Optical, layerwise monitoring of powder bed fusion

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Abstract

In powder bed fusion additive manufacturing, pre-placed layers of powder are successively fused to form three-dimensional components. During part build-up, flaws in the material or part geometry can occur and lead to an unacceptable part quality. Common flaws include porosity, poor surface finish, and thermal deformation. Here, a layer-wise imaging technique is presented for process monitoring. The technique relies on collection and analyses of images taken under oblique illuminations of fused and pre-placed powder layers. Results of three-dimensional reconstruction of image data and identification of potential flaws are presented.

1. Introduction

Additive manufacturing (AM) techniques are becoming increasingly viable for industrial applications. AM of metals is commonly realized through the powder bed fusion additive manufacturing (PBFAM) process. In this process, a component is built layer-by-layer by exposing sequential layers of metal powder to a high-power laser beam that melts and fuses the metal. For each layer, the beam is scanned over predefined paths based on 2D slices of a 3D CAD file. While PBFAM enables design freedoms unmatched by conventional manufacturing techniques, production methods require strict control of processing parameters and process conditions to achieve a high-quality final part, and there are numerous opportunities to inadvertently generate defects during the build. Post-process inspection technologies suitable for components produced by PBFAM, such as 3D microtomography, are often prohibitively time consuming and expensive, and do not offer the potential for mid-process corrective action. Additionally, since PBFAM is frequently used to produce customized, low-production-volume, high-value components, the technology cannot employ traditional statistics-based quality control techinques that are often used during high-volume-production. For these reasons, there is a pressing need for in-process sensing technologies that can be employed to enable in situ monitoring and quality assessment.

Novel sensing and control methods are continuously being developed with the goal of quality control and rapid qualification of AM components. In this work, possible sources of defects and errors in metal-based PBFAM are reviewed, and an optical, layerwise in-process monitoring strategy is introduced and discussed.

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2. Powder Bed Fusion Additive Manufacturing

One of the main draws of PBFAM technology is the opportunity for design and fabrication of complex geometries and internal structures not possible with other techniques. This design freedom allows for the consolidation of intricate, multi-part assemblies and pairs well with advances in topology optimization and modeling. This section provides a summary of the PBFAM process and an introduction to some common defects encountered in the AM process.

2.1 Process summary

In metal PBFAM processes, sequential layers of powder are melted using a laser beam scanned rapidly across the part using a galvanometer-based beam delivery system. The process typically takes place in an enclosure with a controlled atmosphere. In laser PBFAM, the chamber is typically filled with argon or nitrogen to prevent undesirable impacts on microstructure, such as the formation of metal oxides. A schematic representing a characteristic powder bed fusion process is provided in Figure 1. The laser scanning system employs computer-controlled galvanometers to manipulate the laser spot across the powder bed. The focal point of the laser is held in a plane parallel to the build plate by use of a flat-field optic, e.g. f-theta lens, or other means. In some cases, the F-Theta scanning optic is designed to provide a linear relationship between the scan length and the angular velocity for the output beam, which simplifies galvanometer control and makes such lenses ideal for scanning applications.

The powder coating system comprises a powder reservoir, a build platform, a recoater blade (or roller), and a powder overflow reservoir, as shown in Figure 1. Metal powder, with typical mean particle diameter less than 50 µm, is packed into the powder reservoir and leveled. At process initiation, the platform under the reservoir is raised by a predetermined amount, selected to ensure complete powder coverage over the previous layer, with a deposition thickness that is married to the defined laser processing parameters. The recoater blade (or roller) spreads the powder across the build plate leaving behind a uniform layer, with excess powder pushed into the powder overflow reservoir. The thickness of each layer, typically in the range 20–60 µm, is also governed by the volume reduction that occurs during melting, consolidation, and solidification.

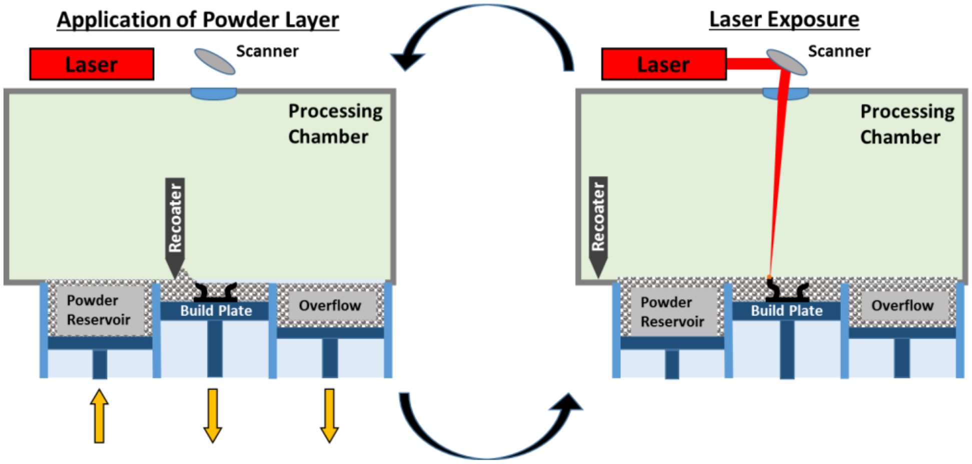

Figure 1. Illustration of the powder bed AM process.

