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Oak Ridge National Laboratory Project Fringe, Testing and Validation on Metal Additive Manufacturing

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Manufacturing Sciences Division

Project Fringe, Testing and Validation on Metal Additive Manufacturing

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ABSTRACT

Oak Ridge National Laboratory (ORNL) worked with Additive Monitoring Systems (AMS) to demonstrate the real-time inspection of additive manufacturing (AM) binder jet fusion 3D printing (BJF). Test coupons on the ExOne Innovent were printed and monitored using AMS's Project Fringe structured light system. Anomalies were detected automatically and classified post build as recoater powder layer non-uniformities, binder powder interaction, depressions, and sub optimal print area. These anomalies were not apparent in the visual spectrum, which suggests that the structured light system has advanced the monitoring techniques state-of-the-art for BJF.

1. PROJECT TITLE

This phase 1 technical collaboration project (MDF-TC-2022-241) began on April 1, 2022 and concluded in December of 2022. The collaboration partner Additive Monitoring Systems is a small business. The results proved that the structured light monitoring technique utilized by Project Fringe was capable of detecting and quantifying in situ anomalies not visible in the visual spectrum.

1.1 BACKGROUND

AMS is a small sensor company that has invented a novel hardware and software monitoring system which measures additive manufactured parts during the printing process. The commercial product, Project Fringe, is the flagship product offered by AMS, currently in mid-stages of development. Project Fringe uses a novel approach to in-process monitoring by utilization of digital fringe projection, a structured light sensing method able to rapidly measure exposed surfaces of parts in-situ.

AMS intended to validate the use of Project Fringe on the BJF process at Oak Ridge in order to prove a successful value-add for in situ defect detection. Additionally, AMS intended to generate representative data which can be shared with customers to showcase the success of measurement on the ExOne Innovent. Oak Ridge benefitted from this testing through the free-use of Project Fringe to evaluate the effects of print parameters on powder spreading and binder powder interaction.

1.2 TECHNICAL RESULTS

The objectives of each task noted in the statement of work were accomplished and are summarized in this results section.

1.2.1 Task 1-1: System retrofit design and integration

Details: Projector and/or camera mounting fixtures will be fabricated for the retrofit of the ExOne Innovent printer at the MDF for the project fringe monitoring system. ***Responsible party:*** Additive Monitoring Systems. ***Desired outcome:*** A semi-permanent fixture will be designed and fabricated to mount the projector and/or camera to cover the majority of the build area for real-time digital fringe projection measurement. ***Results:*** The Project Fringe monitoring system is comprised of a projector and a camera which are synchronized to perform digital fringe projection shape measurement after the binding and recoating cycles of the Innovent MJF system. Mounting fixtures for the camera and projector were designed and tested by AMS onsite at the MDF. Additionally, a trigger sensor and corresponding electronic circuit was designed and fabricated by AMS and the MDF. Details of the fixture design evolution and triggering mechanism are summarized in figures 1-7 .

Figure 1: First iteration projector mounting fixture. See full coverage of the projection field on the buildplate in the bottom left of figure.

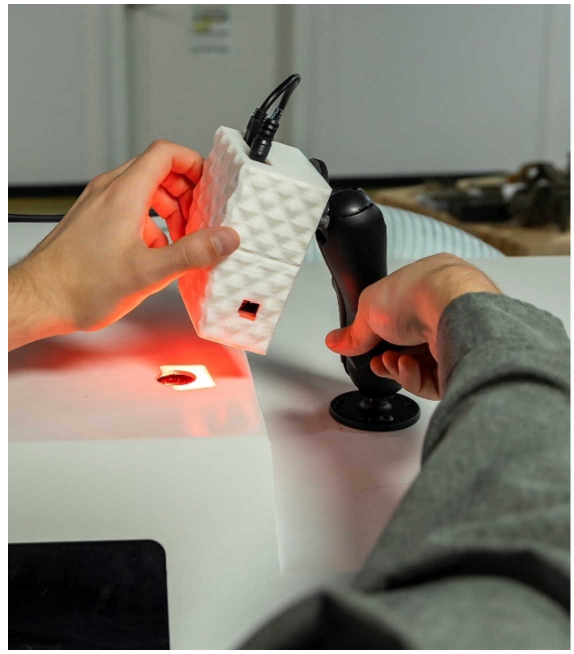

Figure 2: Second iteration of projector mounting fixture. Includes updated dual ball mount and custom projector casing for safety and longevity concerns.

