRODUCTION

In additive manufacturing (AM) parts are fabricated by consolidating material layer-by-layer using an energy source and a three-dimensional computer aided design (CAD) of the part. In the work presented we make use of an AM technique called Selective Laser Melting (SLM) to create parts utilizing a powder bed system. A recoater is used to spread a thin layer of metal powder across the build area to smoothen the surface of the powder across the bed. A laser source then selectively scans over the bed according to the layer data, generated from the CAD file, melting the powder and consolidating it into a homogeneous part. The material not forming part of the design model is left untouched and acts as a support structure for the part. The build platform is now lowered by a layer thickness typically 20-100 μm . This procedure is repeated for each powder layer until part completion is achieved. A schematic overview of a typical SLM machine using a powder bed system is shown in fig. 1.

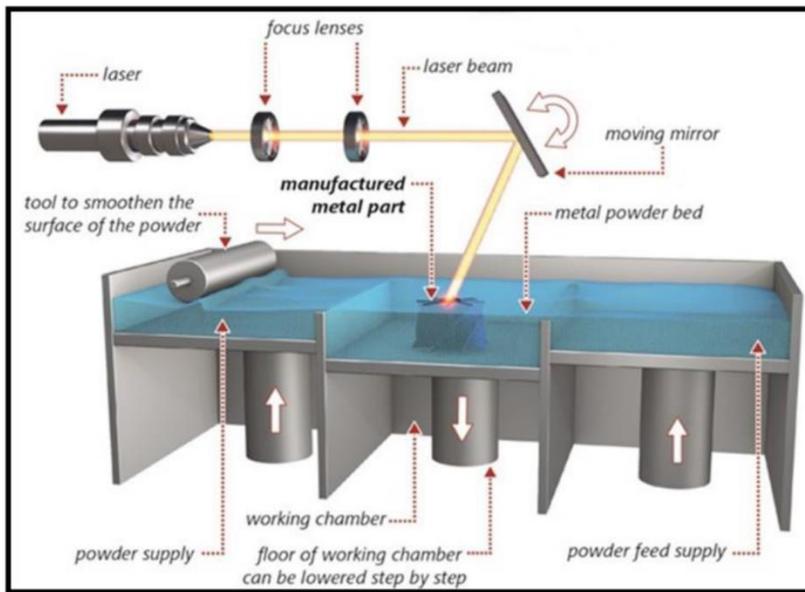


Figure 1: An example of a typical AM machine making use of a powder bed system (Source: empa.ch).

This technology has the advantage over current industrial subtractive manufacturing (SM) (milling and turning) as it allows building of high geometrical complex parts [4]. These two techniques are drastically different from one another and as such the adoption of standards and certification of quality from SM to AM is not possible. New standards and part certification is required for AM as it is a new technology completely different from SM [5, 6]. Verifying the quality of a part is mainly done after part fabrication which does not allow the operator to act upon defects observed during the actual build.

To circumvent this deficiency, it is critical that in-line process monitoring systems are implemented. One can distinguish between two types of in-line process monitoring systems: powder bed monitoring for powder deposition defects [2] and meltpool monitoring to probe the dynamics related to melted powder and the formation of a homogenous part [3]. T. Craeghs et al. [2] demonstrated it is possible for in-line process monitoring of recoater related defects during powder deposition based on the principle that shadow regions will form on uneven surfaces if a light source is placed at an angle relative to the surface normal.

The type of defects one can detect include, but are not limited to:

1. Recoater damage,
2. Extrusion (super-elevation) of sections of the part beyond the new powder layer,
3. Powder deficit and
4. Power recoater hopping.

Each of these can lead to different types of metal powder consolidation defects [1]. Recoater damage and recoater hopping lead to high surface roughness. Part extrusions leads to more powder deposited at the extrusion than the rest of the powder bed which in turn allows the extrusion to grow in size each layer added. Powder deficit cause the solid part to re-melt leading to rising temperature gradients and high stress levels on the metal surface which ultimately lead to cracking. An example of recoater damage leading to high surface roughness can be seen in fig. 2.