Once a layer of powder is atop the build plate (or previous powder layer), the laser scanning system rasters the laser beam across the powder layer to selectively melt powder according to an exposure path created from a 2D slice of a part. Typically, the laser processing parameters are carefully tuned in a preliminary set of experiments, or are prescribed by the system manufacturer for a specific powder and layer thickness. Along each slice, contours represented by poly-lines are exposed along, or offset from, exterior and interior boundaries. The part interior is exposed along line segments called hatches. The order, arrangement, length, and spacing of hatches is prescribed depending upon the material and desired part quality. Two hatching strategies, stripe hatching and contour hatching, are shown in Figure 2.

Typically, part exposure at each layer comprises a contour pre-exposure step, exposure of hatches, and a contour post-exposure step. Each exposure may use different laser and motion settings depending upon underlying and overlaying layer geometry, the distance from an external surface, and the presence of sharp features. After exposure, the build platform is lowered and the process is repeated layer by layer as the AM part is built from the bottom up, surrounded by unfused powder. At the conclusion of the build process, the part must be removed from the build plate and, in most cases, additional processing is required.

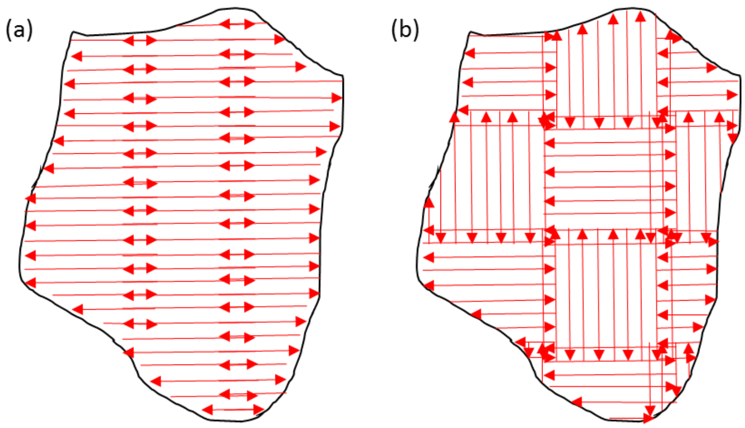

Figure 2: (a) Stripes hatching strategy. (b) Chess or island hatching strategy

Although conceptualy simple, the PBFAM process is complex and numerous factors can impact quality or result in defects. Even with all else held constant, different regions may require changes in processing parameters to achieve comparable quality. In a study by Mertens et al, it was found that down-facing and inclined surfaces both require lower laser power exposures than internal regions of the component in order to reduce clumping and increase the surface quality of the final part [1].

2.2 Process errors and defects

Numerous factors in laser-based PBFAM affect the overall part quality. Laser beam optics, spot size, Rayleigh length, power, wavelength, and raster speed all have a direct impact on how energy is transferred to the metal powder particles. Many of these factors have an inherent confidence interval over which values may vary. Differences in powder alloy composition, surface chemistry, size, morphology, porosity, particle size distribution, powder layer thickness, and packing density all contribute to variations in laser absorption that will affect the process and can influence the final material properties and quality of the build. Parameters such as hatch spacing and thickness must be set correctly to minimize lack of fusion defects and porosity during solidification. Build orientation, placement relative to other components, and design of so-called "supports" can vary local heat build-up and lead to generation of residual stresses and thermal distortion.

Defects generated during the process can be split into three broad categories based on their origin: (1) defects caused by the machine parameters or powder feedstock used in the build, (2) defects resulting from the build plan, which includes part geometry, part orientation, support design, and part location on the build plate, and (3) defects due to miscalibration or damage to the equipment.

Within the first category, defects relating to machine parameters or powder feedstock properties, there are multiple sub-categories. Hatch-based defects are those dependent on the distance between hatch lines, the offset distance from any contours, the length of each hatch line, and temporal and positional accuracy that effect the amount of overlap between the ends of hatch lines. Such defects are commonly embodied as porosity within a layer or a lack of fusion within a hatching pattern. Laser-parameter defects are those based on non-ideal laser power or exposure scan velocity. If the laser power at the powder surface is too low or the exposure speed is too high, there may be insufficient energy transferred to fully melt the powder and fuse it with the previous layer. Additionally, at the high scan velocities employed in this process, slight variations in timing of the laser beam on-off signal can also cause fusion issues. These effects are illustrated in Figure 3, below. If laser power density at the surface is too high or the exposure speed is too low, defects such as gas porosity and thermal distortion may result.

