

Monitoring for Additive Manufacturing Technologies: Report on Progress, Achievements, and Limitations of Monitoring Techniques



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Transformational Challenge Reactor

**MONITORING FOR ADDITIVE MANUFACTURING TECHNOLOGIES:
REPORT ON PROGRESS, ACHIEVEMENTS, AND
LIMITATIONS OF MONITORING TECHNIQUES**

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ABSTRACT

The Transformational Challenge Reactor (TCR) program is leveraging additive manufacturing (AM) technologies to produce multiple nuclear components to be assembled into a fully functional microreactor core. AM was selected as the main manufacturing technology of choice for TCR because it has the potential to disrupt the nuclear industry on two fronts: (1) it enables the manufacturing of very complex geometries with optimized and tailored material properties for the intended use of the component, opening up new options for reactor designs, and (2) it allows for a better understanding of the manufacturing process through real-time in situ monitoring, data analytics, and artificial intelligence that can lead to a streamlined qualification and certification process. Within TCR, the development and deployment of a digital platform aims at addressing the latter opportunity. As part of this effort, the collection of pedigree data sets is vital, should these data be generated before, during, or after the manufacturing process.

This report focuses on the collection of manufacturing process data using systems instrumentation and monitoring. It presents an inventory of the various monitoring modalities installed on the manufacturing systems by the machine manufacturer or specifically designed by our team to fill information gaps. It also provides details on other relevant data streams available and leverageable to evaluate the manufacturing process on all classes of AM systems investigated during the first year of this program. Through examples, the report gives an overview of the data collected and presents a path forward for the digital platform.

1. INTRODUCTION

The implementation and deployment of the digital platform requires three elements: (1) a hardware architecture for data exchange and storage, (2) a software platform for advanced data analytics, and (3) an information rich manufacturing and material database for domain discovery. It is agreed that relevant and valuable data are produced throughout the manufacturing chain, from material provenance, to manufacturing, to material characterization. However, additive manufacturing (AM) being still in its early stages, the quality and wealth of data streams that best describe the AM process are still lacking. During the period of performance covered by this report, we created an inventory of the existing data, identified missing data collection modalities and developed them, and started processing the data to show the potential of such an approach. This document provides an evaluation of the existing sensing modalities installed on the selected AM machines. It describes the development of a sensing platform and required instrumentation on a directed energy deposition (DED) system, binder jetting systems, and laser powder bed fusion systems. It also provides a summary of detection capabilities for each system.

This rest of the document is structured as follows: in the second section we give a brief overview of the various machines considered by the manufacturing team so the reader can better appreciate the objectives and technical choices for each technology. In the third section, we describe the sensing modalities available on those machines and present the new imaging techniques developed and deployed to collect complementary information. We illustrate the findings with examples of data collection and processing results before concluding on the relevance and limitations of the approach toward the evaluation of the manufacturing processes and manufactured parts.

2. ADDITIVE MANUFACTURING TECHNOLOGIES CONSIDERED FOR THE PERIOD OF PERFORMANCE

There are numerous AM technologies available on the market, differentiated by the type of material they can deposit, e.g., plastic or metal; by the deposition strategy they are using, e.g., extrusion, fusion, or jetting; or by the build volume and manufacturing speed. Taking into consideration the Transformational Challenge Reactor (TCR) design and performance requirements, it was strategic to use different printing technologies for different components, to identify the best machines for given applications, and then to down select moving forward. For TCR, special consideration was given to the size of the part, the performance of the materials, and the precision of the details and dimensions of the geometry. For those reasons, the TCR program team investigated printing on a directed energy deposition system (BeAM), a large-volume laser powder-bed system (X Line), a medium-sized laser powder-bed system (M2 or FormUp 350), and binder jet technology (Innovent, M-Flex).

The following subsections provide general descriptions of the AM systems and their in situ monitoring capabilities to help understand the types of data collected and the value of those measurements.

2.1 CONCEPT LASER M2

The General Electric (GE) Additive Concept Laser M2 system (Figure 1) is a metal printer using laser powder-bed fusion technology to manufacture parts. It has a build volume of $250 \times 250 \times 350$ mm and is equipped with two 200 W lasers used for melting a stack of thin layers of powder that describes the 3D geometries. The maximum laser velocity is 7.5 m/s, which, depending on geometry, material, and process parameters, offers a maximum build rate volume of 20 cm³/h. The manufacturing process is done in four steps: (1) each layer is prepared with a specific printing scan strategy and associated process parameters, e.g., laser power and speed; (2) a racking mechanism covers the build plate with a layer of powder; (3) the melting process programmed during step (1) is applied to the layer; the build plate lowers to the desired layer thickness (20 to 80 μ m). This process repeats until completion of the geometry. This system is equipped with standard sensing technologies to ensure its correct mechanical operation. Additionally, two optional technologies are available to assess the quality of the melting process (QM Meltpool) and to assess the quality of the layer of powder (QM Coating).



Figure 1: Concept Laser M2.

2.2 CONCEPT LASER X LINE

The General Electric (GE) Additive X Line system (Figure 2) use the same technology and manufacturing process as the M2 system. However, the X Line has a build volume of $800 \times 400 \times 500$ mm (about 7.5 times the volume of the M2) and uses two 1,000 W lasers. The maximum laser velocity is 7.5 m/s, which, depending on geometry, material, and process parameters, offers a build rate volume of $120 \text{ cm}^3/\text{h}$ (6 times the build rate of the M2). The X Line also offers a partial implementation of the QM Coating system; however, only half the build plate can be monitored.



Figure 2: Concept Laser X Line.

2.3 FORMUP 350

The AddUp FormUp 350 system (Figure 3) is also a laser powder-bed system. Designed for mass production, this machine has a build volume of $350 \times 350 \times 350$ mm (double the size of the M2 system) and uses two 500 W lasers. The maximum laser velocity is 10 m/s. The manufacturing process is done in four steps: (1) each layer is prepared with a specific printing scan strategy and associated process parameters, e.g., laser power and speed; (2) a powder-rolling mechanism covers the build plate with a layer of powder. To avoid materials waste, powder is only rolled in a volume close to the minimum bounding volume of the part using a proprietary selective distribution mechanism; (3) the melting process programmed during step (1) is applied to the layer; and (4) once the layer completes, the stage supporting the build plate lowers to the desired layer thickness (20 to $100 \mu\text{m}$). The process repeats until completion of the geometry. This system is equipped with standard sensing technologies to ensure correct mechanical operation. In addition, a quality control module—for visual operator feedback—comprising a visible-light camera and a microbolometer (thermal camera) is mounted on the top of the machine to look at the powder bed.