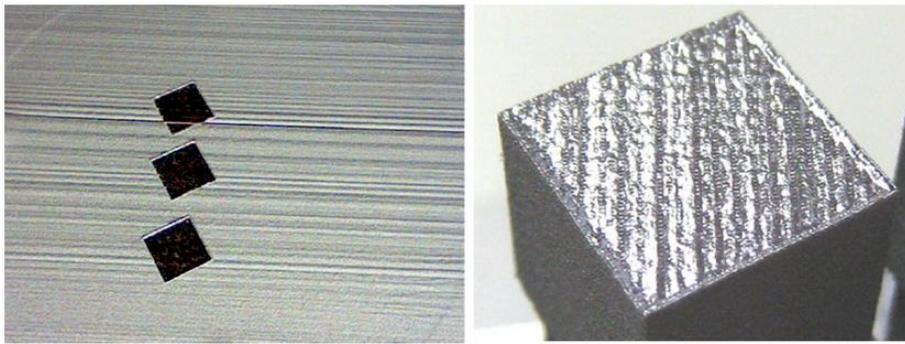


Figure 2: Recoating defects leading to high surface roughness after material consolidation (Source: [2]). (a) Part is still on the powder bed surrounded by powder. (b) Part removed revealing a high surface roughness.

If defects on a new powder layer can be detected before laser melting occurs, a new layer may be suitably recoated or the process can be paused for user controlled rectification.

This work will present an image based system to collect information of powder layer deposition defects using the shadow casting method. A few main defects during recoating will be identified and analyzed to establish the severity and possible impact of the defects on metal powder consolidation. For this, a software package was developed to auto-detect defects. This is aimed towards developing a system which in the future will contribute to quality assurance.

2. METHODOLOGY AND EXPERIMENTAL PROCEDURE

The technique we consider to detect powder layer defects is dependent on the formation of shadows on the powder bed (denoted working chamber in fig. 1) as a result of a light source positioned on one end of the bed and illuminating a powder layer across the powder bed. We implemented a strip LED as the light source where the initial location of the strip was parallel to the powder bed and was positioned 300 mm above and 500 mm right from the centre of the bed.

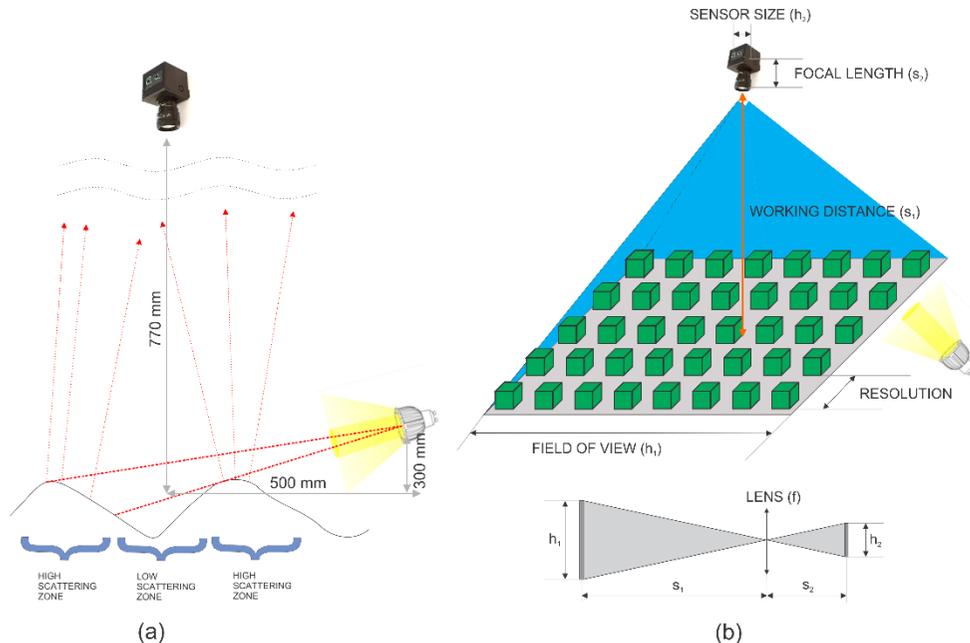


Figure 3 (a) Illustration of shadow casting due to a light source illuminating a powder bed from the right. Regions of high scattering is observed for higher powder levels where low levels of powder result in low levels of scattering. (b) Is the setup used to image the powder bed.

