

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 05-12-2021		2. REPORT TYPE Project Final Report		3. DATES COVERED (From - To) Jun 2019 to Dec 2021	
4. TITLE AND SUBTITLE In-Process Control for L-PBF				5a. CONTRACT NUMBER SP4701-19-C-0027	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Maass, David				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Flightware, Inc. 829 Podunk Road Guilford, CT 06437				8. PERFORMING ORGANIZATION REPORT NUMBER TBD	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Dr. Vaibhab Jain Research and Development/J348 Defense Logistics Agency 8725 John J. Kingman Road - Suite 4317 Ft Belvoir, VA 22060-6231				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified, non-sensitive, and non-proprietary cleared for public release					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT In this program an in-process inspection methodology for laser powder bed fusion (LPBF) was developed using surface height measurements of the melt layer. A full bed optical profilometer was developed capable of capturing almost 100 MM measurements of each layer with high precision. This data was processed through a Flaw detection algorithm and evaluated using about 100 coupons made with approximately 10,000 seeded flaws. The effects of flaw type, flaw severity and flaw size were evaluated using in-process inspection validated using micro-CT. A closed loop control scheme was developed and tested where detected Flaw maps were read by the Printer and layer repairs were made automatically for every Build layer, without Operator intervention. Results are presented and discussed.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 72	19a. NAME OF RESPONSIBLE PERSON David Maass
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 203 458 0722

Final Report

Contract SP4701-19-C-0027

SBIR Topic DLA181-002 “Additive Manufacturing Process Monitoring and Control Technologies”

Program: “In-Process Control for L-PBF”

DLA Program Manager: Dr. Vaibhab Jain

Principle Investigator: David Maass
Flightware, Inc.
(203) 458 0722
david.p.maass@snet.net

Submission Date: December 5, 2021

SBIR Data Rights

Contract No. SP4701-19-C-0027

Contractor Name: Flightware Inc.

Contractor Address: 829 Podunk Road, Guilford, CT 06437

Expiration of SBIR Data Rights Period: June 19, 2026

The Government's rights to use, modify, reproduce, release, perform, display, or disclose technical data or computer software marked with this legend are restricted during the period shown as provided in paragraph (b)(4) of the Rights in Noncommercial Technical Data and Computer Software--Small Business Innovative Research (SBIR) Program clause contained in the above identified contract. No restrictions apply after the expiration date shown above. Any reproduction of technical data, computer software, or portions thereof marked with this legend must also reproduce the markings.

Table of Contents

1	Additive Manufacturing Overview	7
1.1	AM Benefits.....	7
1.2	AM Limitations	7
2	In-situ Inspection.....	8
3	Closed Loop Control	9
4	Program Objectives	10
4.1	In-situ Inspection objectives	10
4.2	Closed Loop Control objectives	10
5	AM Printer	11
6	Methodology.....	12
6.1	Use of Sequential Builds	12
6.2	Evaluation sequence for each Build.....	12
6.3	Nominal and Seeded Flaw Process Parameter Development	13
6.4	Build 1 – Optimization of LTM Algorithm	16
6.5	Build 2 – Development of Optimum Repair processes.....	16
6.6	Build 3 - Development of Optimum Repair processes.....	16
6.7	Build 4 – Demonstration of Closed Loop Control	16
7	In-Situ Inspection Methodology.....	17
7.1	Use of Profilometry.....	17
7.2	Profilometry vs. Thermography	17
7.3	Surface height sensor	18
7.4	Integrated Area Profilometer (IAP).....	19
7.5	IAP Performance Characteristics	23
8	LTM Software	24
8.1	Reading IAP sensor	24
8.2	LTM Algorithm	24
8.3	Flaw Maps	26
9	Closed Loop Control	28
9.1	Repair Process Definition.....	28
9.2	Automatic Repair Process Concept.....	28
9.3	Automatic Repair Process Operation.....	29
10	LPBF Coupon Fabrication	30
10.1	Coupon material	30
10.2	Coupon Layouts	30
10.3	Detailed Coupon Geometry	31
10.4	Build Plan Details	33
10.5	Build 1	33
10.6	Build 2	34
10.7	Build 3	35
10.8	Build 4	38
11	CT Inspection.....	39
11.1	CT Considerations	39

11.2 CT Scanning	39
11.3 CT Data Processing.....	40
12 Results	44
12.1 Single Cube Results	44
12.2 Build 1	45
12.2.1 Coupon fabrication results.....	45
12.2.2 Profilometry results	46
12.2.3 LTM algorithm results	48
12.2.4 CT Results	50
12.3 Build 2	51
12.3.1 Coupon fabrication results.....	51
12.3.2 Profilometry results	51
12.3.3 LTM Algorithm results.....	51
12.3.4 CT Results	51
12.4 Build 3	53
12.4.1 Coupon fabrication results.....	53
12.4.2 Profilometry results	53
12.4.3 LTM algorithm results	54
12.4.4 CT Results	56
12.4.5 Optimum Repair Process Definition.....	59
12.5 Build 4	60
12.5.1 Coupon fabrication results.....	60
12.5.2 LTM algorithm results	60
12.5.3 CT Results	63
13 Discussion and Conclusions	70
14 Acknowledgements.....	72

List of Figures

Figure 1 - AM2 Metal AM Printer at Open Additive	11
Figure 2 – Test coupons created during Process parameter optimization	13
Figure 3 – Power density variation over test coupon matrix.....	14
Figure 4 – Polished cross-sections at various process conditions	14
Figure 5 – Initial Nominal and Flaw process conditions used	15
Figure 6 - Nominal and Flaw process conditions used in Build 3 and 4.....	16
Figure 7 – Surface characterization by profilometry	17
Figure 8 – Keyence VJ-8080 laser line profilometer sensor.....	18
Figure 9 – Profilometer sensor mounted in the AM powder in the EWI AM printer in Phase I.....	19
Figure 10 – Multiple sensor passes are needed to cover the entire print bed.....	20
Figure 11 – EWI designed and built the IAP incorporating the AM2 Recoater frame	20
Figure 12 – IAP Interface Graphical User Interface (GUI)	21
Figure 13 – Sensor deflection (sag) was measured and corrected.....	21
Figure 14 – IAP in place at the Open Additive AM2 printer.....	22
Figure 15 – Video of the IAP in operation in AM2 Printer (click to activate).....	22
Figure 16 – Color coded height map of the AM2 bed with 25 coupon melts with closeup of one melt region	23
Figure 17 – Highest density point grid for the IAP sensor system	23
Figure 18 – Stitched map of the entire 150 x 150 mm print bed.....	24
Figure 19 –Conceptual operation of LTM algorithm (from Reference 4)	25
Figure 20 –Conceptual operation of LTM algorithm (from Reference 5)	25
Figure 21 – LTM plot from a layer made with known lack of fusion process parameters: (A) LTM map of a nominal layer, and (B) LTM map of a flawed layer (from Reference 5).....	26
Figure 22 – Flaw maps are generated to define sections of the layer area that are flawed	27
Figure 23 – Block diagram for closed loop control	28
Figure 24 – Detailed flow chart for closed loop control data exchange.....	29
Figure 25 – Nominal layout of 25 coupons on the AM2 print bed	30
Figure 26 - 3D view of the 25-coupon layout on the AM2 print bed.....	30
Figure 27 – Coupon Cone, Fiducial and Flaw Regions.....	32
Figure 28 – Partial build of coupons in the print bed (with all powder removed) also showing contour lines used for IAP calibration.....	32
Figure 29 – Geometry of the Fiducial region (one of six in the coupon)	33
Figure 30 – Flaws were evenly distributed within nine regions of the AM2 build volume (3 lateral XY regions and 3 height Z regions)	34
Figure 31 – Location of each seeded keyhole porosity and lack of fusion flaw within the 25 coupons in Build 1	34
Figure 32 – Revised Nominal process parameters used in Build 3	36
Figure 33 – Nominal (yellow), LOF repair (blue) and KP repair (orange) coupon locations on the Build 3 print bed.....	37
Figure 34 – Description of Skip Count nomenclature for Repair processes used.....	38
Figure 35 – Four coupons were scanned simultaneously for CT scans	39
Figure 36 – The selected voxel size defines the X-ray field of view.....	40
Figure 37 – Each group of four coupons were scanned in five overlapping vertical regions	40
Figure 38 – CT post processing steps	41
Figure 39 – Conceptual "fly-through" of a CT scan illustrating porosity variation along the coupon Z dimension	41