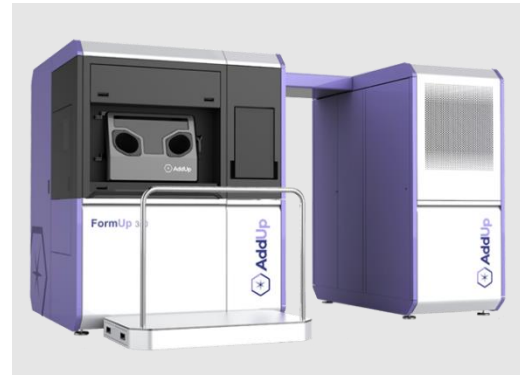


Figure 3:FormUp system.

2.4 BEAM MODULO 400

The AddUp BeAM Modulo 400 system (Figure 4) is a metal printer that uses DED—coupling the thermal energy of a laser with blown-powder technology—to fuse materials by melting them as soon as they are deposited. The blown-powder technology uses nozzles to concentrate a stream of metallic powder toward the focal point of the laser, creating a melt pool that will solidify to add to the geometry. In contrast to the laser powder-bed and binder-jet systems, the DED machine can operate in a free-form configuration, i.e., the entire part as well as the print head can move in space in a 5-axis configuration to adapt to the intricacies of the geometry. This system is equipped with standard sensing technologies to ensure its correct mechanical operation. In addition, a standard camera provides a live view of the inside of the

chamber, and a high-speed infrared sensitive camera mounted coaxially to the laser beam path allows for real-time assessment of the melt pool. The machine has a build volume of $600 \times 400 \times 400$ mm. It is equipped with a single 500 W or 2,000 W laser, up to five powder distributors for powder refill or online powder mixing, and a five-axis table to reposition the part in space for free-form manufacturing. The printing process has a build rate of up to $130 \text{ cm}^3/\text{h}$. The manufacturing process is done in three steps: (1) a scan strategy for each layer (print head and five-axis table) is programmed using G-code (note that the layers do not have to be flat in this system), (2) a set of process parameters is also defined for each layer, and (3) the printing process programmed during step (1) is applied to the layer. This process repeats until completion of the geometry.



Figure 4: BeAM Modulo 400.

2.5 INNOVENT⁺

The ExOne Innovent⁺ binder jet system (Figure 5) is a metal printer using binder jetting technology to manufacture parts. It has a build volume of $160 \times 65 \times 65$ mm and is equipped with a liquid deposition head similar to a traditional ink jet printer to deposit the binder used to glue together the metal particles. The completed green part is a solid but fragile mixture of binder and metal powder that must be further post-processed to attain a higher final density. The printing process has a build rate of $166 \text{ cm}^3/\text{h}$. The manufacturing process is done in five steps: (1) each layer is configured with a specific set of process parameters; (2) a rolling mechanism covers the build plate with a layer of powder; (3) the binder deposition process operates similarly to the ink jet printing process (the print head moves in a predefined pattern over the build plate, depositing binder only

when needed); (4) a radiative heating element scans the build plate to dry the binder; and (5) once the layer completes, the stage supporting the build plate lowers to the desired layer thickness (30 to $200 \mu\text{m}$), and the process repeats until completion of the geometry. At this time, the Innovent⁺ system is only equipped with standard sensing technologies to ensure correct mechanical operation. There is no standard image-base in situ monitoring available to assess the layer of powder or the quality of the binder deposition.

2.6 M-FLEX

The ExOne M-Flex binder jet system uses the same technology and manufacturing process as the Innovent⁺ system. However, the M-Flex has a build volume of $400 \times 250 \times 250$ mm (about 37 times the volume of the Innovent⁺). The printing process is very fast, with a build rate of $1,600 \text{ cm}^3/\text{h}$ (10 times the build rate of the Innovent⁺ and 13 times the build rate of the X Line). Like the Innovent⁺, the M-Flex has limited instrumentation.



Figure 5: ExOne Innovent⁺.



Figure 6: ExOne M-Flex.

3. INSTRUMENTATION OF THE ADDITIVE MANUFACTURING TECHNOLOGIES – EXISTING AND NEW SENSING MODALITIES

In this section, only the physical features of interest for detection are described as the features differ between machines. Then we provide an exhaustive list of the various sensing modalities, either installed by the manufacturer or developed at Oak Ridge National Laboratory (ORNL), and all the data streams available and recorded on all platforms to detect features or defects. Finally, we provide in each case a few examples to illustrate the importance of deploying in situ monitoring capabilities.

3.1 FEATURES OF INTEREST

Five of the machines described in Section 2 use a powder bed to deposit the raw materials. Only the BeAM system uses DED. Despite using different techniques to fuse the materials, all powder-bed systems present similar features in the layer of powder either before, during, or after the printing process. Firstly, if the raking or rolling mechanism used to spread powder is not operating correctly, the micrometer-thick layers of powder will inevitably display characteristic visible signatures. Secondly, the laser-powder interaction is highly dynamic, often resulting in the ejection of molten or partially molten material known as spatter. This spatter can land back on the powder bed where it may introduce defects in neighboring parts. Spatter would normally occur during the manufacturing process. However, by controlling the printing strategies and process parameters, it is possible to reduce their importance or impact. Thirdly, superelevations occur when the parts start swelling or delaminating due to the local heat distribution and/or a buildup of residual thermal stresses. Many of these examples can be seen in Figure 7, and a partial list of these defects is shown in Figure 8. The textural uniqueness of anomalies makes them ideal for identification using computer vision techniques.