A single layer of powder is illustrated as an oscillating wave of peaks and troughs as shown in fig. 3(a). If the light source is positioned on the right with a camera above the bed, the light impinges on the positive slope of the powder and illuminates extrusions with shadow regions formed over the troughs. This is also true of the light source positioned on the left; however, the opposite of the case above occurs. Hence, the light intensity captured by a camera (represented as a grayscale intensity measurement) can provide information regarding the surface roughness of new powder layers deposited on the powder bed. Fig. 3 (b) shows the optical setup used during image collection. Visual detection of the powder bed was achieved with a CMOS camera (Mightex, SME-B050-U) mounted 770 mm above the powder bed (working distance, s_1).

A 12 mm lens (f) was used to image the powder bed (h_1) onto the CMOS chip (h_2) leading to an object to image transformation of roughly $150 \mu\text{m}/\text{pixel}$ and a field-of-view of 28.5×38 mm. To resolve a feature on the powder bed the required resolution is at least twice the object to image transformation. This implies at best we can only resolve defects the size of $300 \mu\text{m}$ and larger with the current system in place. To simplify mathematical computations during image processing, a square section of the image is selected leading to a field-of-view 20.8×20.8 mm (1400×1400 pixels). Experimentally, it was necessary to induce powder bed defects based on the recoater to ensure their adequate detection and sampling. This was achieved by using an old recoater which exhibited several defects on the powder bed after powder deposition as shown in fig.4 (a). The defects include (1) Recoater damage, (2) Super-elevated part, (3) Powder deficit and (4) Recoater hopping due to momentary mechanical failure of the recoater. Such defects can lead to the fabrication of a poor quality part or even part failure.

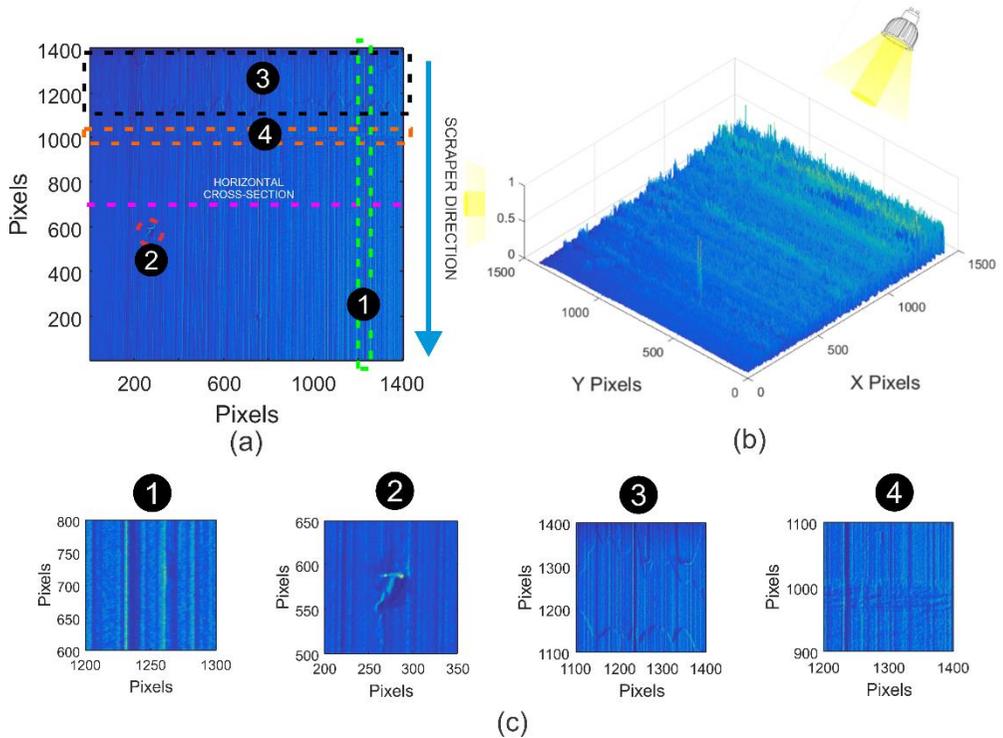


Figure 4: (a) 2D representation of powder bed defects artificially created on the powder bed. (c) Defects include: (1) Recoater damage, (2) Super-elevated part, (3) Powder deficit and (4) Recoater hopping due to momentary mechanical failure of the recoater. (b) Shows the 3D representation of imaged object.

As previously stated, the defects shown in fig. 4(a) are typically identified through a visual inspection of the powder bed which necessitates the presence of an operator at all times. In future this will be circumvented using an in-situ imaging system with complimentary software to identify the defects.