Figure 40 – Porosity calculation from binary pore image.....	42
Figure 41 – Porosity values (black line) exacted from CT images	43
Figure 42 – More granular view of porosity plot	43
Figure 43 – More granular view of porosity plot	44
Figure 44 – Powder and melt thickness during initial layer fabrication	44
Figure 45 – More granular view of porosity plot	45
Figure 46 – Nominal laser flux used in Build 1.....	45
Figure 47 – LTM output was sensitive to hatch angle as seen in Phase I	46
Figure 48 – 90° vs. 67° incremental hatch schemes.....	46
Figure 49 – 90° vs. 67° incremental hatch schemes.....	47
Figure 50 – KP and LOF flaws exhibit clearly differentiated surface topologies	47
Figure 51 – Flaw severity has a relatively small effect on the surface profile or roughness	48
Figure 52 – 1 mm LOF flaws were barely visible in the profile data.....	48
Figure 53 – Typical flaw detection results for Nominal layer	49
Figure 54 – Typical flaw detection results for 10 mm Lack of Fusion flaw	49
Figure 55 – Typical flaw detection results for 10 mm Keyhole flaw.....	49
Figure 56 – Porosity extracted from regions surrounding 10 mm diameter flaws	50
Figure 57 – Detail of porosity surrounding seeded Flaw layers.....	50
Figure 58 – Build 2 Coupons.....	51
Figure 59 – 3D CT scans of a section of a Build 2 coupon showing numerous ball-like porosity regions.....	52
Figure 60 – 2D CT slices sections showing cuts through ball-like porosity regions.....	52
Figure 61 – Spatter porosity observed in other parts produced by Open Additive.....	53
Figure 62 – Surface profiles (height maps) for three different flaw states	54
Figure 63 – Surface profiles (height maps) for the two 3 mm flaw types	54
Figure 64 – The effects of LTM parameters was evaluated to determine optimum settings	56
Figure 65 – Porosity for unrepaired (control) Flaws	56
Figure 66 – Overlap of Repaired and Unrepaired (control) Flaws	57
Figure 67 – Porosity for repaired Keyhole Porosity flaws.....	57
Figure 68 – Porosity for repaired Lack of Fusion flaws	58
Figure 69 – Rank stacking of the 19 Repair processes used in Build 3	59
Figure 70 – Single repair process used the average laser fluence from optimum Keyhole and LOF repairs	60
Figure 71 – Total detected flaws by coupon number.....	61
Figure 72 – Detected flaws per Melt layer by coupon	61
Figure 73 – Flaw detection in Seeded Flaw and Nominal Layers.....	62
Figure 74 – Porosity extracted from Coupon 1 CT scan	64
Figure 75 – Thermal exposure variation with Flaw size	65
Figure 76 – LOF peak porosity as a function of Flaw size.....	68
Figure 77 – LOF peak porosity as a function of Flaw severity.....	68
Figure 78 – Keyhole peak porosity as a function of Flaw size	69
Figure 79 – Keyhole peak porosity as a function of Flaw severity	69

List of Tables

Table 1 - Initial Process Parameters.....	15
Table 2 – Keyence LJ-V8080 Sensor Characteristics	18
Table 3 – Integrated Area Profilometer (IAP) Sensor Performance	23
Table 4 – Repair parameters used in Build 3	36
Table 5 – Repair parameters used in Build 3	37
Table 6 – Compromise Repair Process Determination	59
Table 7 – Detected Flaw Statistics	62
Table 8 – Peak LOF Porosity for Control Coupons (i.e., not Repaired)	63
Table 9 – Peak Keyhole Porosity for Control Coupons (i.e., not Repaired)	65
Table 10 – Peak LOF Porosity for Repaired Coupons.....	66
Table 11 – Peak Keyhole Porosity for Repaired Coupons	67
Table 12 – Statistical Scatter of Mean Peak Porosity form CT data.....	71

1 Additive Manufacturing Overview

1.1 AM Benefits

Additive Manufacturing or AM creates a physical part directly from a computer or 3D CAD model. This eliminates much of the time and cost associated with nonrecurring Tooling and setup required with more traditional manufacturing methods and provides many advantages in a broad range of use applications.

For DLA, AM has great potential to simplify and improve its mission of supplying spare parts. This mission is challenging due to several factors including a diminishing or extinct supply base in many cases, need for legacy parts without tooling or data, small order volumes, minimum order quantities, inventory management and difficult to predict parts needs. With AM, ideally a spare part can be printed as needed, on demand and potential at the point of need.

The most mature form of metal AM is laser powder bed fusion or LPBF. Here a thin layer of metal powder is first spread over a base plate. Then a focused laser beam prescribes a path over the powder bed to selectively melt the powder in desired areas, and this material cools and solidifies very rapidly. This process is repeated for the next layer or “slice” of the part, and the molten metal regions merge. Repeating this process thousands of times for thousands of slices through the part creates a three-dimensional solid part.

1.2 AM Limitations

AM was first reduced to practice about 30 years ago and is relatively new as an accepted manufacturing method. Therefore, there is less user familiarity and industry guidance for the use of AM. Compared with established manufacturing methods such as machining, forging and casting there are very few established and accepted industry standards and specifications for AM parts. In addition, there are perhaps 20 different classes of AM, and new methods are constantly being invented and brought to market.

Many of the systems that DLA supports are mission critical, and those systems tend to have many different parts, components and subsystems which are critical to the proper and safe operation of that system. It is imperative that when DLA supplies a part, that it has very high confidence that the part meets the same requirements as the original component did when the system was originally qualified. However, many of these parts were made using conventional methods. Therefore, it is DLA's obligation to assure that any AM method used to provide spare parts be able to meet or exceed these original requirements.

The nature of AM, and LPBF in particular, is that there is almost always some level of defects present. Therefore, to use LPBF to make parts, it is desirable to:

- Detect the number and size of defects required for part compliance with a very high level of reliability. Typically, this is interpreted as inspection methods that have a 90% probability of detection (POD) with 95% confidence.
- Minimize the number and size of defects to the maximum extent possible.

This program is focused on advancing the state of the art of LPBF for these two objectives.

2 In-situ Inspection

Quality Assurance typically includes final inspection, where a finished part is carefully examined to assure compliance with all requirements defined for the part by the drawing, model, specifications, etc. With respect to the quality of a component's base material, nondestructive inspection (NDI) methods such as CT scan, ultrasonic inspection, eddy current, dye penetrant and other methods are commonly used.

While this is effective to assure that only "good" parts are accepted, it is not very efficient or cost effective. Final inspection assessment is only performed *after* completion of all manufacturing steps, and all manufacturing cost have already been expended.

Therefore, it is common to also employ in-situ or inprocess inspection. In this case, some level of inspection is performed *during* manufacturing to detect defects or anomalies as early as possible to provide the best opportunity to correct the problem.

For example, it is well known that cutting tools wear during machining and consequently material removal rate is reduced with increasing machining time. This means that the machined surface may no longer occur where programmed because the cutter no longer is removing the material intended when the depth of cut was programmed. Therefore, it is common in CNC machining to perform intermediate or inprocess inspection of certain part features during machining to explicitly measure tool wear.

With LPBF parts are made layer-by-layer where layers are generally 30 to 50 μm thick (roughly .001 to .002 inches). Material defects such as keyhole porosity, lack of fusion, balling, hot earring, etc. are generally created at the layer level, for a variety of reasons. Therefore, the best opportunity to detect any LPBF flaws is at the layer, immediately after the melt layer has been formed.

In-situ inspection of LPBF provides the opportunity to improve yield and reduce unit cost, both of which are important to enhance the use of AM in industry. For example, we may have a part comprised of 5,000 layers. Consider the case where a flaw or defect is inadvertently created on layer 700. Using only final inspection such as CT scan, this defect would be found after completion of part printing, possible stress relief, removal from the build plate, support removal and possible surface finishing. If the flaw exceeds the maximum allowed criteria (a "fatal flaw") the part is rejected, and all the cost and value of the operations performed so far is lost.

By contrast, detection of this fatal flaw at layer 700 and immediately scrapping the part saves 86% of the printing costs for the remaining layers as well as the cost of additional operations performed before final inspection.

3 Closed Loop Control

In many cases, manufacturing flaws can be repaired, and additional flaws prevented, by immediately performing corrective or remedial actions.

Using the example of tool wear inspection for CNC machining cited earlier, if significant tool wear is observed, the worn cutter can be replaced with a new or resharpened cutter. This brings the process back into control and the remaining part made to specification.