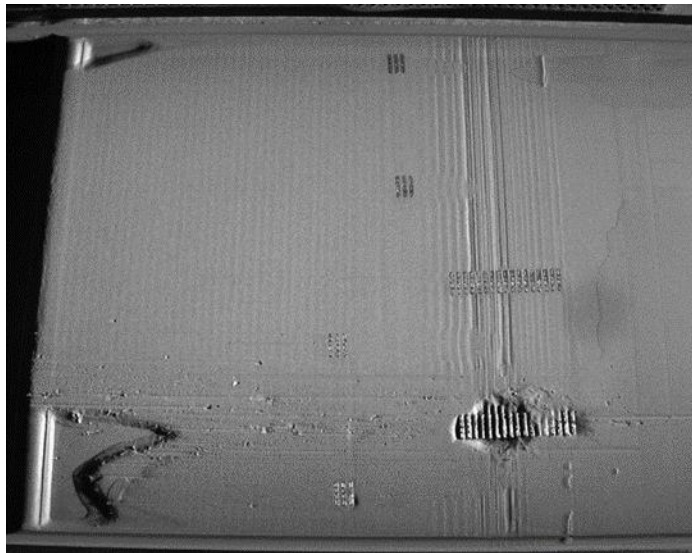


Figure 7: Example of visual imagery of the top layer in a powder-bed system showing multiple examples of texture features characteristic of defects.



Figure 8: Nonexhaustive list of defects found in powder-bed systems.

During the printing process on powder-bed systems, the quality of the melt pool will impact the quality of the build: if the melt pool size is not controlled, the material may not fuse correctly, leading to porosity or other defects. Once a layer is complete, the printed region is clearly visible as it contrasts with the unmelted powder. Assessing the geometric accuracy of the parts shown in Figure 9 is possible. However, at the operating temperature of a laser powder-bed system, being able to identify porosity (superficial or

below the surface) is impossible with an imager operating in the visible range. Alternative techniques should be considered. Because the presence of pores is typically the result of unfavorable melting conditions, sensor data coming from the machine (current, laser power, etc.), coupled with the printing scan strategy, may allow for preemptive identification of such unfavorable conditions.

In the case of the BeAM system, a laser and a material feed nozzle are combined to build large-scale free-form geometries. Because the part is not buried in a volume of unmelted powder, the part's thermal conditions can change drastically, which can result in multiple forms of geometrical defects (e.g., swelling, surface finish, wall movement), physical defects (lack of fusion, cracks, delamination, or incomplete geometry), material defects (porosity, incorrect microstructure growth), etc. We are therefore interested in measuring the geometric accuracy of the parts and the variation of their surface temperatures.

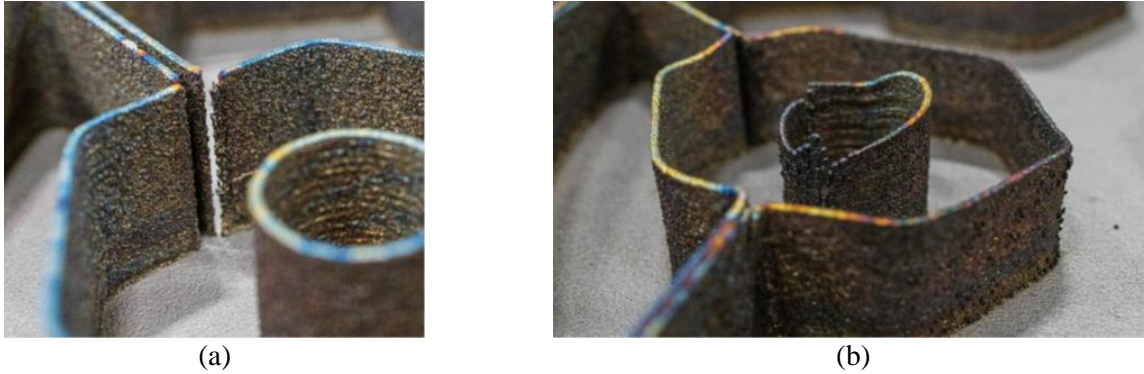


Figure 9: Two examples of physical defects encountered with a directed energy deposition system.

3.2 LOG FILE PARSERS

Log files are produced at the conclusion of each build for the laser powder-bed machines. Preliminary parsers have been developed to allow for the plotting of various sensor data streams as a function of build height. Figure 10 shows an example of these data from the Concept Laser X Line 2000R machine. Additional parsing and search capabilities will be implemented as part of the TCR digital thread database.

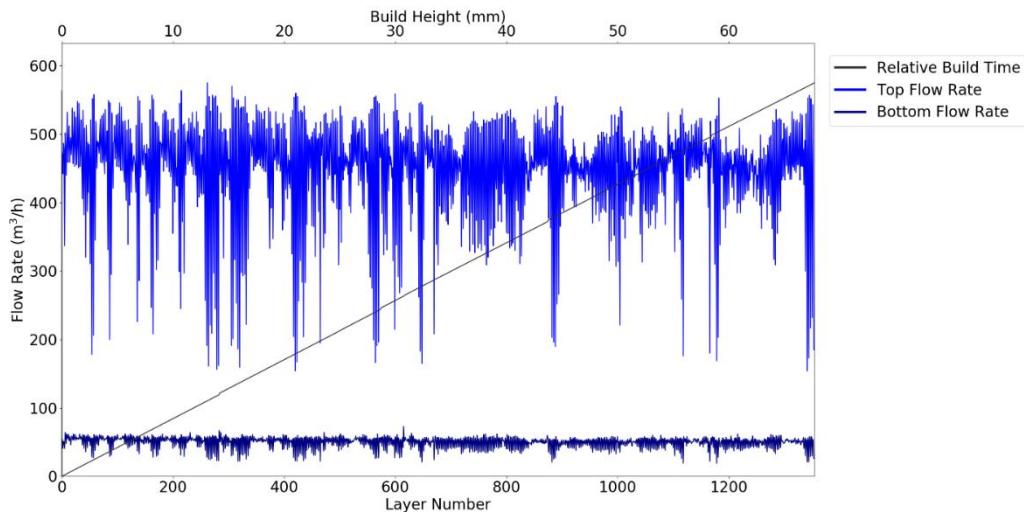


Figure 10: The argon flow rate within a Concept Laser X Line 2000R build chamber during a print.