Figure 3: First iteration of camera component, lens and custom mount for FOV of the buildplate

Figure 4: second iteration of camera component, lens and custom mount to obtain FOV of the buildplate

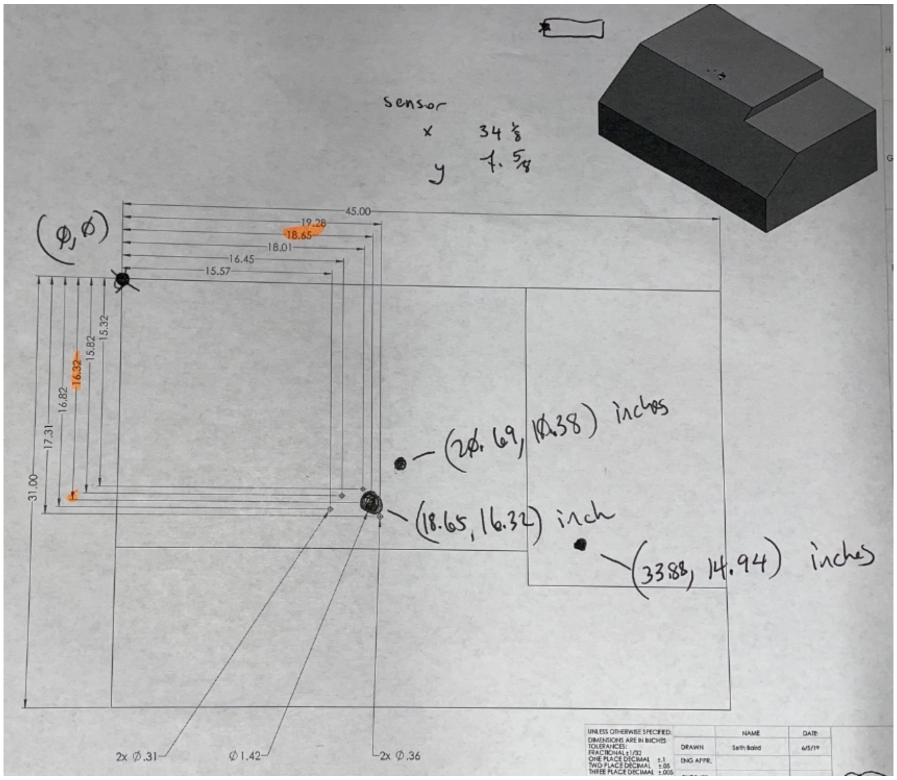

Figure 5: Mounting location diagram for Project Fringe on the ExOne Innovent.

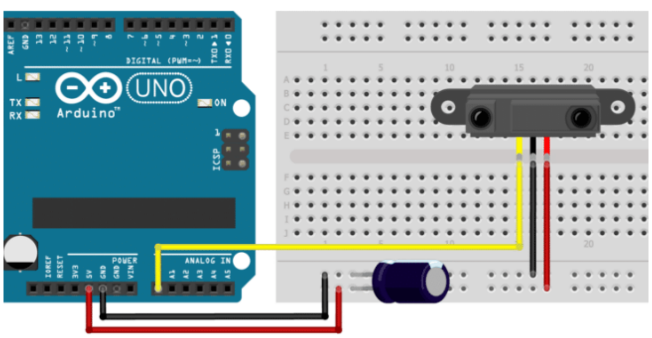

Figure 6: the wiring diagram used for the distance sensor (measurement triggering)

Figure 7: Location of the digital to analogue converter (Arduino) used to acquire distance sensor data and trigger Project Fringe

1.2.2 Task 1-2: Data collection

Details: A series of specimens will be 3-d printed while data is recorded by project fringe and image analysis. ***Responsible party:*** Additive Monitoring Systems, ORNL. ***Desired outcome:*** Several datasets from different sensors are recorded. ***Results:*** After several iterations of the camera fixture, projection fixture, triggering strategy, several test builds were used to observe the Project Fringe surface measurement capability. This section showcases detected anomalous phenomenon observed.