For LPBF, melt flaws like lack of fusion or keyhole porosity may be repaired by using a separate melt laser pass to remelt the layer and remove the melt flaw. With LPBF the laser melts not only the topmost powder layer, but also 3 to 5 layers beneath it and this is necessary for all layers to intermix and form a 100% dense substrate. If a flaw was just formed, performing a “Repair” laser melt scan provides the opportunity to melt out the flaw.

We use the term “closed loop control” here in the context of the layer level. In other words, a layer is formed, it is inspected and, if a flaw is present, repairing the layer last made with a separate Repair laser melt scan. This is different (and simpler) than applying closed loop control on the melt laser itself, with dynamic control of the laser power and scan speed.

4 Program Objectives

4.1 In-situ Inspection objectives

The challenges to performing effective LPBF insitu inspection at the layer level are:

- Developing an inspection hardware system capable of determining layer quality to the precision and resolution necessary for flaw detection.
- Integrating the inspection hardware into an AM printer such that inspection functions can be suitably integrated with part AM manufacturing programs.
- Detecting LPBF melt flaws at the layer level with high reliability. High reliability is quantified by low false negative (missed detections) and low false positive (incorrect detection) rates.
- Defining the spatial boundary of flaw regions, which become the lateral boundary of the Repairs applied.
- Identifying the flaw type. This is important to help define the appropriate Repair process.
- Performing the inprocess inspection as quickly as possible. LPBF insitu inspection as used in this program occurs between completion the melt layer and powder spread for the next layer. As such, this adds to the overall layer cycle time. Since LPBF is already considered “slow” vs. conventional manufacturing, we wish to minimize the incremental time required.

4.2 Closed Loop Control objectives

The challenges to performing effective closed loop control at the layer level are:

- Automatically transferring flaw location and type information from the in-situ inspection system to the AM printer software such that Repairs can be automatically performed (i.e., without Operator intervention).
- Developing optimum Repair processes for specific flaw types to reduce or eliminate existing layer melt flaws.
- Demonstrate the fully closed loop control system and assessing its effectiveness in flaw reduction.

5 AM Printer

The printer used in this program is called the AM2 printer as shown in Figure 1 and is located at Open Additive in their Beavercreek, OH facility. It features a 400-watt laser operating at 1070 nm wavelength. The print bed is 150 x 150 mm and the print volume is 150 mm tall for a total build volume of 3.4 MM mm³ or roughly 206 cubic inches.

This is a research machine and progenitor of the PANDA® unit offered commercially by Open Additive. It features an open architecture that allows the User to access almost all the machine's operating parameters.



Figure 1 - AM2 Metal AM Printer at Open Additive

6 Methodology

6.1 Use of Sequential Builds

Experimental data was generated in a series of LPBF builds made in Open Additive's AM2 R&D printer. We designed a series of experiments to maximize the data generated within any one build by using as much of the build volume as possible by producing as many standard geometry Coupons as possible within the build volume. Variations of interest (such as flaw characteristics, repaired vs. not repaired, etc.) were then distributed between Coupons and build layers. A total of four Builds and 100 Coupons were produced, as further described below.

6.2 Evaluation sequence for each Build

For each Build the following procedure was used:

- A Build Plan was created to define the experimental effects desired. This was generally defined as an Excel spreadsheet.
- The Build Plan was programmed using the DMC software that controls the AM2 printer. The programming was developed so that specific features of each Coupon on each build layer (such as hatch angle, laser power, scan speed, hatch distance, etc.) were pulled directly from the Build plan spreadsheet. This avoided countless hours otherwise needed to hard code these details into the Build program.
- Coupons were made as programmed. In addition to powder spreading and laser melt operations, three types of profilometry scans could be performed, as programmed:
 - Scan of the spread powder ("P scan") – This data was selected in Build 1 for later analysis but was not used in subsequent Builds because it adds Build time without additional data value. After scan, the data is immediately saved to disk.
 - Scan of the Melt layer ("M scan") – After every melt layer, it was scanned and the melt layer topography data was saved to disk.
 - Repair Scan ("R scan") – After Repair was performed the repaired melt layer was rescanned to provide a QA record of the Repair quality.
- Profilometry data was processed using the LTM metric described below. In Builds 1, 2 and 3 LTM processing was performed offline because time was not a factor. In Build 4 (Closed Loop Control demonstration), LTM processing was performed in real time to provide the flaw information needed to define and perform layer Repairs as soon as the layer was created.
- For Build 4, any Coupon found to contain a flaw was Repaired immediately after the layer was formed. Immediately after the Repair was performed an "R" or Repair scan was performed to capture the data for subsequent inspection.
- Coupons were then sent out for CT scan to determine the actual flaw state to a high resolution (20 μm voxels).
- The CT data was used to extract and generate plots of Porosity vs. layer number. Intentional or seeded flaws were identified and the actual as-formed porosity was compared with the flaw conditions (flaw type, flaw size and flaw severity).
- Porosity data was analyzed to determine:
 - How well insitu flaw detection performed.
 - Trends for the effect of flaw parameters (flaw type, flaw size and flaw severity) on insitu flaw detection.
 - Trends for the effect of flaw parameters (flaw type, flaw size and flaw severity) on actual flaw generation derived from CT scan.

6.3 Nominal and Seeded Flaw Process Parameter Development

To perform this work, it was first necessary to establish process parameters for Nominal (i.e., flaw free) material as well as for flawed material. Two types of microstructural flaws were included – lack of fusion or LOF (which generally occurs because insufficient laser energy is applied to full melt and consolidate all powder particles in the melt pool region) and keyhole porosity or KP. Keyhole formation occurs when vapor pressure from the laser spot generated when powder particles are melted (liquid phase) and vaporized (gas phase) exceeds the recoil pressure of the melt pool, and the resulting gas pore is driven deeply enough into the melt that it cannot surface before the melt pool cools, resulting in a trapped gas pore.

Furthermore, we evaluated three levels of seeded flaws that that we arbitrarily labelled “33%”, “67%” and “100%”. Despite the numeric nomenclature, these labels have no real quantifiable basis and could have just as easily been labelled Low, Medium and High severity. We used the criterion that a 100% severity flaw was unmistakably noticeable by visual examination of a polished section taken from a sample at low magnification.

To generate Nominal and Seeded Flaw process conditions several test cubes were produced with a range of laser power (85 to 400 watts) and laser scan speeds (275 to 1,400 mm/sec) as shown in Figure 2. These coupons were then cut, polished and examined for flaws (porosity) as noted in Figure 4.

The linear applied laser energy density or flux was calculated as:

$$F = \frac{P}{u} \text{ were}$$

F = laser energy density (watt-sec/mm)

P = laser power (watts)

u = scan speed (mm/sec)

These values are shown on Figure 3.