3.3 DATA COLLECTED ON THE CONCEPT LASER M2 AND X LINE SYSTEMS

The Concept Laser M2 laser powder-bed system is equipped with two in situ imaging technologies: QM Coating and QM Meltpool. QM Coating can be used to determine the quality of the layer of metal powder during the deposition process. A schematic of the QM Coating system is shown in Figure 11. It uses a 5 MP visible-light camera to capture an image of the entire build area immediately after powder fusion and powder deposition for each layer. An example of these images is presented in Figure 13a.

The QM Meltpool system is a melt pool monitoring module using two sensors mounted coaxially to the laser beamline, as shown in Figure 12, to quantitatively assess the melt pool quality—in terms of size and intensity—as a function of light radiation measurements. Specifically, the system is composed of the following components.

1. An on-axis photodiode with a sensitivity in the 350 nm–1,100 nm range continuously captures light intensity data in the region around the melt pool at a rate of 10 kHz–100 kHz. These data are then spatially mapped (Figure 13b) by ORNL-maintained software. This system, installed and maintained by Concept Laser, is duplicated for each of the machine's two lasers.
2. An on-axis visible-light camera continually calculates the number of pixels (in the region around the melt pool) with light intensities above an arbitrary global threshold at a rate of 10 kHz–100 kHz. These data are then spatially mapped (Figure 13c) by ORNL-maintained software. This system, again, installed and maintained by Concept Laser, is duplicated for each of the machine's two lasers.

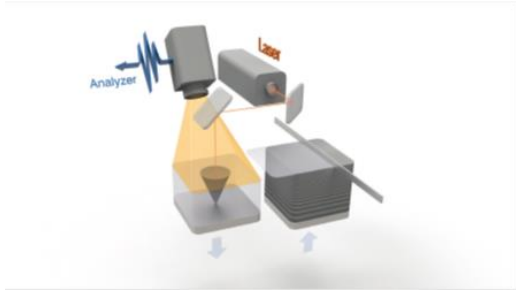


Figure 11: Schematic of the QM Coating module.

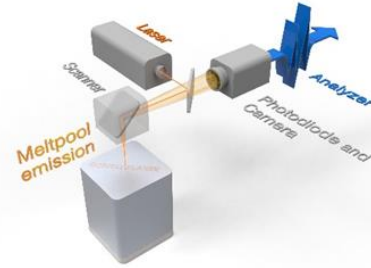


Figure 12: Schematic of the QM Meltpool module.

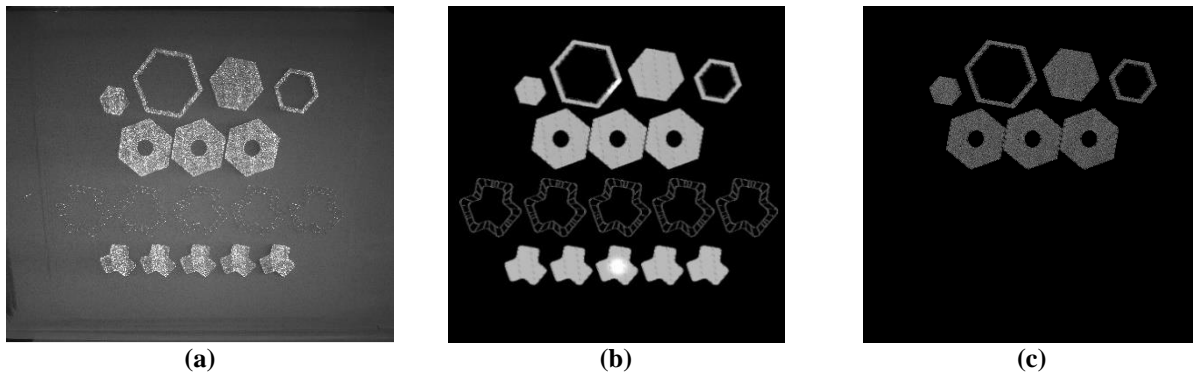


Figure 13: Examples of images from QM Coating and QM Meltpool: Visible-light powder-bed image (a), spatially mapped on-axis photodiode data (b), and spatially mapped on-axis camera data (c). Note that for all the builds to date, the on-axis camera for at least one of the two lasers has malfunctioned.

At the end of each build, a log file is produced that reports various machine error states and time-dependent sensor streams, including build chamber gas (argon) flow rates, build chamber oxygen concentrations, build plate temperature, and temperatures of selected components in the laser optic trains. This system is installed and maintained by Concept Laser. Additional metadata such as the name of the technician setting up the machine and information about the powder batch are collected using ORNL-maintained software (see Figure 14). Layer-wise information regarding the intended part geometry is stored in STL files and converted into images (with different colors representing melted areas, support material, etc.) using a slicing software. Once collected, the in situ images are processed for defect detection using ORNL artificial intelligence (AI) models and registered to the STL information; some sample results are shown Figure 15 and Figure 16.

In contrast, the Concept Laser X-Line 2000R laser powder-bed system does not produce the same data streams as the M2 system. There is no QM Meltpool system, and the QM Coating system is only partially implemented: a 12 MP visible-light camera is installed on the machine and can capture half of the build area, but layer-wise image capture for this camera has not been automated by Concept Laser. Image capture triggered by ORNL-maintained software has been demonstrated, but no data have been collected during a build due to ITAR restrictions for the non-TCR builds run on the X Line 2000R to date. As for the M2 machine, at the end of each build a log file reporting various machine error states and time-dependent sensor data is produced.

The screenshot shows a web-based metadata entry form titled "Peregrine - Metadata Manager". It includes an "Apply" button at the top left. The form contains several fields with labels and values:

- *build name: TCR Base Manifold 2a
- *build start date (YYYY-MM-DD): 2019-08-16
- *layer thickness (μm): 50.0
- *material type: SS 316L
- feedstock batch details: 316 powder 2019 batch
- machine operator: Chase Joslin
- qualitative build quality (0-3): 3
- ambient humidity (RH%): 45.0
- ambient temperature (°C): 20.0
- notes: (empty text area)

Figure 14: Example of metadata entry for the Concept Laser M2 machine.