Within the 2D representation (fig. 4(a)) of the powder bed image, the broken boundaries for the various defects are not easily differentiated. If we consider a 3D representation, however, it is possible to observe the noisy information landscape but not the powder deficit defect. Therefore, standard procedures of identifying the outlines of defects using edge detection algorithms are not possible and more comprehensive software analysis is required.

3. DATA ANALYSIS AND RESULTS

The analysis of the defects induced on the powder bed was achieved through the development of software to automatically identify the defects as shown in fig. 4. Images of the powder bed were captured in a standard laboratory environment where the powder bed was exposed to several ambient light sources. The light source used to illuminate the powder bed was also not a point source, but consist of an array of LEDs. These all lead to increased background layer noise which needed to be suppressed as far as possible before locating the powder layer defects.

The data from the camera images are greyscale values that range from black, zero intensity (0) to white, maximum intensity (255). A 2D polynomial fitting function was utilized to

establish the localized image averages (considered as background noise) and subsequently subtracted it from the original image. This changes the data boundaries from -255 to 255 which were renormalized to range from -1 to 1. A 2D smoothing algorithm was then applied to the image (weak filtering) which reduced the effective resolution, but ironed out sharp contrast differences between neighboring pixels not associated with the formation of shadows from the illumination light source. Depending on the type of defect, different image processing methods were utilized to identify the powder layer defects. The subsections that follow demonstrate the procedures implemented to identify some of the powder bed defects as shown in fig 4.

3.1 Recoater

Recoater related defects appear as lines parallel to the recoater coating direction across the powder bed. In our case, this is seen as bright and dark vertical lines in fig. 5(a).

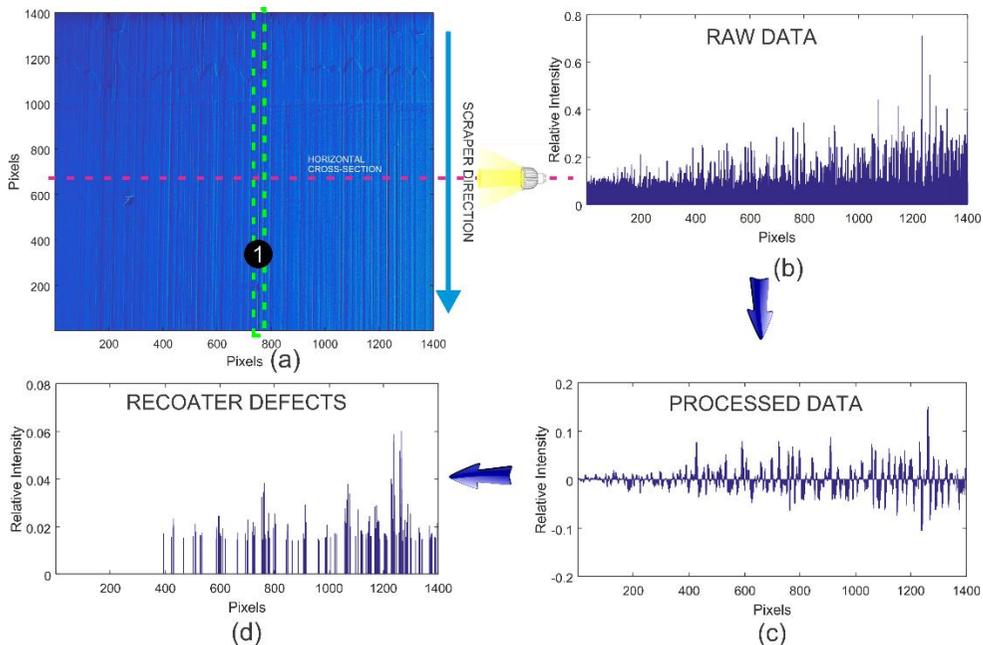


Figure 5: (a) Unfiltered images taken of the powder bed exhibit vertical lines which is associated with recoater related defects. (b) A cross-sectional cut ((a), pink line) perpendicular to the recoater coater direction is selected for processing to search for recoater damage. The data from (b) undergoes several filtering processes (c) to clean-up the information before finally being subjected to intensity filtering to isolate the location of recoater damage (d).