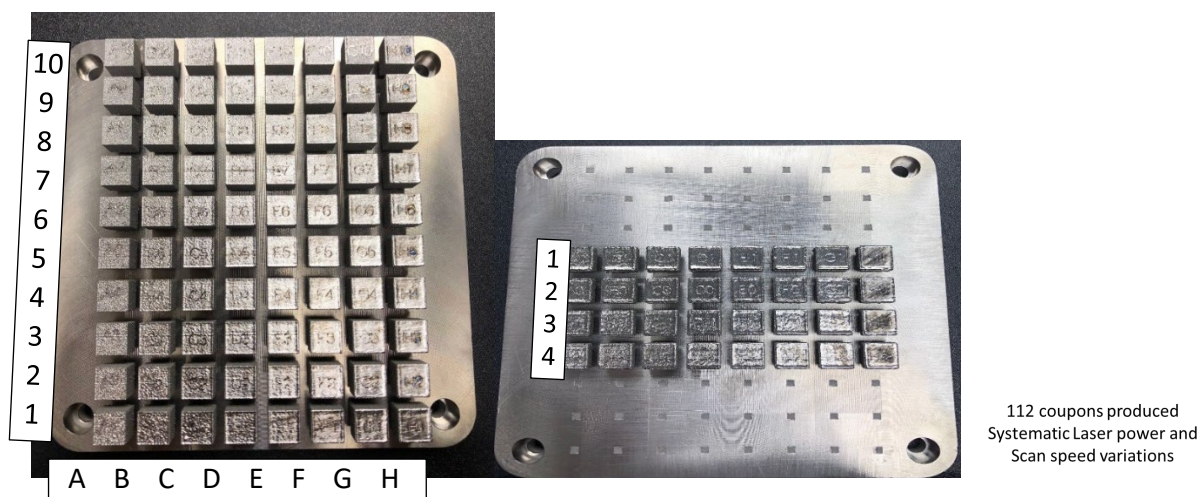


Figure 2 – Test coupons created during Process parameter optimization

Power Density (watt-sec/mm ²)										
Power (watts)										
Row	Scan (mm/sec)	Spacing (μm)	A	B	C	D	E	F	G	H
			85	130	175	220	265	310	355	400
10	1400	90	0.67	1.03	1.39	1.75	2.10	2.46	2.82	3.17
9	1300	90	0.73	1.11	1.50	1.88	2.26	2.65	3.03	3.42
8	1200	90	0.79	1.20	1.62	2.04	2.45	2.87	3.29	3.70
7	1100	90	0.86	1.31	1.77	2.22	2.68	3.13	3.59	4.04
6	1000	90	0.94	1.44	1.94	2.44	2.94	3.44	3.94	4.44
5	900	90	1.05	1.60	2.16	2.72	3.27	3.83	4.38	4.94
4	800	90	1.18	1.81	2.43	3.06	3.68	4.31	4.93	5.56
3	700	90	1.35	2.06	2.78	3.49	4.21	4.92	5.63	6.35
2	600	90	1.57	2.41	3.24	4.07	4.91	5.74	6.57	7.41
1	500	90	1.89	2.89	3.89	4.89	5.89	6.89	7.89	8.89

Power (watts)										
	Scan (mm/sec)	Spacing (μm)	A	B	C	D	E	F	G	H
			320	331	342	353	364	375	386	400
1	400	90	8.89	9.19	9.50	9.81	10.11	10.42	10.72	11.11
2	355	90	10.02	10.36	10.70	11.05	11.39	11.74	12.08	12.52
3	315	90	11.29	11.68	12.06	12.45	12.84	13.23	13.62	14.11
4	275	90	12.93	13.37	13.82	14.26	14.71	15.15	15.60	16.16

Figure 3 – Power density variation over test coupon matrix

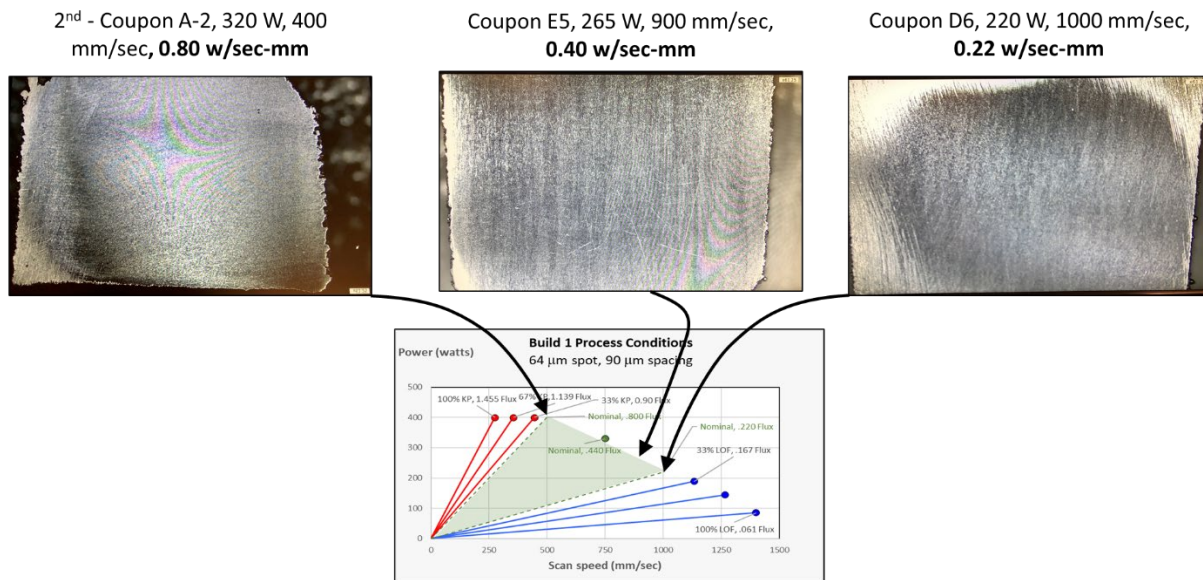


Figure 4 – Polished cross-sections at various process conditions

From this data it was established that:

- Nominal, high energy density limit = 0.80 watt-sec/mm
- Nominal, low energy density limit = 0.22 watt-sec/mm
- Nominal midpoint = 0.44 watt-sec/mm
- 100% keyhole porosity = 1.46 watt-sec/mm
- 100% lack of fusion = 0.061 watt-sec/mm

To calculate “33%” or Low flaw severity and “67%” or Medium flaw severity we simply interpolated between the respective edge of the Nominal process space and the 100% flaw severity condition. For

keyhole porosity we were limited by 400-watt maximum laser power and simply adjusted scan speed to obtain the desired laser flux. For lack of fusion, both laser power and scan speed were adjusted to provide the desired laser flux. All process conditions used are plotted in Figure 5 and shown in Table 1.

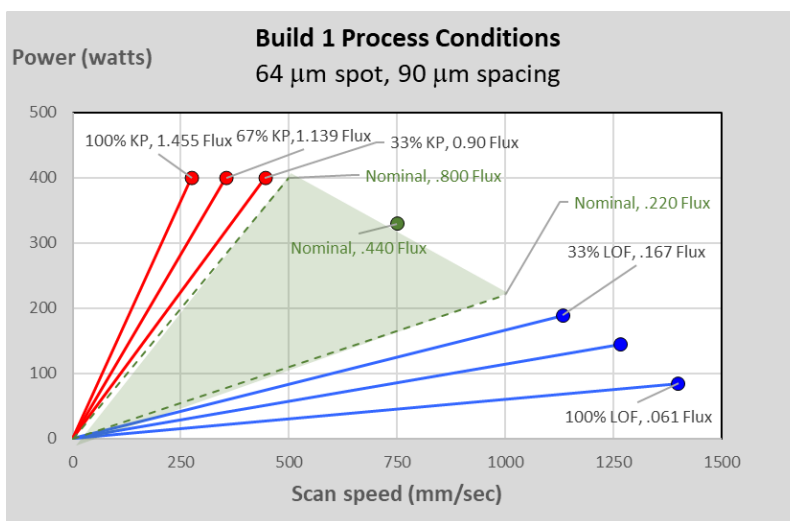


Figure 5 – Initial Nominal and Flaw process conditions used

Table 1 - Initial Process Parameters

Condition	Severity	Power watts	Speed mm/sec	Laser flux watt- sec/mm
Nominal	100%	330	750	0.440
KP	100%	400	275	1.455
KP	67%	400	355	1.127
KP	33%	400	444	0.901
LOF	100%	85	1,400	0.061
LOF	67%	144	1,267	0.139
LOF	33%	189	1,133	0.217

After CT results were obtained from Build 2 and 3 as described below, it was seen that significant porosity occurred in layers that were made to Nominal conditions (0.44 watt-sec/mm). It was learned that the earlier process trials used a relatively crude method for polishing sample cross-sections which resulted in some smearing of the cross section that obscured porosity present. Therefore, we remade additional coupons and now used better polishing equipment prior to porosity examination. This resulted in a new definition of Nominal process parameters (0.33 watt-sec/mm) used in Build 4 as shown in Figure 6. In fact, subsequent CT results from Build 4 verified that almost no porosity was observed in layers made with these nominal conditions.

Build 3 CT also showed very little LOF porosity even at 100% severity. So, the flux for 100% LOF was reduced by roughly 30% to 0.41 watt-sec/mm based in additional coupon fabrication, sectioning, polishing and examination. As seen in Figure 6, in Build 4 we also changed from three flaw severity levels (33%, 67% and 100%) to two levels (50% and 100%).