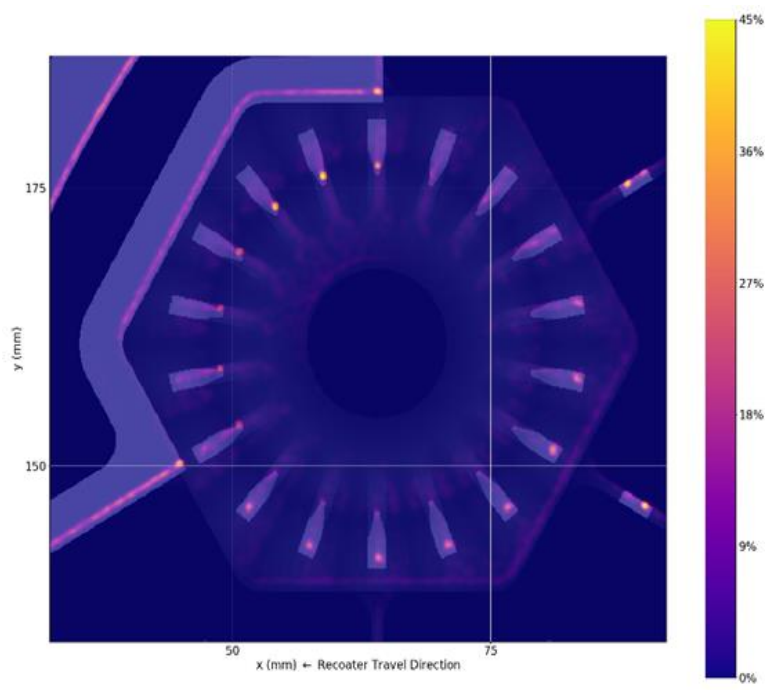


Figure 15: A heat map indicating the cumulative detections of minor superelevations throughout the height of the build for a Concept Laser M2.

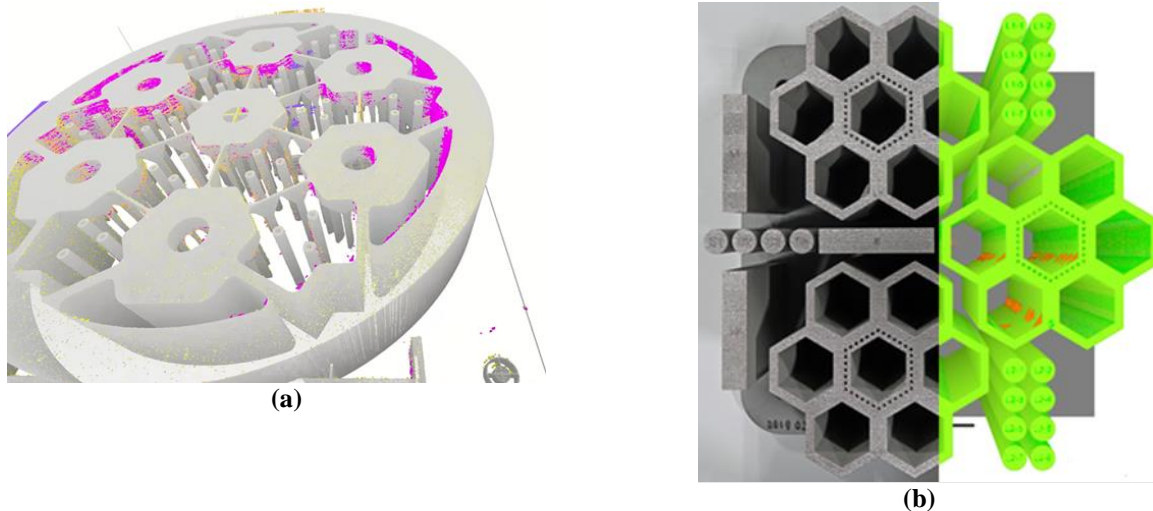


Figure 16: Example of a 3D defect map created using artificial intelligence models: (a) bottom portion of the microreactor, (b) overlay of the quality control assessment over a picture of the physical part.

3.4 DATA COLLECTED ON THE FORMUP 350 SYSTEM

The machine manufacturer has placed two cameras on the top of the FormUp 350 system (Figure 17a): a 5 MP visible-light camera captures an image (Figure 17b) of the entire build area immediately after powder fusion and powder deposition for each layer, and a 0.3 MP microbolometer captures a thermal image (Figure 17c) of the entire build area immediately after powder fusion for each layer.

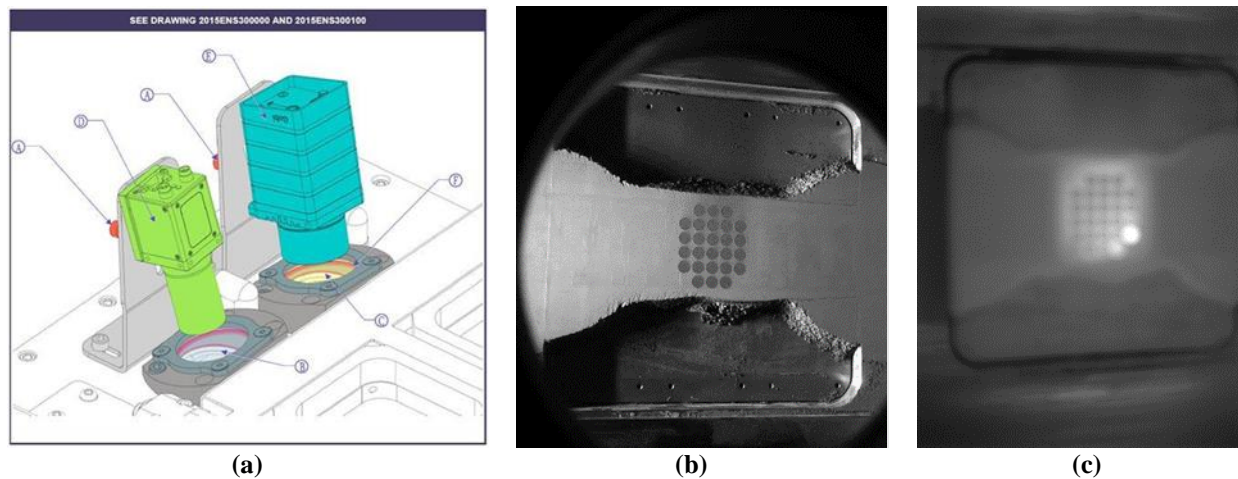


Figure 17: FormUp 350 system: (a) camera configuration on the top of the print chamber on the FormUp 350 system, (b) visible-light powder-bed image, and (c) thermal powder bed image.