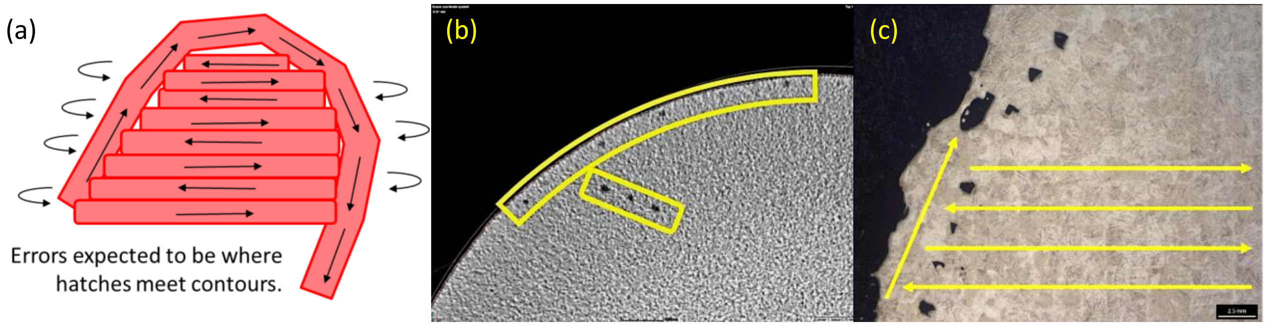

Figure 3. (a) Schematic that illustrates mechanism by which lack-of-fusion defects can occur at the overlap of hatch with contours due to position or temporal innacuracies in the scanning system, (b) an X-ray CT scan highlights defects found in a test coupon built with laser power set to 70% of nominal, and (c) macroscopic image illustrating similar lack-of-fusion defects in a part built using the equipment supplier standard processing recipe (courtesy of Moog, Inc.).

If the powder reservoir is insufficiently packed before the build process or the so-called "charge amount" (i.e. the amount of powder swept across the bed during each pass of the recoater blade) is set too low to account for powder consolidation during processing, powder shorting may occur. This results in a non-uniform powder layer as seen in Figure 4.

Figure 4. Image highlighting an example of powder shorting within the process chamber.

The second category of defects encompasses those related to part geometry and support structures, as these may lead to defects resulting from thermal gradients and distortion during the build. Cantilevered parts with insufficient support structure will deform and cause a defect known as super-elevation. The part deforms upwards, and shown in Figure 5a, and can interfere with the recoater blade as it spreads subsequent layers of powder. If support structures are not adequate, the stress may grow until the build fails, as shown in Figure 5b. Upon contact with the raised surface, the powder blade may catch and spring forward, flicking powder and causing a nonuniform powder layer as seen in Figure 6. The resulting non-uniform powder layer thickness is a likely cause of additional defects in subsequent layers due to the impact of the variation on laser-material interaction.

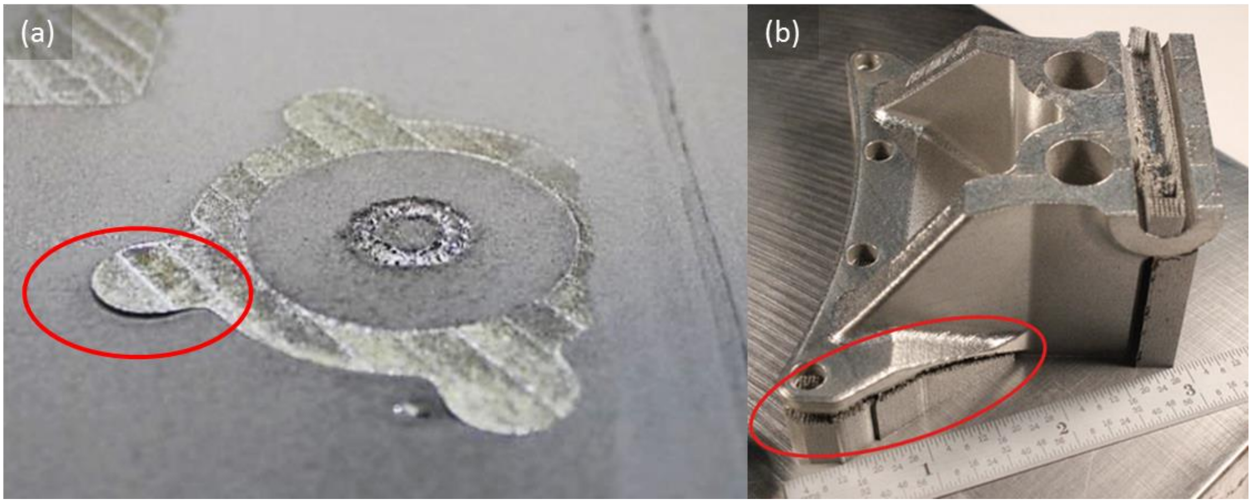

Figure 5. (a) Example of thermal distortion during the build resulting in disturbance above the plane of the powder bed. This distortion resulted in interference with the recoater blade that causes this build to be aborted prior to completion. (b) Photograph of a different component illustrating how support structure may fail before the build is complete (CAD model courtesy Honeywell, Inc.).

Figure 6. Image taken during PBFAM build highlighting powder flicking due to recoater blade spring-back.

Another source of defects related to the build plan is part location on the build plate. Laser spot elongation occurs near the edges of the build plate due to high scanner deflection angles, as shown in Figure 7, and any angular inaccuracy of the galvanometers has a larger effect further from the center of the build plate. This type of error in the build process can lead to lackof fusion, porosity, and geometric variations in the final part.

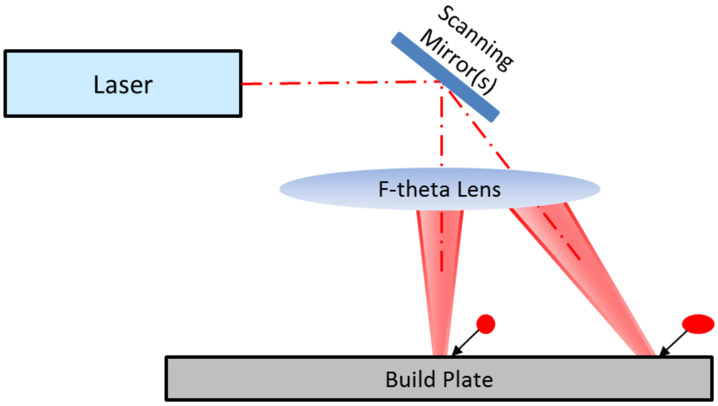

Figure 7. Illusatration of how exposure location impacts the shape of the laser beam spot.