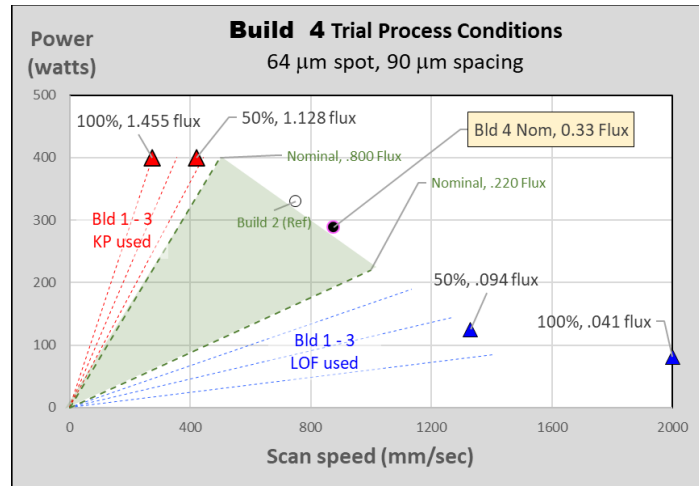


Figure 6 - Nominal and Flaw process conditions used in Build 3 and 4

6.4 Build 1 – Optimization of LTM Algorithm

The objective of Build 1 was to acquire topography data for a range of flaws so that the LTM algorithm could be tuned or refined to detect these flaws most accurately, i.e., generate a high percentage of true positives (flaw detection) and true negatives (no flaws) and low percentages of false positives and false negatives (missed detection).

6.5 Build 2 – Development of Optimum Repair processes

The original objective of Build 2 was to evaluate a range of Repair processes to determine which ones were most effective (i.e., optimum) for repairing specific flaw conditions. This Build was created improperly (as further described in [section 9.6](#)) and therefore was repeated in Build 3.

6.6 Build 3 - Development of Optimum Repair processes

As noted above, Build 2 was inadvertently created with flawed optics and the data was not usable. Therefore, the Build 2 plan was repeated in Build 3.

6.7 Build 4 – Demonstration of Closed Loop Control

Using the data from various Repair processes from Build 3, an optimum Repair process was selected and used in Build 4. Most of the effort in Build 4 was to implement the software that allowed Flaw maps detected by the LTJM code to be imported and used to guide the DMC code used to program and control the AM2 laser to perform the Repairs on a layer-by-layer basis. The effectiveness of this approach was evaluated by comparing CT porosity results from coupons that were not repaired (6 of the 25 coupons) with those that were (19 of 25 coupons).

7 In-Situ Inspection Methodology

7.1 Use of Profilometry

Profilometry is the description of the height variation (i.e., roughness) of surfaces. This is typically characterized as an average variation – R_a for an average height variation along a line or S_a as the average height variation across a surface. There are many other parameters that describe surface roughness such as the distance between peaks as shown in Figure 7. These characteristics are defined in ISO 4287 and 4288.^{1,2}

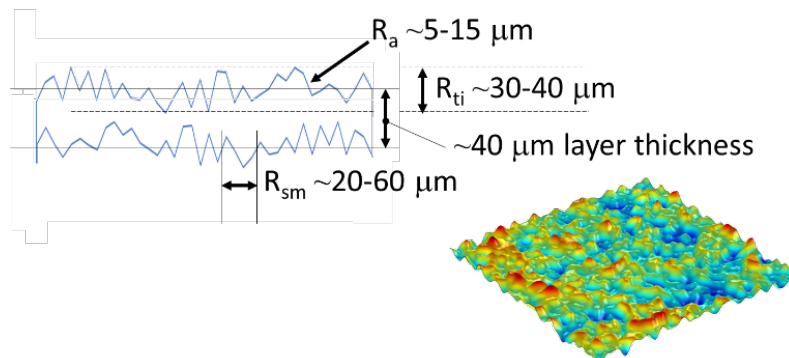


Figure 7 – Surface characterization by profilometry

7.2 Profilometry vs. Thermography

Most of the in-situ inspection activity for LPBF measures the temperature of the melt. Typically, either full bed thermography or a localized melt pool monitoring is used. In both cases, the intent is to capture local thermal anomalies to detect and localize the presence of *process* variations. The logic behind this is that since a well-defined nominal process is needed to convert raw powder into a 100% dense solid *part*, any *process* anomalies could lead to potential part anomalies or flaws.

We employ a different in-situ inspection philosophy. Ultimately it is the *part* quality we wish to examine as the part is made, therefore we use a sensor to measure *part* quality directly, layer-by-layer. We use a sensor that measures the dimensions of the formed part surface immediately after the layer is completed (i.e., after the melt pool has solidified across the surface of that melt layer). The surface characteristics of the layer directly correlates with the quality of solid metal in the topmost melt layers of the part at that point in time.

In this sense, we believe the LTM in-situ inspection methods provides a more direct measurement of the item of interest (metal part quality). Other methods such as thermography detect *process* anomalies, which then must be converted to part anomalies or flaws by relying on knowledge of process-part quality relationships. While knowledge and simulation of process-part quality relationships continues to improve, this is very complex subject involving many mechanisms such as laser absorption and reflection, heat transfer, melt dynamics, melt solidification, vapor recoil pressure, melt pool thermal distribution, surface

¹ ISO 4287:1997 Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters

² ISO 4288:1996 Geometrical Product Specifications (GPS) - Surface Texture: Profile Method - Rules and Procedures For The Assessment Of Surface Texture

tension, Marangoni convection, powder denudation, spatter, laser plume, scan path effects, grain structure and other effects.³

Therefore, using profilometry is both simpler and potentially a more accurate and reliable means to assess ins-situ part quality.

7.3 Surface height sensor



Figure 8 – Keyence VJ-8080 laser line profilometer sensor

Many laser line profilometers are commercially available with excellent performance. These devices use triangulation to determine the surface height along a laser line projected from the device. We used a sensor from Keyence shown in Figure 8 with performance characteristics as described in Table 2.

Table 2 – Keyence LJ-V8080 Sensor Characteristics

Item	Value
Line width	35 mm Nominal (mid-range) 30 mm minimum 39 mm maximum
No. measurement points along line	3200 and 1600 (see below)
Point spacing along line	12.5 μm and 25 μm depending upon sampling rate
Z height repeatability	0.4 μm
Max continuous data rate*	16,000 lines per second @ 25 μm 8,000 lines per second @ 12.5 μm
Max continuous data rate*	25.6 MM points per second

* Without data binning (compressing data and losing data resolution)

This sensor can be triggered (i.e., commanded to acquire a line or profile of data) in several ways. In continuous mode it can capture profiles at up to 64,000 lines per second, but at high speed the data is lumped into “bins” or ranges of height and therefore data resolution is lost. It can capture full data resolution for the 3200 points along the line at 4,000 Hz or lines per second.

³ Kyogoku, H. and Ikeshoji, T., “A review of metal additive manufacturing technologies: Mechanism of defects formation and simulation of melting and solidification phenomena in laser powder bed fusion process”, Mechanical Engineering Review, Japan Society of Mechanical Engineers. Vol. 7, No. 1, 2020

The sensor can also be triggered by an external controller and that was mode used in the Integrated Area Profilometer (IAP) as described below. In this case the sensor captures a profile every time the encoder advances by a preset amount. We used a trigger spacing of 9.5 μm corresponding to the incremental travel of the sensor carriage for one encoder pulse. At this spacing, the sensor was capable of recording 8,000 profiles per second with full line resolution (3200 point per profile at 12.5 μm spacing). In other words, operating in this mode captured 25.6 MM Z height measurements per second to very high resolution (0.4 μm height or Z repeatability).

7.4 Integrated Area Profilometer (IAP)

The sensor measures the height of points along a profile line 35 mm long, but the print bed is 150 mm wide. Therefore, it is necessary to raster the sensor across the bed to achieve full coverage. One axis of motion already exists with the Recoater bed, so mounting the sensor to this carriage provides coverage across the full length of the bed in this direction. This is what was done in Phase I at EWI, as shown in Figure 9. Note that the sensor used on Phase I only had a 15 mm long profile.

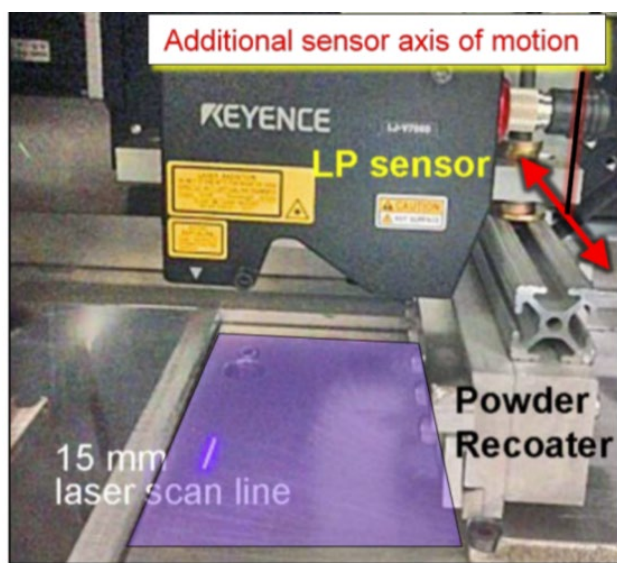


Figure 9 – Profilometer sensor mounted in the AM powder in the EWI AM printer in Phase I

To achieve full coverage across the entire bed requires that the sensor also be indexed across the width of the bed, as shown in Figure 10. Initially 5 passes were made so the 35 mm wide provided coverage of the complete 150 mm wide bed with generous overlap margins. We later reduced the number of passes to four overlapping passes which still provided adequate overlap. Reducing from 5 to 4 passes reduced scan time by 20%, reducing hours from the Build time for Coupons consisting of about 3500 layers.