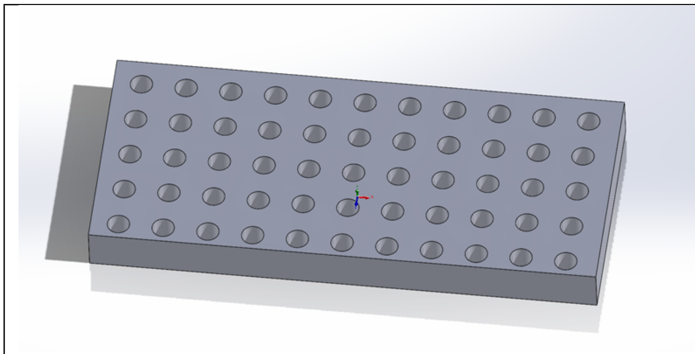

Figure 8: Test specimen geometry (CAD)

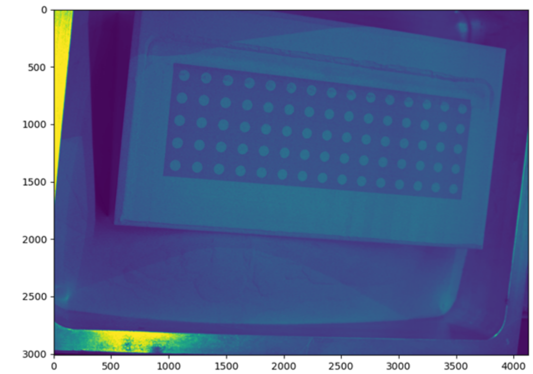

Figure 9: a visual image of layer 18 after the binding process

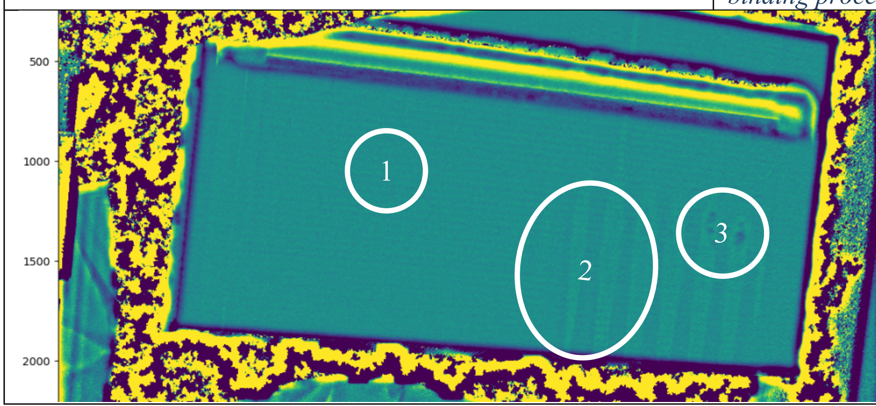

Figure 10: the height anomaly scan performed by Project Fringe. Several in situ anomalies are indicated, including horizontal height based streaks (1), vertical powder recoating anomalies (2), and several powder depressions (3).

As shown in figures 8-10, Many defects are not apparent in visual spectrum. In fact, the part geometry creates binded-unbinded contrast which can dominate the visual spectrum, making it difficult to achieve contrast for crucial height-based defects. Additionally, once matured and properly calibrated (Phase II objective), these defects can be quantified with statistical uncertainty.

1. **horizontal height-based streaks**
    a. Approximately 15-30 microns tall
    b. These height undulations occur parallel to recoat-roller movement
    c. Expert has confirmed that they are caused by the recoat-roller cross section being not –perfectly circular (Dan Brunermer, ex 20 year ExOne Tech Fellow)

2. **Vertical powder recoating anomalies**
    a. Light areas show raised streaks height defect
    b. Expert suggests:
    c. caused because excess binder is deposited at beginning of deposition pass (Dan B)
    d. And/or recoater roller not perfectly aligned to build plate
    e. Also aligned with areas between empty-circles

3. **Powder depressions**
    a. **Approximately 80 microns depressed**
    b. Dark areas show depression in layer height after binding
    c. Suggests an excess of deposited binder was not absorbed, creating material liftoff from the recoat-roller

d. Corresponds to areas of the part with large solid binded regions in the part

Databases for the reported anomaly build are available upon request to niall@phase-3d.com, and are shared with Oak Ridge National Laboratory, care Dr. Amy Elliot.