Recoater related defects can be identified by selecting a horizontal cross-section (as illustrated in fig. 5(a), the pink line) of the 2D camera data as shown in fig 5(b). Fig. 5(c) is the processed data after background subtraction showing the greyscale values below and above the averaged greyscale value. Not all the lines in fig. 5(a) are due to recoater damage as there is a tolerance in the acceptable layer flatness (or surface roughness) related to the particle size being coated as well as the surface roughness of the recoater. The roughness of the recoater is typically in the nanometer range for a new recoater which implies that the surface roughness will typically be of the order of the particle sizes which in general range between 40-100 μm .

To identify recoater related damage, we determined the steepness between neighboring pixels where 2 standard deviations from the average greyscale value (fig. 5(d)) is considered as recoater damage. Recoater damage was primarily observed on the right side of the powder bed due to the close proximity of the light source where the light intensity is

higher and thus produces more scattering. The low light intensity on the left side of the powder bed resulted in the software not adequately identifying recoater damage. This problem can be mitigated by implementing a secondary light source on the left of the bed. Two images may then be successively captured for each light source and superimposed to illustrate a fully illuminated bed. In this particular case the cross-section was selected in the middle of the vertical axis. Several of these cross-sections across the image along the vertical may be selected to improve defect detection.

3.2 Extrusions and super-elevated parts

Super elevated parts are sections of the built part which extends beyond the newly recoated powder layer. These can be identified by comparing the build outline (from the computer generated slice files) with the powder bed images taken after powder deposition. Extrusions, however, not related to the actual part (for instance large sputtered particles); require the complete powder bed to be evaluated and not only the areas where a build is in progress. From fig. 4 it is clear that the vertical lines created by the recoater dominates and will influence most procedures used to identify other powder layer defects. To prevent this we sampled over the horizontal axis with a gradient based algorithm while searching for local centre of mass locations within the image. This allowed us to identify a super-elevated part as shown in fig. 6 (left). Fig. 6 (right) is zoomed in on the location where the super-elevated part was detected.

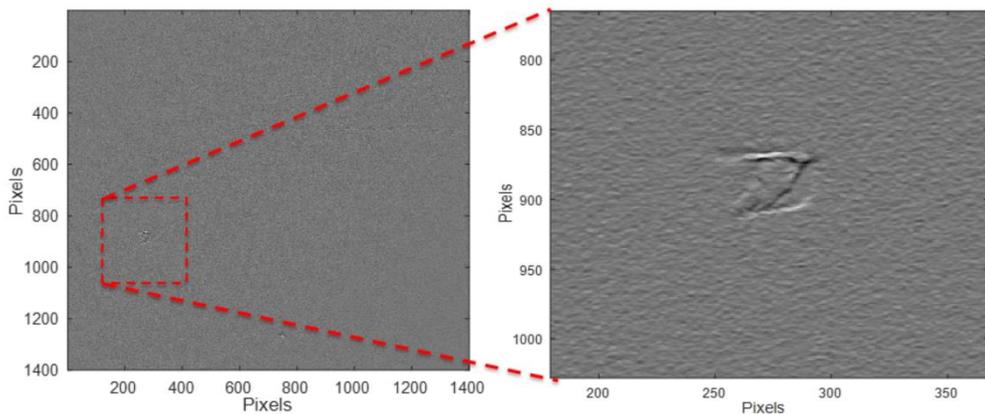


Figure 6: (left) Defect number two in fig. 2 which is an extrusion of the part beyond the powder bed powder layer. (right) Zoomed into the area where the extrusion is observed.

In this particular case we were searching for the defect with the largest gradient differences in relation to its neighborhood. In general, detecting extrusions are not only based on gradient detection methods, but also incorporate algorithms searching for the physical transverse size (number of pixels) of the defect. Due to the low camera resolution it is possible for a single pixel to represent part of an extrusion as well as part of the background if the defects are small. In this case our current approach may not be used due to the poor contrast of the elevated section in comparison to its neighborhood. This may be overcome by implementing higher resolution cameras which will aid in detecting smaller defects on the powder bed.

3.3 Powder deficit

Identifying locations of powder deficit is more difficult to identify than part extrusions due to the low signal to noise ratios observed at the edges created between high (normal) and low (deficit) powder levels. In our experiments the low camera resolution complicated our efforts to detect powder deficits due to the associated edges consisting of roughly 8 pixels

with poor contrast leading to poor resolvability of the edges. Furthermore, in certain cases the image at the edge comprise of defects from both the recoater and powder deficit as shown in fig. 7 (a), orange dashed circle. In this section the edge is broken by a distance of roughly 15 pixels which extends beyond the thickness of the edge itself and therefore cannot properly be reconnected using edge connection algorithms without connecting other unrelated sections to the edge. The location of the light source on the right side of the powder bed also lead to good resolvability for edges facing the light source (fig. 5(a), red dashed line) vs. edges facing away from the light source (fig. 5(a), yellow dashed line).