To produce the IAP required that the original Recoated blade motion system of the AM2 printer be retrofitted with an additional axis of motion across the width of the bed. This system was designed and built by EWI and is shown in a partially assembled state in Figure 11. A second motor, encoder and slide mechanism were added to the existing Recoater carriage. Control of this axis was performed by the same DMC operating system used by the AM2 printer for all other functions.

Separate software was written to control and integrate operation of the sensor and the two motion controllers. While the point spacing of the profilometer is fixed in the width direction, it is user-selectable in the length or scan direction. The line-to-line spacing between profiles is defined by the User, with a

minimum spacing of 9.5 μm (the distance for one encoder count). The software accepts the User defined spacing, calculates the nearest multiple of 9.5 μm and uses that value for the line-to-line profile spacing. The User also inputs the desired scan velocity, but there is an upper limit based on the maximum acquisition frequency of the sensor (8,000 Hz). The software checks the User-entered velocity and issues a warning if the selected value will exceed the capacity of the sensor. The IAP software graphical user interface (GUI) is shown in Figure 12.

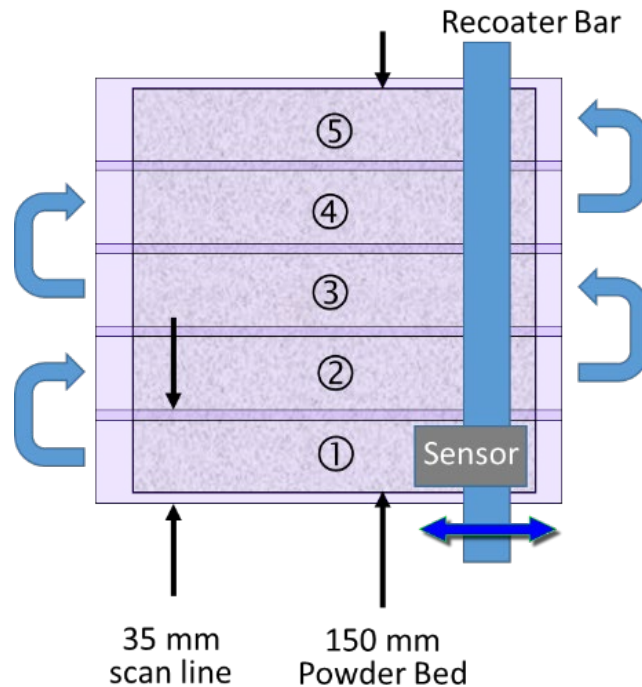
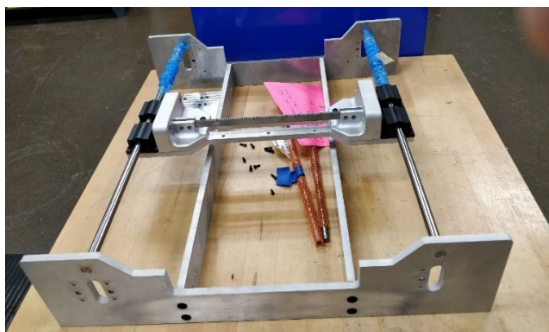
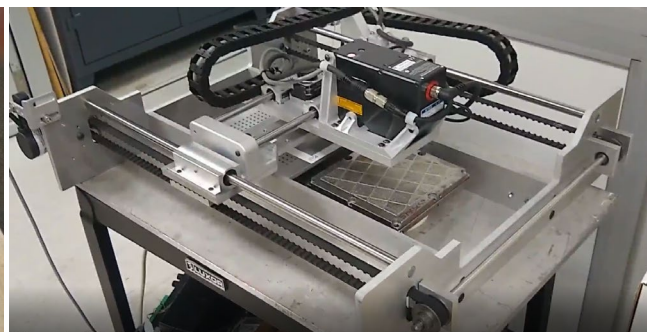


Figure 10 – Multiple sensor passes are needed to cover the entire print bed



AM Recoater frame



Completed IAP system (motors and encoders not shown)

Figure 11 – EWI designed and built the IAP incorporating the AM2 Recoater frame

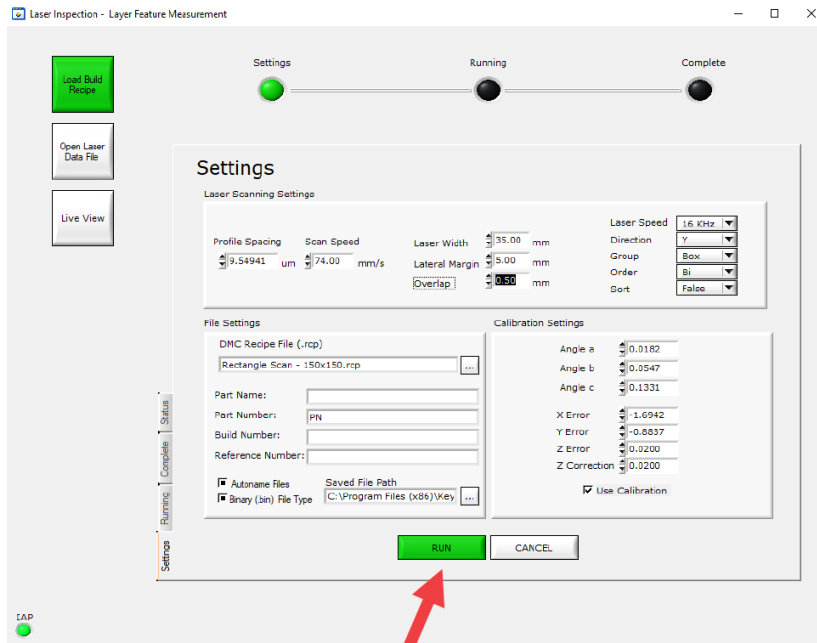


Figure 12 – IAP Interface Graphical User Interface (GUI)

The IAP system was then installed in the AM2 printer and calibrated. We found that the mass of the sensor (about 2 pounds) caused the carriage system to deflect slightly as the sensor was moved over the bed area. Those these deflections were small in absolute terms (less than 0.25 mm or 250 μm) relative to the melt layer thickness (40 μm) or roughness ($\sim 15 \mu\text{m}$) they are large and therefore had to be considered and corrected. This “sag” deflection was measured for many positions over the bed surface as seen in Figure 13. A fifth order polynomial surface in the X and Y coordinates was fit to this data and used to correct measured values.

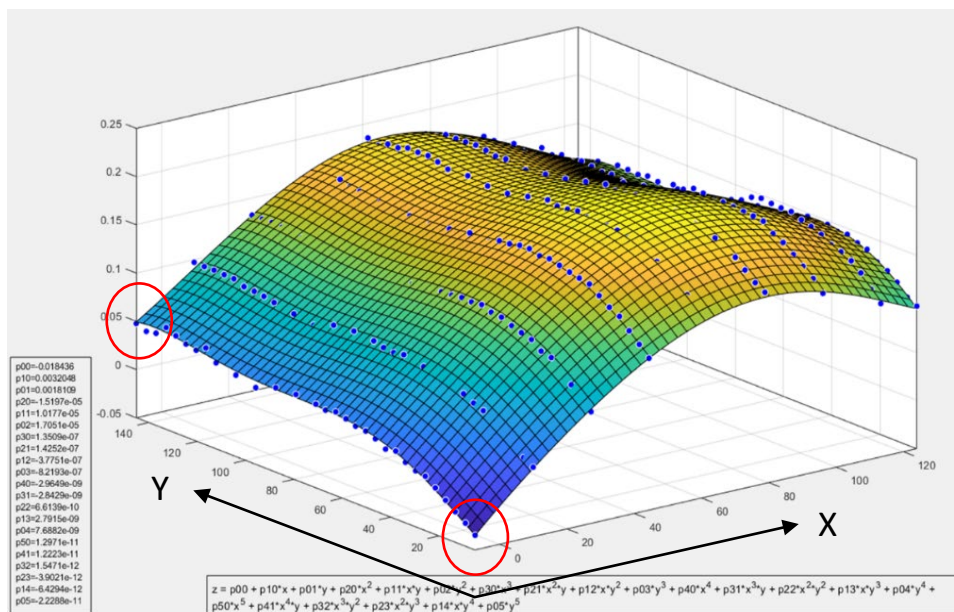


Figure 13 – Sensor deflection (sag) was measured and corrected

The IAP installed in the AM2 printer is shown in Figure 14 and a video of the IAP scanning the print bed is shown in Figure 15 (click to activate).