The third defect category covers issues that result from damage, misalignment, or other errors within the PBFAM system. Partially fused clumps of powder or spatter from the melt pool may adhere to the recoater blade or be plowed across the powder bed during recoating. This leads to troughs within the powder and a non-uniform powder layer, as shown in Figure 5. The recoater blade may also impact distorted parts and "bounce" before settling, leading to regular perturbations in powder thickness, also shown in Figure 8. Defects may result from damage to the recoater blade or roller, a miscalibrated laser or stage position, or damage to the laser optics. Thermal deformation can lead to damage to the recoater blade or roller, and such nicks and gouges may result in striations and variations in thickness of the powder layer, shown in Figure 8. Uneven powder layers lead to changes to the physical interaction of the laser beam with the material resulting in inconsistent processing and, in some cases, porosity. A miscalibrated stage or laser scanner/galvanometer can also result in parts with innacurate final dimensions. Damage to laser optics may result from contamination or reflected energy from the powder bed, and can influence the local laser beam spatial energy distribution.

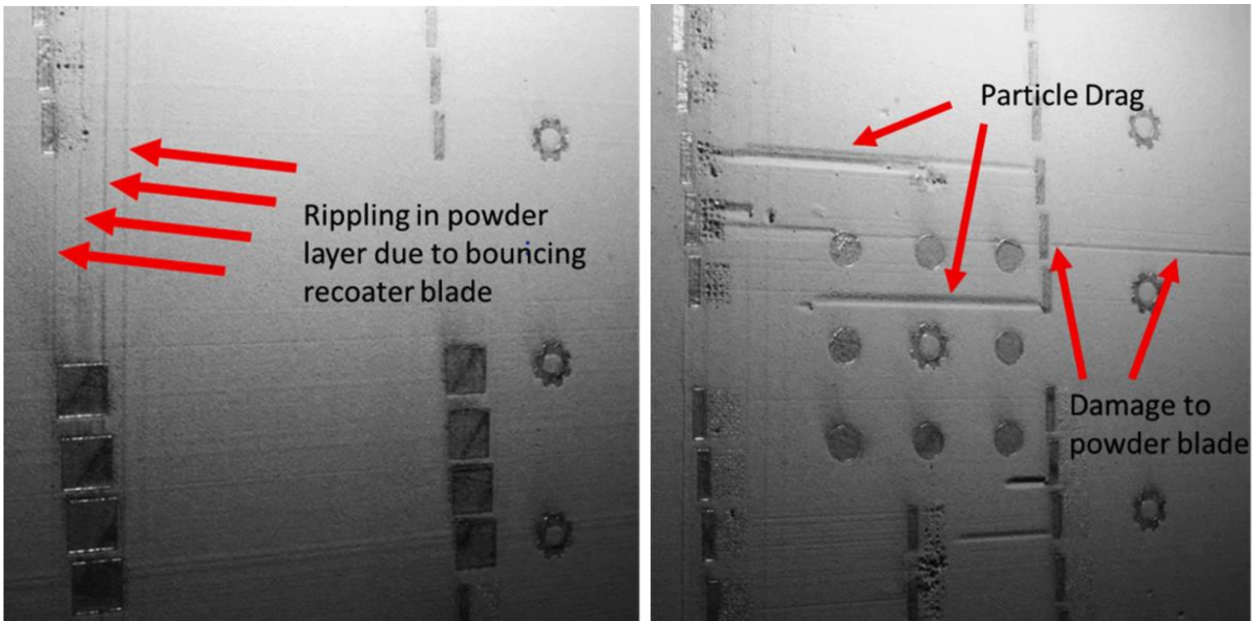

Figure 8. Image taken during a PBFAM build showing defects in the powder layer from recoater blade bouncing, particle drag, and damage to the recoater blade.

Each of these sources of process inconsistencies and defects can be monitored either directly or indirectly with a wide range of sensing technology. As sensing methods improve, the opportunity for in-process control for parameter adjustment and mitigation of process anomalies is likely to become a viable way to decrease defects in as-deposited PBFAM builds.

3. Optical, Layerwise Monitoring Of Powder Bed Fusion Additive Manufacturing

Investigations by Jacobsmühlen et al. used a 29 megapixel CCD camera mounted outside of an EOSINT M 270 chamber window using modular tube construction for easy adjustment [2, 3]. Images resolution was estimated to be ~24 µm/pixel, and at various times images were captured with two light sources after powder recoating. Exposed regions—regions appearing shiny due little or no powder layer atop them—were automatically identified using image processing techniques based on contrast, and were highlighted for the operator. These regions typically corresponded to locations where thermal distortion during processing led to displacement of components upward above the thickness of the next powder layer. Images were also captured immediately following the laser melting step. Jacobsmühlen et al. [2, 3] concluded that such imaging techniques could be used to detect geometric features for purposes of controlling dimensional accuracy and detecting powder contamination and recoater damage, but details to automate this detection were not provided.