At the end of each build a log file is produced that reports various machine error states and time-dependent sensor streams, including gas (argon) flow speed, build chamber oxygen concentration, the torque on the recoater arm during powder deposition, build plate temperature, and temperatures of selected components in the laser optic trains. Processing the images with ORNL AI models produces maps of defect locations within the layer as shown in Figure 18.

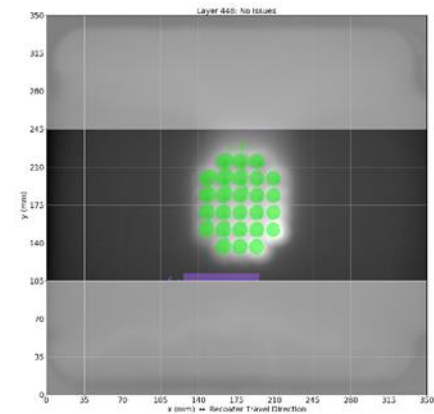


Figure 18: Artificial intelligence–produced defect map.

3.5 DATA COLLECTED ON THE INNOVENT⁺ SYSTEM

The ExOne Innovent binder jet systems are not equipped with any standard in situ process monitoring. Therefore, ORNL has developed their own imaging module: a 20 MP visible-light camera installed at the top of the build chamber (Figure 19) captures an image (Figure 20) of the entire build area immediately after binder deposition and powder deposition for each layer. This is a system installed and maintained by ORNL.

1. Additional metadata such as the name of the technician setting up the machine and information about the powder batch is collected using ORNL-maintained software.
2. Layer-wise information regarding the intended part geometry is stored in STL files and converted into images (with different colors representing melted areas, support material, etc.) using a slicing software.

Current binder-powder combinations allow for identification of the part outlines in the visible spectrum; however, several binder-powder combinations proposed for the TCR program will require imaging in a different spectrum using active illumination. This second-generation imaging system may also allow for quantitative determination of as-deposited binder saturation levels and is currently under development.

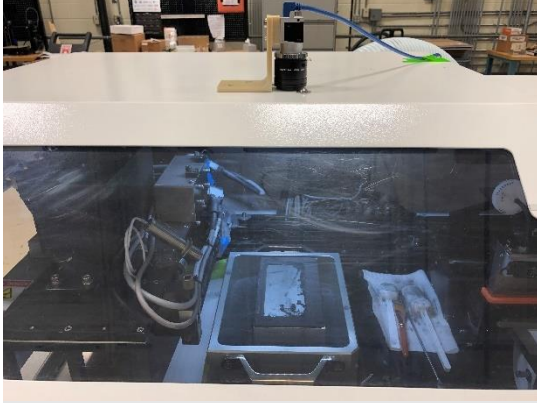


Figure 19: 20 MP camera imaging the powder-bed area.

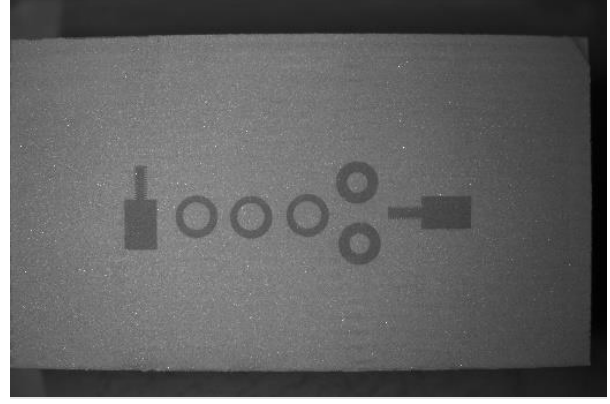


Figure 20: Visible-light image of the powder bed.

3.6 DATA COLLECTED ON THE M-FLEX SYSTEM

The ExOne M-Flex binder jet system is not equipped with any standard in situ process monitoring equipment. Therefore we developed our own imaging module composed of two cameras: a 10 MP visible-light camera captures an image [Figure 21(a)] of the entire build area immediately after binder deposition and powder deposition for each layer. This is a system installed and maintained by ORNL. The second camera, a 0.3 MP mid-wave infrared (MWIR) camera, captures an image [Figure 21(b)] of about 80% of the build area immediately after binder deposition and powder deposition for each layer. This is also a system installed and maintained by ORNL [Figure 21(a)].