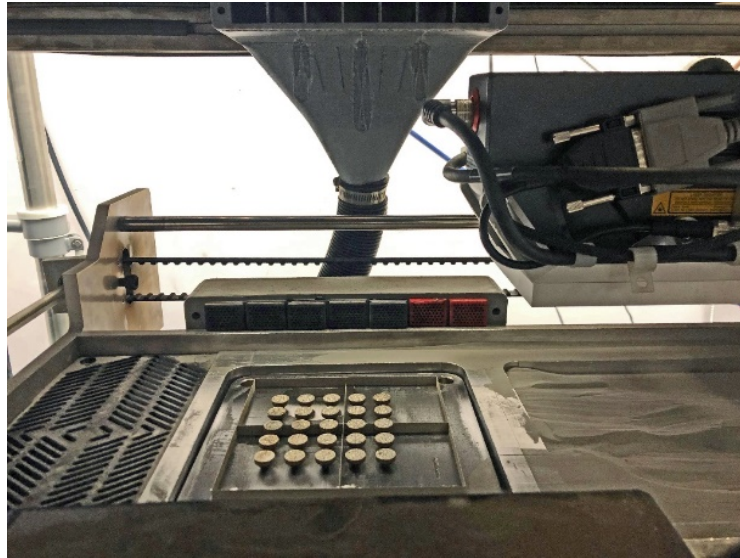


Figure 14 – IAP in place at the Open Additive AM2 printer

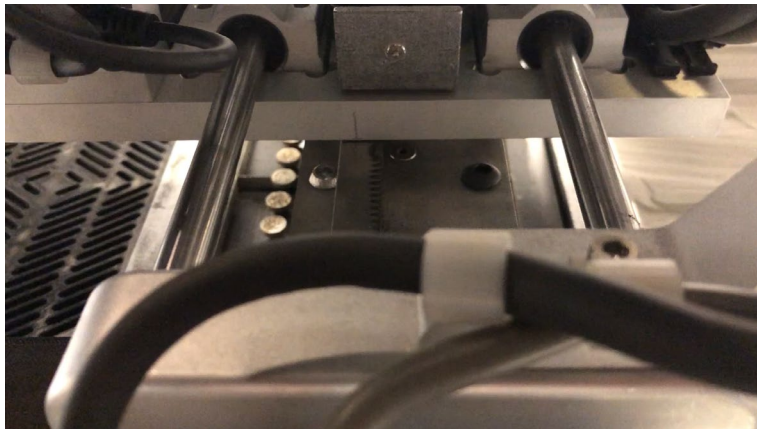


Figure 15 – Video of the IAP in operation in AM2 Printer (click to activate)

A typical topography scan or height map generated from the IAP is shown in Figure 16. The scan covers the complete 150 x 150 mm bed and each pixel represents an area 12.5 μm wide by 9.5 μm tall. The height of each pixel is represented by the pixel color, with the height scale shown at the right of the map.

In this case, a melt layer for one of the coupon Builds is shown where 25 coupons have been printed in a 5 x 5 grid. A closeup of a single coupon is shown at the right of the figure. Note that the melted region is bluer (lower height) than the surrounding yellow-green region, which is powder. This occurs because the solidified metal is higher density than the surrounding powder and therefore its top surface is lower than the original powder before melt. Also note the height variation within the metal surface (color variations). Peak heights are as much as 250 μm higher than the minimum height. This height information is the raw data used by the LTM algorithm to assess melt material quality.

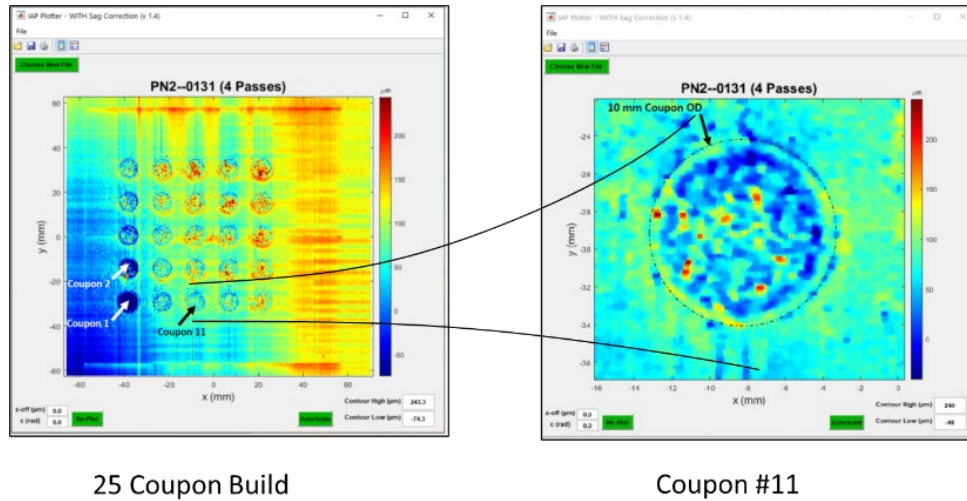


Figure 16 – Color coded height map of the AM2 bed with 25 coupon melts with closeup of one melt region

7.5 IAP Performance Characteristics

The IAP sensor system collects surface profile data as noted in Table 3 and shown in Figure 17.

Table 3 – Integrated Area Profilometer (IAP) Sensor Performance

Item	Value
Print Bed size	150 x 150 mm
Points acquired	95 MM (maximum)
Scan speed (data points)	25.6 MM points/sec
Z height repeatability	0.4 µm
X point spacing	12.5 µm
Y point spacing	User selectable: 9.5 µm smallest up to any multiple of 9.5 µm
Best (smallest) data grid spacing	12.5 µm x 9.5 µm

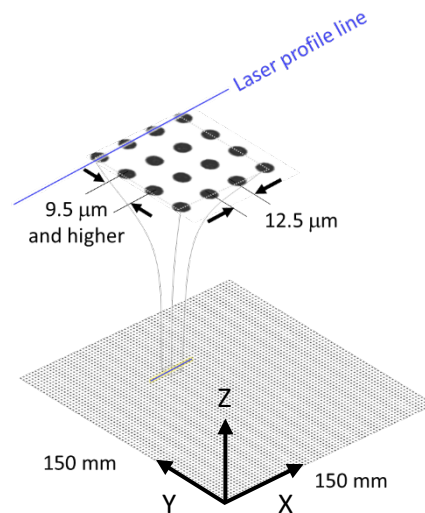


Figure 17 – Highest density point grid for the IAP sensor system

8 LTM Software

8.1 Reading IAP sensor

As previously noted in [section 7.4](#) the IAP performs four passes or scans of the bed for 100% coverage, creating 4 separate binary scan files. We elected to use binary files to achieve maximum data compression without data loss. Each binary file was 75 Mb so a complete set of 4 scan passes is about 300 Mb.

Software was written to read the four files, seamlessly combine them and then plot the data as shown in Figure 18. The software also allows the user to zoom to any section of the bed, and to change the minimum and maximum Z height for the Z color scale. The default is to determine the minimum and maximum Z values within the bed area, and autoscale the color Z scale to those values.

Figure 18 shows a scan of a melt layer of twenty-five (25) 10 mm diameter coupons, laid out in a 5 x 5 grid approximately evenly spaced over the bed surface.