EOS GmbH Electro Optical Systems has released software, called EOSTATE, that utilizes an integrated a 1.3 Megapixel industrial camera in the ceiling of an EOS processing chamber [4]. Images are taken after exposure in each layer and run through edge detection algorithms. Data on the edges are stored to create a record of part layers. The recoating step is completed and a second image is taken. This second image is also run through an edge detection algorithm. If any edges are detected, it signifies insufficient recoating. The process can be paused for evaluation or recoating can be repeated before continuing.

An additional technique developed by Craeghs et al. [5] takes a line measurement of gray values of the powder layer transverse to the direction of recoater blade motion. The gray value standard deviation is set according to a uniform powder layer and images of subsequent recoating steps are compared to the uniform powder coating. Any striping or deviation from uniformity is identified as a peak or dip outside the gray value standard deviation.

4. Development Of A High-Resolution, Layerwise, Optical Laser PBFAM Monitoring System

Here we describe the development of a high-resoultion, powder-bed moitoroing system utilized a consumer-grade 36.3 megapixel DSLR camera (Nikon D800E) with image size up to 7,360 x 4,912 pixels, mounted inside the EOS M280 build chamber, with multiple flash modules to enable imaging of layer of an AM build both immediately after recoating and after laser exposure. The camera is shrouded inside a custom designed, 3D printed enclosure and argon gas is fed directly onto the camera both to provide direct-flow convective cooling and to to prevent powder infiltration by creating positive pressure within the enclosure. To ensure the system has the flexibility to be installed on other systems, the control software does not integrate with the EOS M280 control software, but rather relies on a proximity sensor (Automation Direct CM1-AP-1H) to monitor and coordinate image capture based on the position of the recoater arm.

The flash groups are custom modules based off of Holga manual shoe-mount flashes with a guide number (GN) of 22 m that are strategically located at various locations within the build chamber, as shown in Figure 9, to provide high image contrast for a range of surface anomalies. Diverse lighting options are considered an important part of the imaging system in order to simplify automated defect detection.

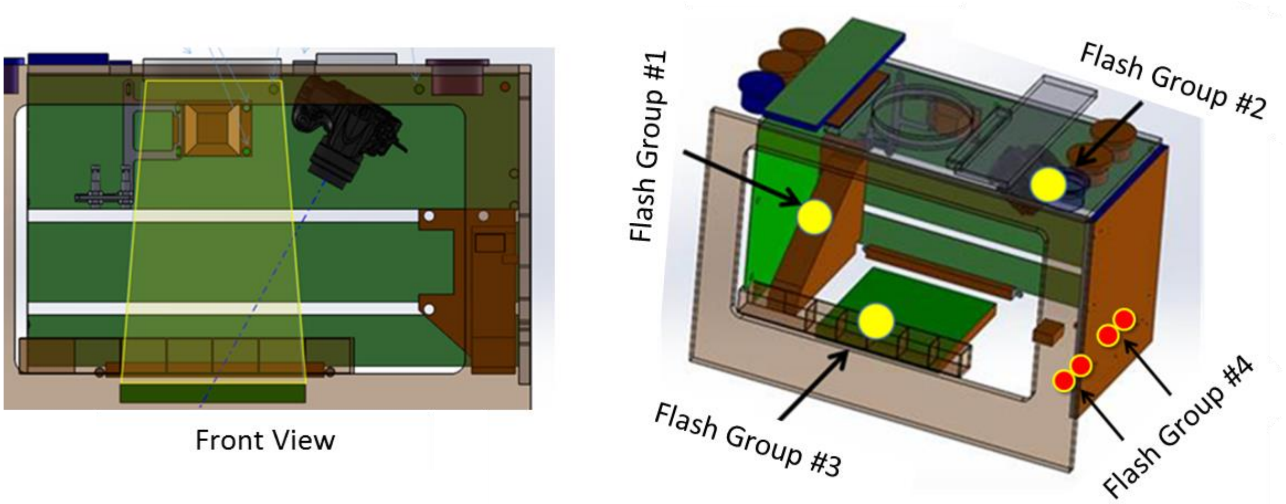

Figure 9. Schematics that illustrate the mounting locations of the camera and flash groups within the build chamber. (The camera enclosure is not shown to avoid confusion).

Two lenses have been employed in testing to achieve different resolutions and fields of view. The original lens, which was used for all build images in the remainder of the paper, was a Nikon 28 mm f/2.8D AF Nikkor lens, achieved a resolution as fine as approximately 50 µm/pixel across the 250 x 250 mm build plate. The second lens, a Nikon 105 mm f/2.8D AF-Nikkor, achieved a resolution as high as approximately 15 µm/pixel across a trapezoidal region of the build plate 135 x 62/78 mm. These estimates were achieved by imaging a machinist rule, as shown in Figure 10.