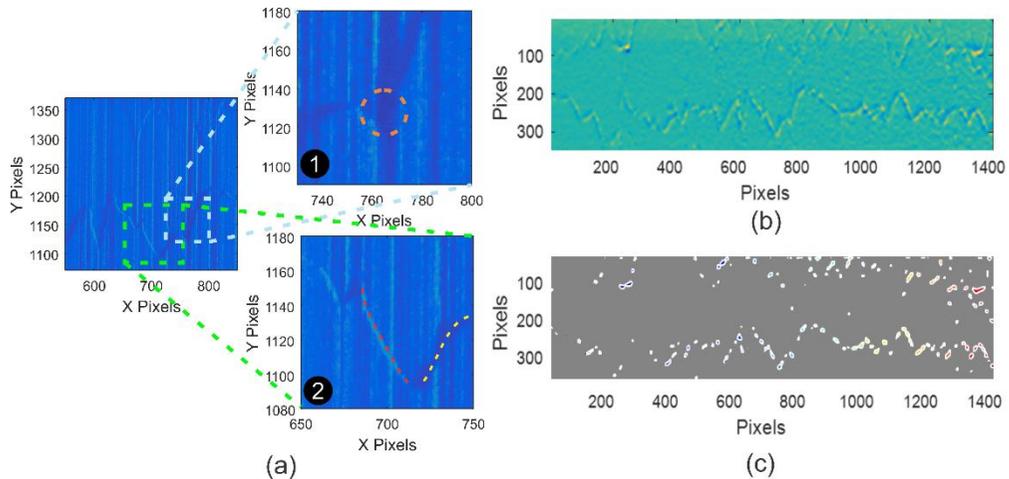


Figure 7: (a) Powder deficit observed due to scraper defects. The orange dashed circle show overlap between defects from scraper damage and the edge created between the low and high powder levels. The red dashed line show an edge facing the light source which can be resolved while the yellow dashed line faces away from the light source and is poorly resolved. (b) Low intensity filtering combined with gradient based algorithms to identify the edge between low and high powder layer levels. (c) Powder deficit located after thresholding.

Converting the grayscale images to binary white (1) and black (0) allowed us to partially resolve the edges by suppressing data below a preselected threshold value. Unfortunately this also removes in part information related to the edge between high and low powder layer levels. Fig. 7(c) shows the part of the edge identified. The edges on the left of the powder bed weren't identified due to too low signal to noise ratios.

3.4 Recoater hopping

Recoater hopping does not necessarily lead to a single horizontal line, but can lead to several closely located lines as shown in fig. 8(a) as it consist of intermittent areas of dumping to much powder or pressing into the new created powder layer forming a powder deficit section. Similar to the case for detecting powder deficit one finds the signal to noise ratios very low related to image sections exhibiting recoater hopping defects. Furthermore, the defect lines face the light source causing low light scattering henceforth small shadows with low contrast. A similar approach was taken as in the case of detecting powder deficit. Similar to the defect of powder deficit only part of the hopping could be identified as shown in fig. 8(c).