1.2.3 Task 1-3: Benchmarking and ideal projection parameters are developed for *Project Fringe*

Responsible party: Additive Monitoring Systems, ORNL. ***Desired outcome:*** *Project Fringe* measurement parameters such as projection angle, fringe pitch, and number of fringes are explored to determine maximum achievable sensitivity. Anomaly classification capabilities are compared to the other sensors (if present). **Results:** Benchmarking Project Fringe on the Innovent system has been successful, in which parameters have been evaluated according to the theoretical and experimentally validated parameters in [0]. A parameter study was performed to evaluate the projection color for the copper printed as part of this study. The results of different projection colors are shown in figures 11-13.

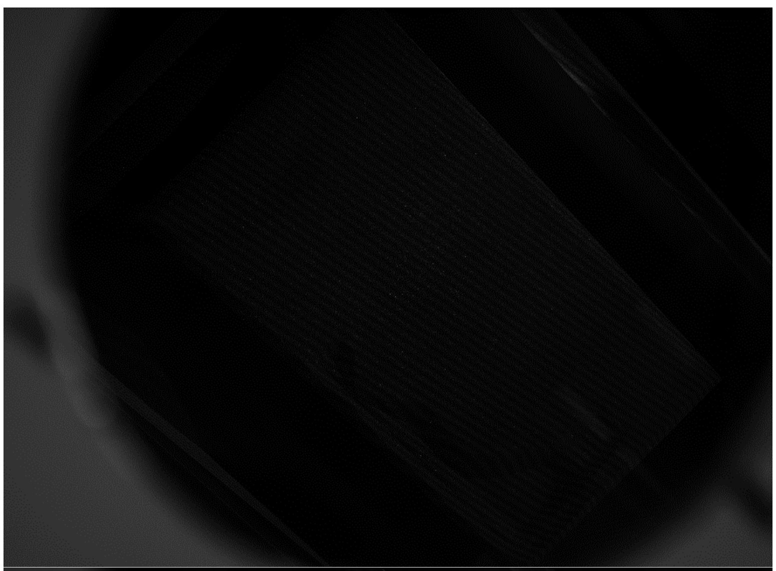

Figure 11: fringe image recorded with blue projection. Poor contrast is observed between light and dark fringe areas.

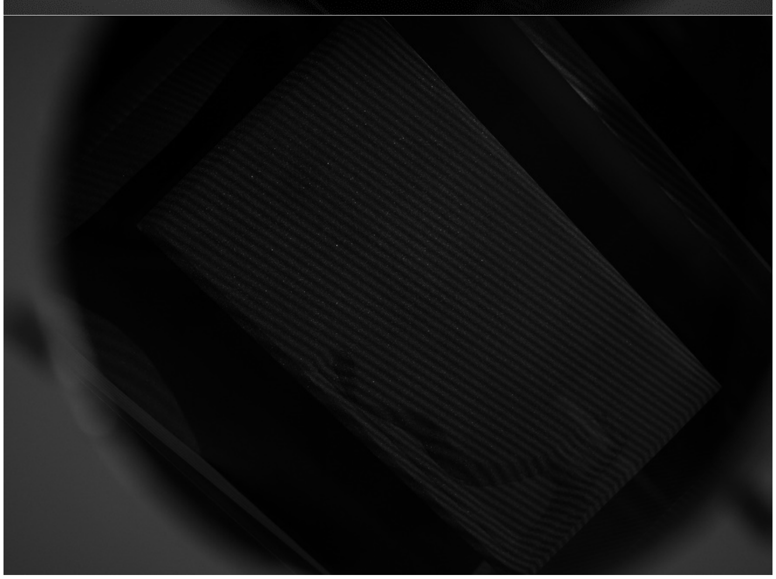

Figure 12: fringe image recorded with green projection. Semi-poor contrast is observed between light and dark fringe areas.