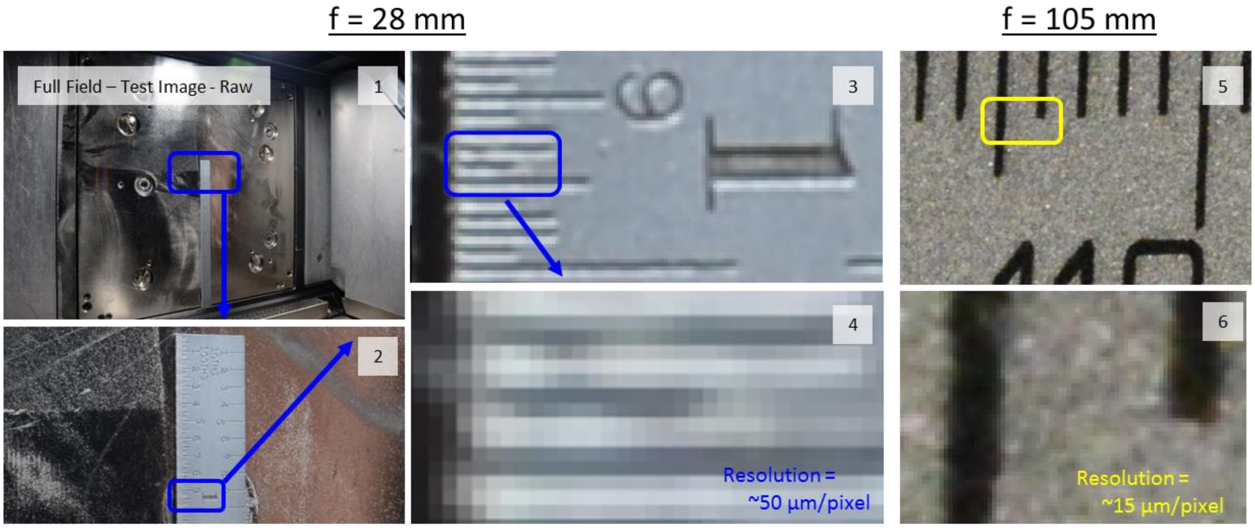

Figure 10. Image resolution measurements of both lens employed in this study.

To assess the ability of the camera system to detect defects, a build was fashioned to intentionally generate a range of defects. A sketch of the build is shown in Figure 11. Cantilevered “diving boards” were included with a range of different support structures to induce various levels of deformation. Gear-like shapes were utilized to stress the control system in an attempt to generate defects near the contour-hatch interface. Gears were also placed “downstream” of diving boards to generate defects by the expected powder disruption caused during distortion. Finally, a series of cylinders was included with intentional variation of laser power, scan velocity, and hatch spacing to create embedded lack-of-fusion defects. The objective of this build is to enable comparison of acquired images to parts with actual characteristic defects generated during PBFAM processing.

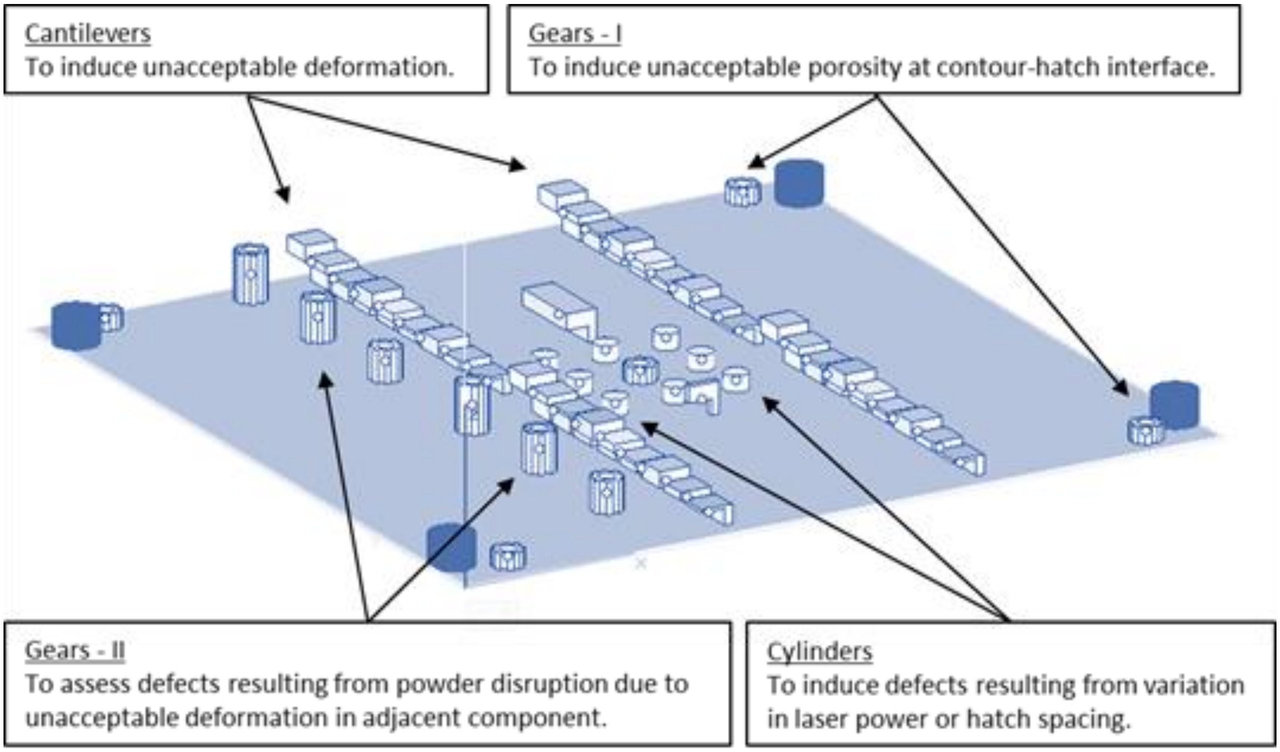

Figure 11. "Intentional Defect" build plan.