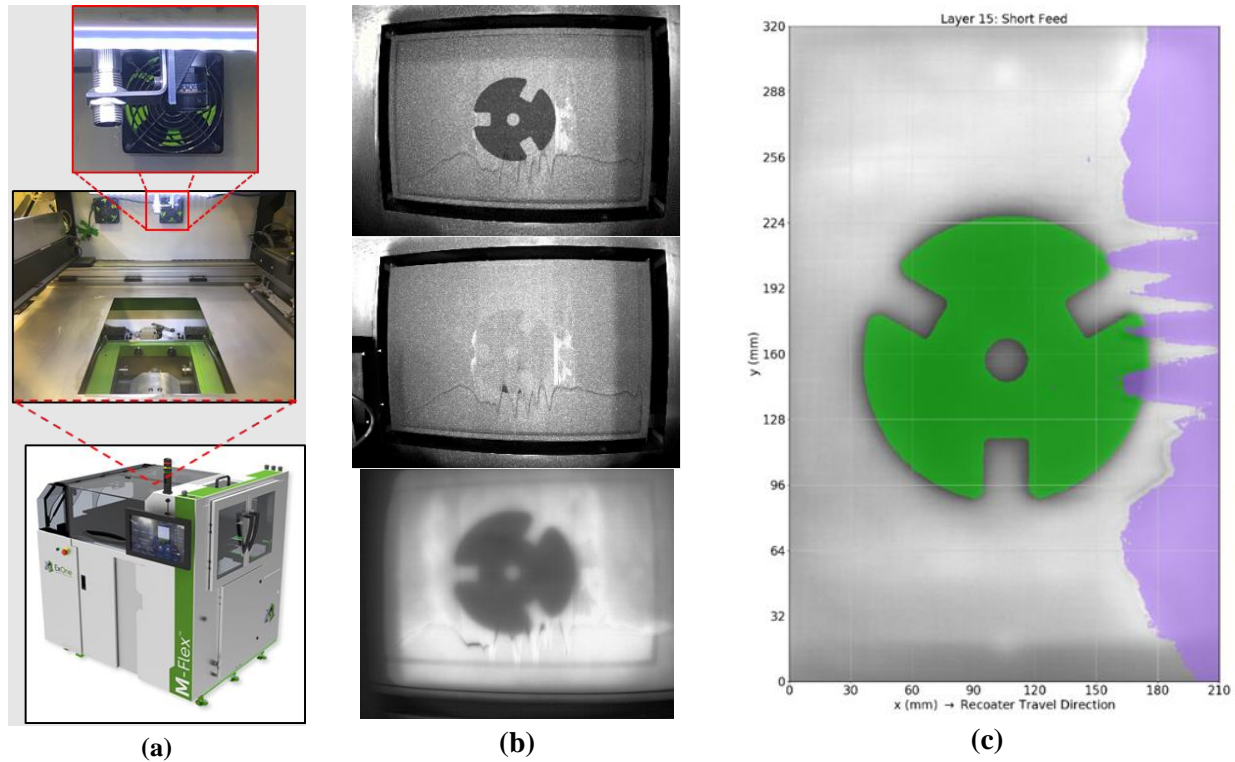


Figure 21: ExOne M-Flex system showing components of the imaging module and related examples: (a) location of the cameras inside the machine, (b) example of imagery capture with the cameras, and (c) results of the classification algorithm.

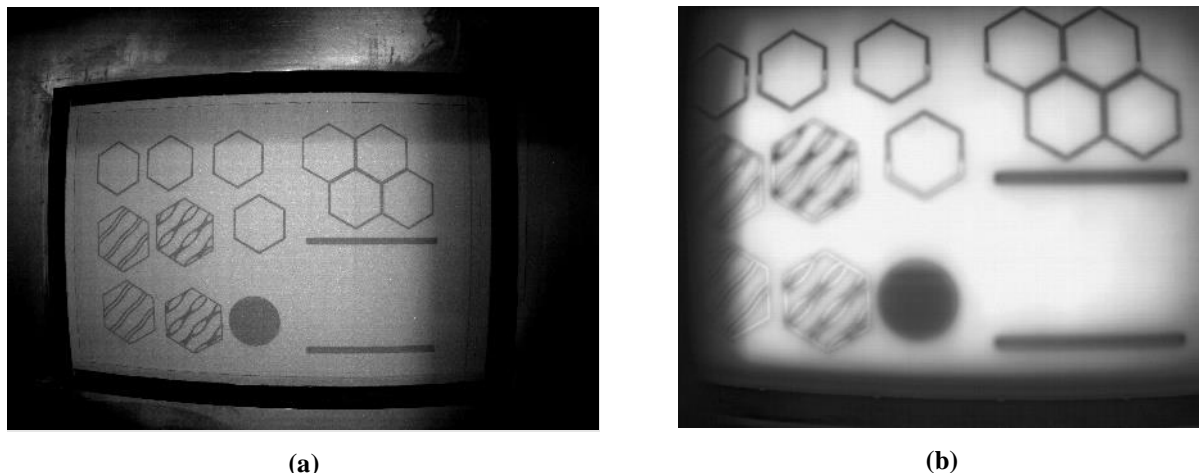


Figure 22: Images from the ExOne M-Flex camera module: (a) visible-light powder-bed image and (b) mid-wave infrared camera powder-bed image.

Additional metadata such as the name of the technician setting up the machine and information about the powder batch is collected using ORNL-maintained software. Layer-wise information regarding the intended part geometry is stored in STL files and converted into images (with different colors representing melted areas, support material, etc.) using slicing software. Moving forward, modifications will be made to the imaging system to protect it from abrasive powders (e.g., SiC) and to ensure that the MWIR camera's field of view covers the entire build area.

3.7 DATA COLLECTED ON THE BEAM MODULO 400 SYSTEM

The AddUp BeAM Modulo 400 DED system only has melt pool monitoring capability in its standard configuration. Therefore, to retrieve geometrical and thermal information during the manufacturing process, we developed an imaging module capable of three functions: (1) retrieving the 3D geometry of the object at a high frame rate, (2) monitoring the thermal gradient in space, and (3) measuring in situ strain using digital image correlation. The system includes the following.

- An array of eight 20 MP Basler Ace visible-light cameras and four 640 by 512 pixel FLIR Boson long-wave infrared cameras situated off-axis in groups of three monitoring the build volume, as shown in Figure 23(b). As shown in Figure 24(c), these cameras are arranged so as to have two high resolution visible-image cameras at about a 5° stereo angle to one another to provide 3D depth mapping, with an infrared camera placed between the visible-light cameras. Figure 24(e) and Figure 24(f) show sample images from the two cameras.
- A 1.6 MP FLIR Blackfly monochrome visible-light camera, coaxial with the heating laser [Figure 24(a)]. The field of view is 2.2 mm in diameter, and the current maximum resolving power is $22\text{ }\mu\text{m}$ due to optical constraints, as shown in Figure 24(d). The data acquisition rate is 78 frames per second, which at typical processing speeds equates to about 0.5 mm of melt pool travel per frame, allowing for multiple melt pool frames for every spatial coordinate in the part. This is a system installed and supported by the manufacturer, BeAM.