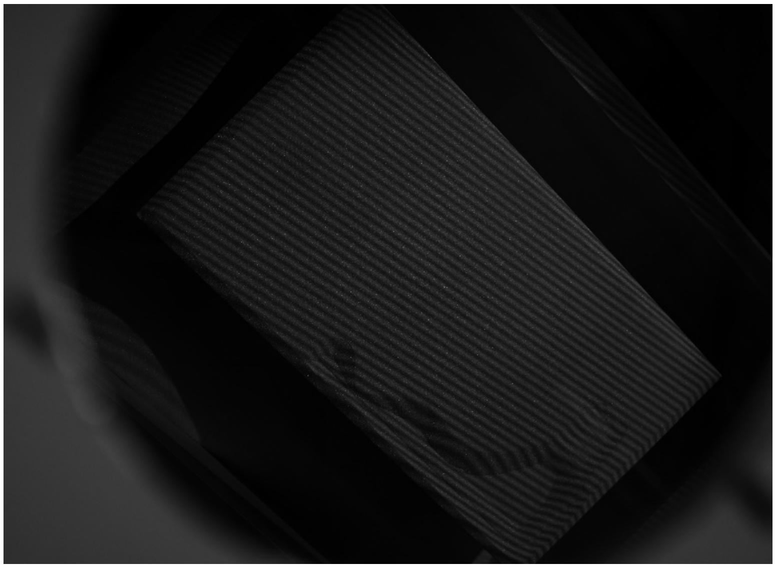

Figure 12: fringe image recorded with red projection. Good contrast is observed between light and dark fringe areas.

1.3 IMPACTS

BJF is a complex manufacturing process under enormous pressure to increase throughput, part quality, and part repeatability [1]. To increase these manufacturing efficiencies, development of *in-situ* monitoring is required to verify part quality in real-time to mitigate the effects of late-stage part rejection during final inspection. Additionally, real-time layer-wise monitoring is beneficial during the parametric development of printing settings, to ensure that physical printing mechanisms (such as recoat layer) are consistent, and not responsible for variance in final part properties. In addition to industry [2] and academic consensus [3], multiple US agencies (Department of Energy, Department of Defense, US Airforce) have cited *in-situ* monitoring for AM as a crucial activity for national security [4,5,6].

Oak Ridge National Laboratory and the Manufacturing Demonstration Facility (MDF) have historically performed research and development of *in-situ* monitoring systems, advancing the state-of the art by exploring real-time melt pool monitoring [7,8], convolutional neural networks [9], and the combination of multiple feature data [10]. However, the bulk of this work has been performed on powder bed fusion (PBF) AM, as opposed to BJ AM. Amy Elliot's group includes the development of new alloys and processing parameters for BJ systems, where real-time monitoring can be implemented to reduce process uncertainty and parametric testing requirements.

1.4 SUBJECT INVENTIONS

N/A

1.5 CONCLUSIONS

The goals of this technical collaboration were met and the results suggest further value in exploration of the impacts of observable phenomenon. AMS and Oak Ridge intend to propose a phase II technical collaboration to evaluate the impacts of measured anomalies on final part characteristics including sintering strain and porosity.

[0] O'Dowd, Niall M and Wachtor, Adam J and Todd, Michael D. (2021). Effects of digital fringe projection operational parameters on detecting powder bed defects in additive manufacturing. *Additive Manufacturing*, *48*, 102454.

[1] Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., Nandwana, P., & Chmielus, M. (2021). Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, *119*, 100707.

[2] https://www.investor.exone.com/news-releases/news-release-details/exone-and-ssi-partner-drive-volume-production-metal-binder

[3] Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., Nandwana, P., & Chmielus, M. (2021). Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, *119*, 100707.

[4] *Additive Manufacturing: Building the Future*. (2019). U.S. Department of Energy.

[5] Fielding, J., Davis, A., Bouffard, B., Kinsella, M., Delgado, T., Wilczynski, J., Marchese, K., & Wing, I. (2016). Department of defense additive manufacturing roadmap. *US Department of Defense, Washington, DC*.

[6] Pacinda, M. (2021). *AFRL "x-ray vision" tool to reduce costs, time for 3D part qualification*. U. S. Air Force News.

[7] Scime, L., & Beuth, J. (2019). Melt pool geometry and morphology variability for the Inconel 718 alloy in a laser powder bed fusion additive manufacturing process. *Additive Manufacturing*, *29*, 100830.

[8] Scime, L., & Beuth, J. (2019). Using machine learning to identify in-situ melt pool signatures indicative of flaw formation in a laser powder bed fusion additive manufacturing process. *Additive Manufacturing*, *25*, 151–165.

2. PARTNER BACKGROUND

Phase3D provides in-process part quality data to additive manufacturers to decrease schedule delays and reduce energy waste of final part scrap. Their flagship product is a patent pending optical in-process monitoring system which can instantly detect several major part-compromising defects. Unlike most in-development quality control methods, their monitoring system is able provide statistical data fast enough to allow current-layer alteration and decision making. The monitoring system is able to retrofit any existing MAM machine, and is designed to provide feedback process control without any training or manual operation.