Examples shown in Figure 12 illustrate how the various lighting schemes enhance the contrast of different features on each layer. Comparing these images highlights the need for multiple lighting scenarios to identify a range of possible defects. For example, non-uniform linear perturbations in the powder layer are readily revealed with Flash Group #4, but are nearly impossible to detect with Flash Group #2. Higher contrast will simplify development of algorithms for automated feature extraction.

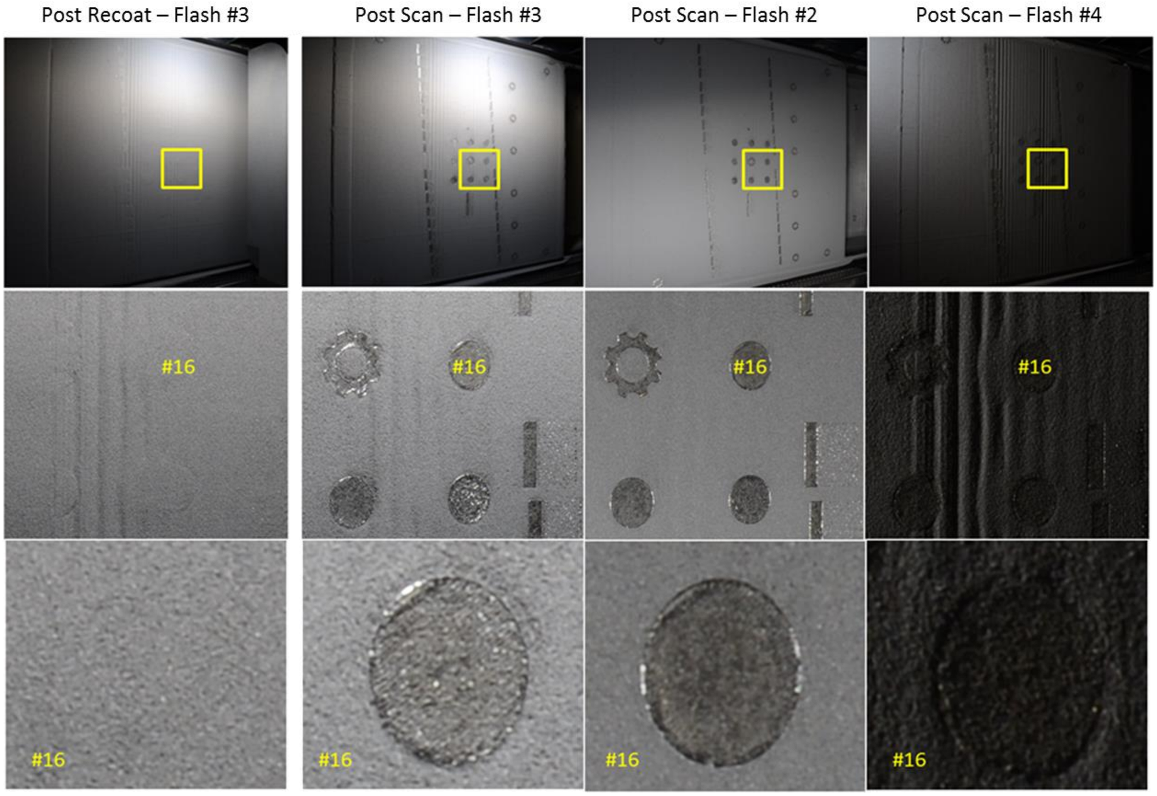

Figure 12. Images collected with various lighting schemes throughout a build demonstrate how the lighting location can be used to enhance surface perturbations.

Post-processed and analyzed images can be stacked to create 3D models, an example of which is shown for the "intentional defect" build in Figure 13. Ongoing efforts will attempt to correlate internal defects embedded within these components detected by 3D X-ray computer tomography of built parts to the sensor data.

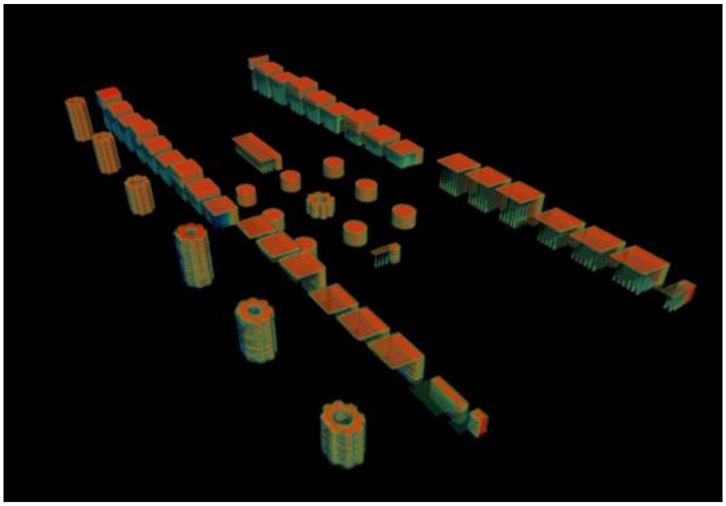

Figure 13. Images acquired at each layer can be stacked to create a 3D representation of the sensor data.