Figure 23: BeAM Modulo 400 system imaging setup: (a) position of the imaging module around the build plate of the manufacturing system, (b) close-up view of the imaging system, (c) example of a thermal image captured during printing, (d) example of a visible image of the same object with the result of the strain measurement overlaid as a color map.

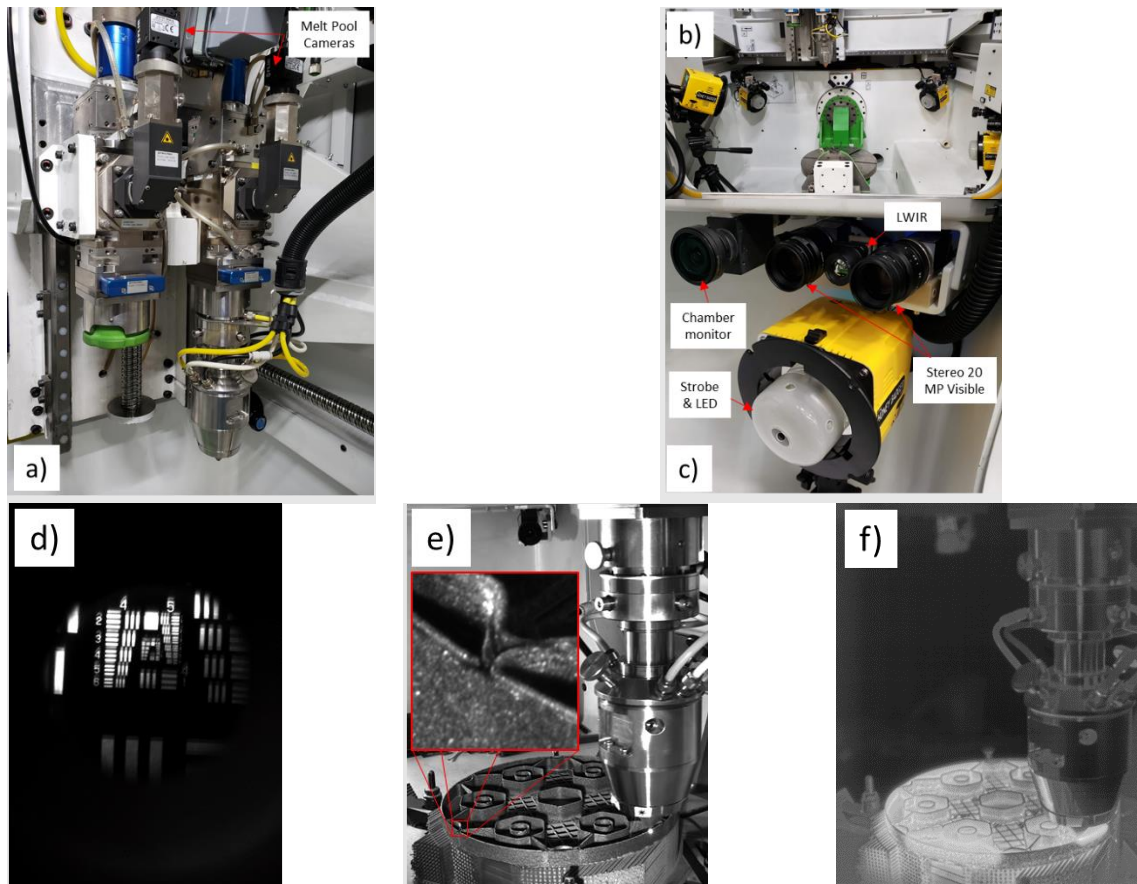


Figure 24: BeAM Modulo 400 system cameras and images. BeAM laser and nozzle head assembly, with coaxial melt pool camera (a); off-axis 14-camera array located in the four corners of the chamber, including two wide angle chamber monitor cameras, eight stereo 20 MP visible light inspection cameras, four 640 by 512 pixel FLIR Boson long-wave infrared cameras, and four mounted strobe/LED illumination sources [(b) and (c)]; melt pool camera resolution grid image (d); visible off-axis camera image (e); and an infrared image (f).

The data analytics pipeline for the BeAM is still in the early stages of development. However, initial work has begun on extracting features from the on-axis melt pool camera with the eventual goal of correlating these in situ features with defects in the final part. Figure 25 shows an example extraction of features such as ejected spatter particles (yellow overlays) and scale-invariant descriptions of the melt pool's morphology (green and blue “starbursts”).

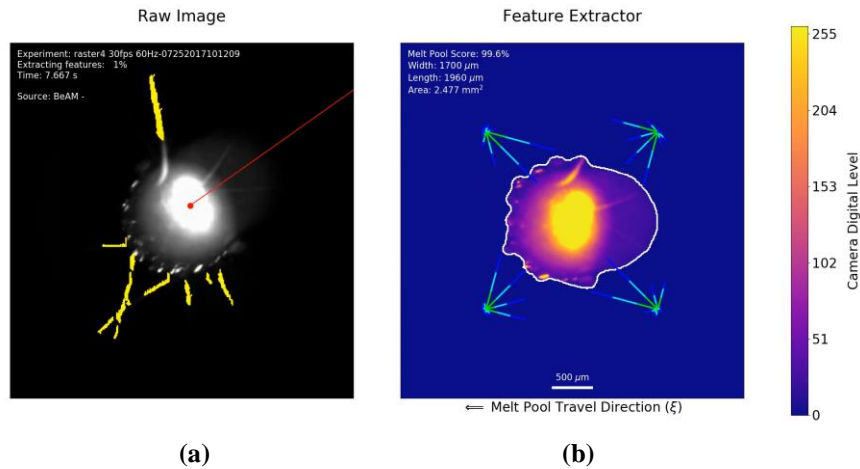


Figure 25: Example of extraction of features. An example frame of data from the melt pool camera (a) and the corresponding feature extraction (b). Note that the overlaid scale bar is not properly calibrated in this image.

4. CONCLUSION

Various sensing modalities are available on the AM technologies evaluated—either installed by the machine manufacturer or specifically designed and installed by ORNL staff in support of the TCR program. Additional work is needed to refine these sensing modalities. However, incorporation of these sensing modalities allows for a better understanding of the manufacturing process, especially when connected with data analytics and AI to detect defects.