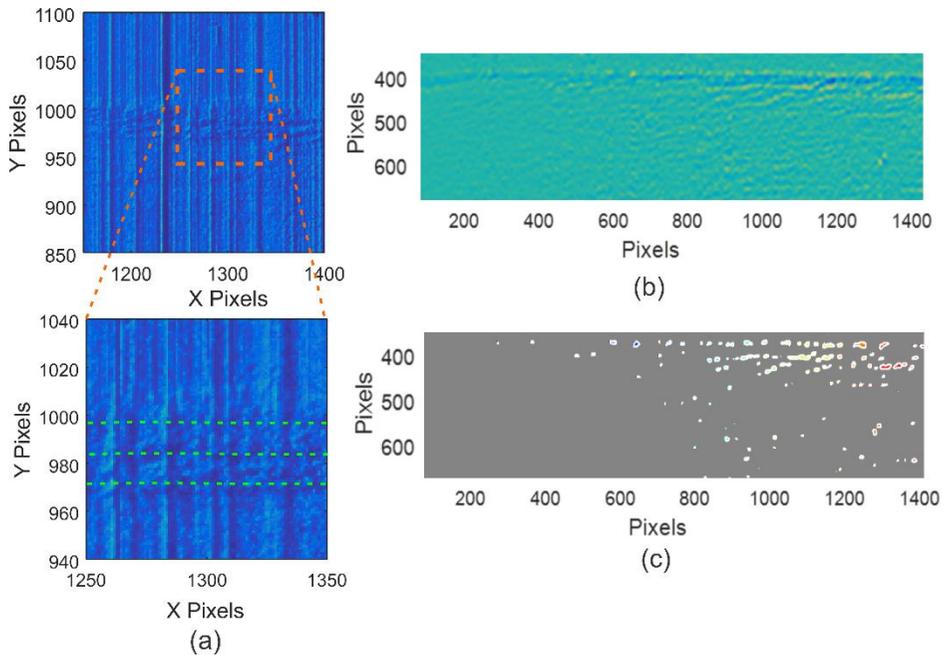


Figure 8: Recoater hopping observed as intermittent sections of too much powder deposited as well as sections of the recoater pressing into the new layer deposited. (b) Filtered data before thresholding. (c) Filtered data after thresholding.

This implies the current state of the setup does not allow one to identify proper identifiers for the various defects which is necessary to deploy in machine learning.

4. FUTURE WORK

In this work, we have developed software approaches to identifying defects. Further success in identifying powder bed defects strongly correlates with an improvement in the optical measurement system. The two main contributors to poor defect resolvability in this work were:

1. Poor lighting conditions
2. Low camera resolution

In our experiments, defects were best detected in regions closest to the light source due to high scattering levels leading to higher signal to noise ratios. A close to collimated light source over the bed will result in more evenly detected defects across the left and right side of the powder bed. Furthermore, light sources on different sides of the powder bed are proposed to enhance edge features pointing away from the light sources. To be able to resolve smaller features and provide sufficient information on defects, high resolution cameras will be implemented in subsequent work to obtain a resolution of approximately 50 $\mu\text{m}/\text{pixel}$.

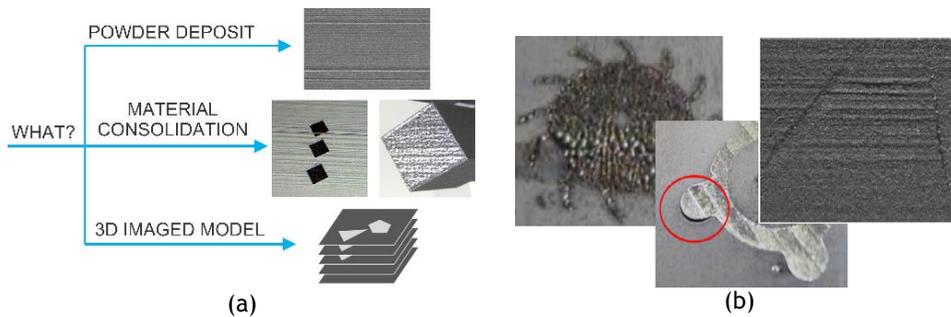


Figure 9: (a) Different areas considered for future work. This includes imaging the powder bed after metal powder consolidation as well as constructing an imaged 3D model of the built to investigate dimensional mismatches between the parts built and the CAD of the build. (b) Powder consolidation defects one would like to identify. (1) Balling effect of particles, (2) part extrusion, (3) delamination of the part.

This new system will be extended to also monitor the part after metal powder consolidation to quantify how powder layer defects influence consolidation (fig. 9(a)). Fig. 9(b) shows 3 different features one could detect using the same setup as that for the powder bed monitoring. Future work also includes the construction of an imaged 3D model of the build to investigate dimensionality mismatches between the built part and the CAD of the build.

5. CONCLUSION

Certifying AM parts plays a key role in the success of the adoption of AM built parts in industry. We have performed preliminary monitoring experiments and developed complimentary software to detect powder bed defects. To achieve this we made use of several different approaches leading to the successful identification of recoater damages as well as part extrusions. The main contributors to poor defect resolvability has been identified while also providing possible solutions. In future this will aid us to improve our current detection system to also resolve powder deficit and powder hopping defects successfully.

The final output for this work will provide fundamental information regarding consolidation defects related to powder layer deposition towards part qualification by process monitoring.

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