In separate testing, analysis of acquired images for a specific test component reveals numerous anomalies in the surrounding powder layer partway through the build. Raw images from each layer, Figure 14a, were analyzed and stacked into a 3D image, in Figure 14b. The analysis included fusion of data from multiple flash groups and subtraction of consecutive images, show clear evidence of a bouncing recoated blade and dragged agglomerated powder. By viewing the data in 3 dimensions, it is straightforward to assess when these phenomena occurred, and also 3D location within the component that may be affected. This part is known to have generated enough residual stress during the build that it failed the support materials that held the component to the build part partway through the AM process (see Figure 5), resulting in an aborted build. It is apparent from the 3D sensor data that the failure occurred some layers after the supports had been completed.

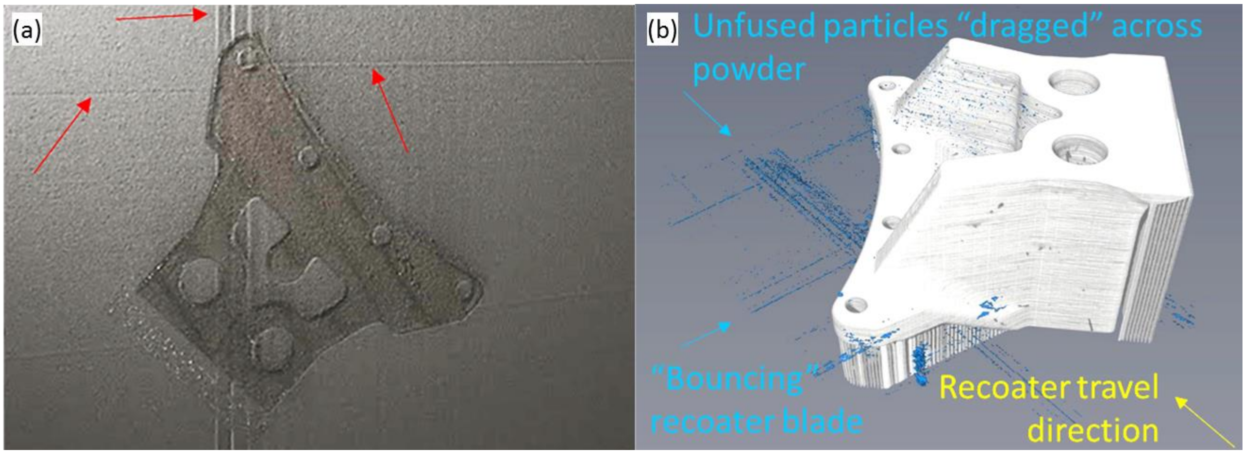

Figure 14. Images collected from each individual layer, example shown in (a), can be stacked to generate 3D models of the sensor data, as shown in (b). (CAD model courtesy Honeywell, Inc.).

Current efforts are focused on executing an improved "intentional defect" build using the f = 105 mm lens for increased resolution, on developing strategies for improved image analysis, and in developing algorithms to correlate features in the images to anomalies in 3D X-ray computed tomography scans of the various components.

5. CONCLUSIONS

Laser-based metal powder bed fusion additive manufacturing is a process that faces many technical challenges in ensuring repeatable production quality. Slight alterations in any of the numerous processing parameters, or process perturbations which may occur for a large number of reasons, can result in defects in the final part. At the same time, the PBFAM process enables an enormous design space due its inherent ability to produce components and features that are not possible with traditional manufacturing techniques. New techniques of in-situ sensing and control of machine variables and build attributes will be critical to ensure consistent results. Key machine variables that influence the AM process include accuracy and repeatability of the laser beam, scanner characteristics, chamber environment, and the effects of powder characteristics. Layerwise optical image capture and analysis techniques are being developed to enable correlation to known defects.

These efforts represent significant progress, and further study is expected to enable in situ quality assessment to enable large-scale acceptance and commercialization of PBFAM.

6. ACKNOWLEDGEMENTS

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References

[1] Mertens, R..; Clijsters, S.; Kempen, K.; Kruth, J.P.; "Optimization of scan strategy in selective laser melting of aluminum parts with downfacing areas", *Journal of Manufacturing Science and Engineering*, vol. 136, pp. 061012-1–061012-7, Dec 2014.

[2] Jacobsmühlen, J.; Kleszczynski, S.; Witt, G.; Merhof, D., "Robustness analysis of imaging system for inspection of laser beam melting systems," *Emerging Technology and Factory Automation (ETFA), 2014 IEEE* , pp.1–4, Barcelona, 16-19 Sept. (2014)

[3] Jacobsmühlen, J.; Kleszczynski, S.; Schneider, S.; Witt, G.; "High resolution imaging for inspection of laser beam melting systems," *Instrumentation and Measurement Technology Conference (I2MTC), 2013 IEEE* , pp. 707–712, Mineapolis, MN, 6–9 May (2013)

[4] Krauss, F., "EOS DMLS Monitoring", EOS marketing literature, Dec 2013.

[5] Craeghs, T; Clijsters, S; Yasa, E; Kruth, J.P.. "Online Quality Control of Selective Laser Melting." *Proceedings of the Solid Freeform Fabrication Symposium 2010*. pp. 212 – 226, Austin, Texas, USA (2011).