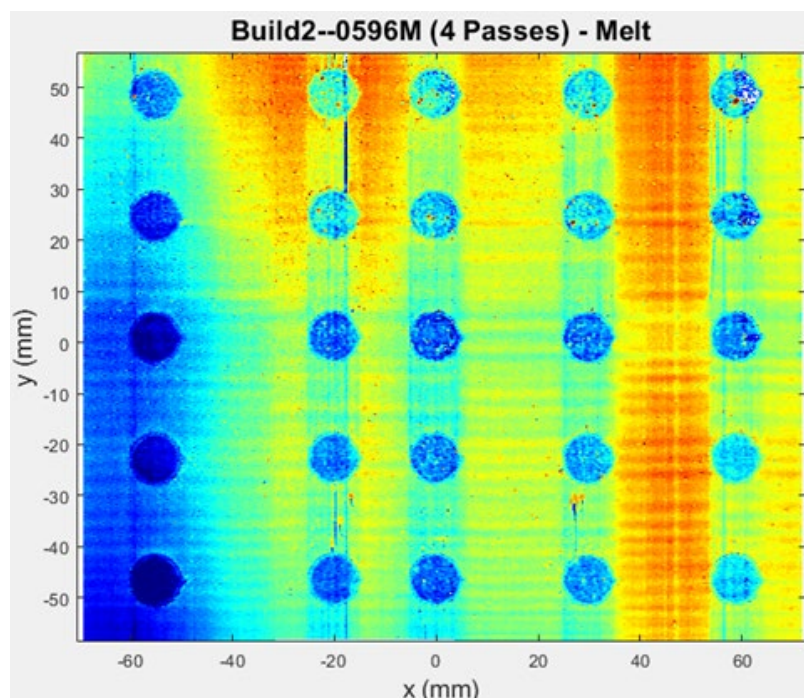


Figure 18 – Stitched map of the entire 150 x 150 mm print bed

8.2 LTM Algorithm

The basic LTM algorithm uses a texture variation detection scheme developed by Timm and Barth⁴ as shown conceptually in Figure 19. The procedure includes:⁵

⁴ F. Timm and E. Barth, "Non-Parametric Texture Defect Detection Using Weibull Features," in Proceedings Volume 7877, Image Processing: Machine Vision Applications IV (Bellingham, WA: SPIE, 2011).

⁵ D. Maass, "Demonstration of Closed-Loop Control for Laser Powder Bed Fusion (LPBF)", ASTM STP 1631, 2020, Proceedings of Fourth ASTM Symposium on Structural Integrity of Additive Manufactured Materials and Parts on October 7–10, 2019 in National Harbor, MD, USA.

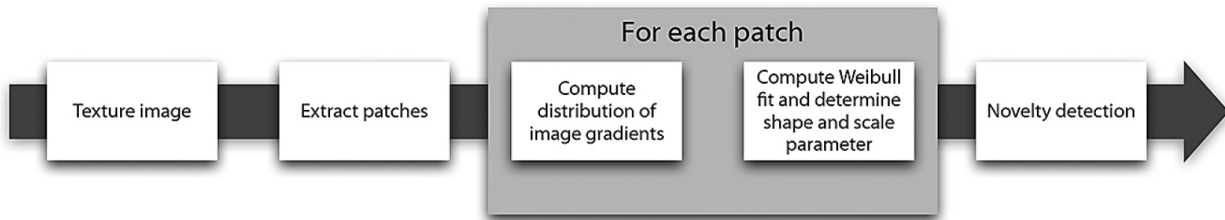


Figure 19 –Conceptual operation of LTM algorithm (from Reference 4)

- Segmentation of a layer profile image into many smaller subimages or “windows” representing small regions of the layer Calculation of the Gaussian image gradient values within each window
- Determination of Weibull probability distribution of Gaussian image gradient values for each window, defined by two probability density function (PDF) values: shape and scale, which are sometimes referred to as k and λ .
- Plotting the shape and scale PDF values for each window on a common layer plot, as shown in Figure 20. This is called a Mohalanobis plot.

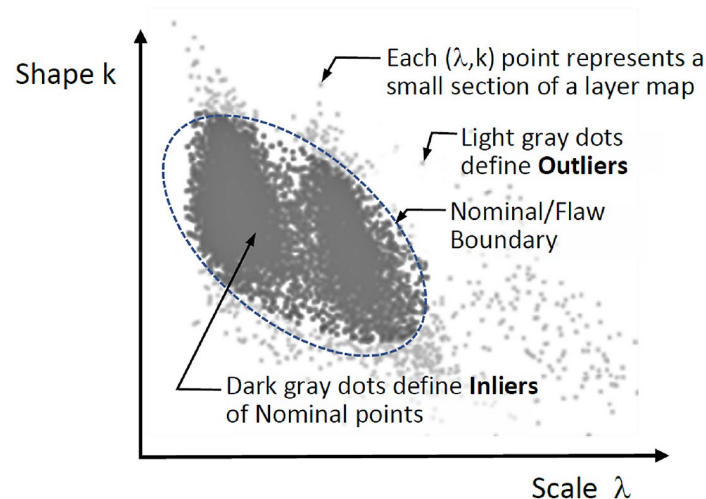


Figure 20 –Conceptual operation of LTM algorithm (from Reference 5)

The LTM or Mohalanobis plot in Figure 20 includes overlays of many nominal quality layers, and it is apparent that most of the X,Y values tend to cluster in an elliptical region in the center of the plot. Using statistical methods to determine inliers and outliers, inlier points are marked dark gray while outliers are marked light gray. The dashed ellipses indicate the outlier boundary.

The points (layer regions) of any newly created layer are similarly processed and each point is marked black if within the boundary (i.e., a nominal quality region) or **red** if outside the boundary. In the example shown in Figure 21-A, most of the current layer regions are nominal (black points), with only a few possible flaws or **red** points. However, other layer LTMs can be different, such as shown in Figure 21-B. Here, most of the current layer regions points are **red** and likely are flaws. In fact, this scan was derived from data for a layer that had been intentionally produced with process conditions known to create lack of fusion flaws.

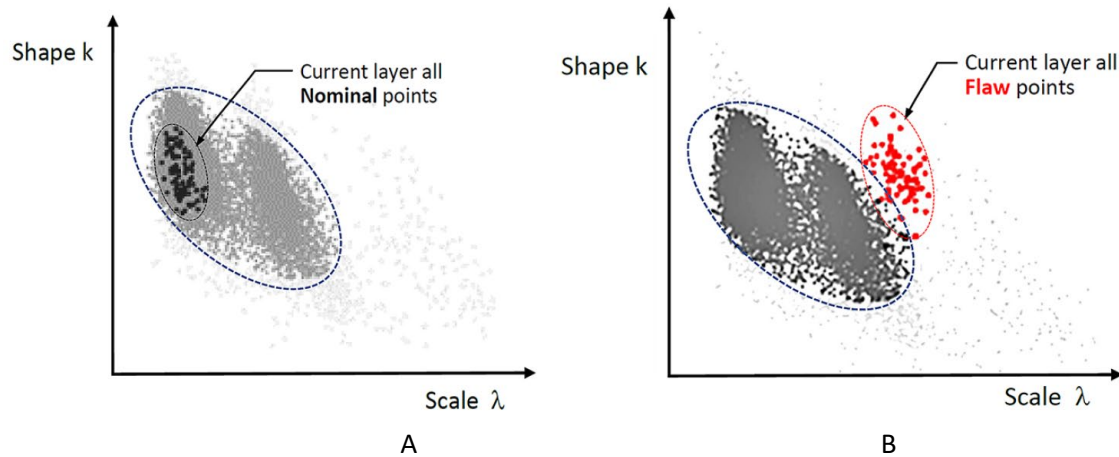


Figure 21 – LTM plot from a layer made with known lack of fusion process parameters:
 (A) LTM map of a nominal layer, and (B) LTM map of a flawed layer (from Reference 5)

Note that to generate the Nominal/Flawed boundary requires that many layers of Nominal quality material be first created and analyzed. In Build 1, 2 and 3 these Nominal calibration layers were produced immediately above the cone region of the coupon and comprised 100 layers. In Build 4 the Hatch strategy was changed to create 360 separate fill hatch angles in a repeating group (referred to as the 67° incremental hatch as further described in [section 12.2.1](#) below). It was determined that separate Nominal calibration layers were required for each of nine groups of hatch angles (0° to 10°, 10° to 20°, etc.) Therefore, to obtain sufficient Nominal calibration layers for each Hatch angle group, a total of 630 calibration layers were created.

8.3 Flaw Maps

Each of the flawed **red** points in Figure 21-B is from a region of the height map represents as subimage or “window” of the complete part scan. Therefore, this window is marked as a flaw X,Y section of the overall layer map. This is shown in Figure 22 where the red regions shown in the 10 mm diameter circular cross section represents a flaw. The balance of the circular cross section does not contain detected flaws and is shown as a beige color. The size of the flaw detected by this approach is defined by the size of the subimage or “window”. In addition, we sample subimages with a user-defined amount of window overlap to generate more reliable flaw detection.

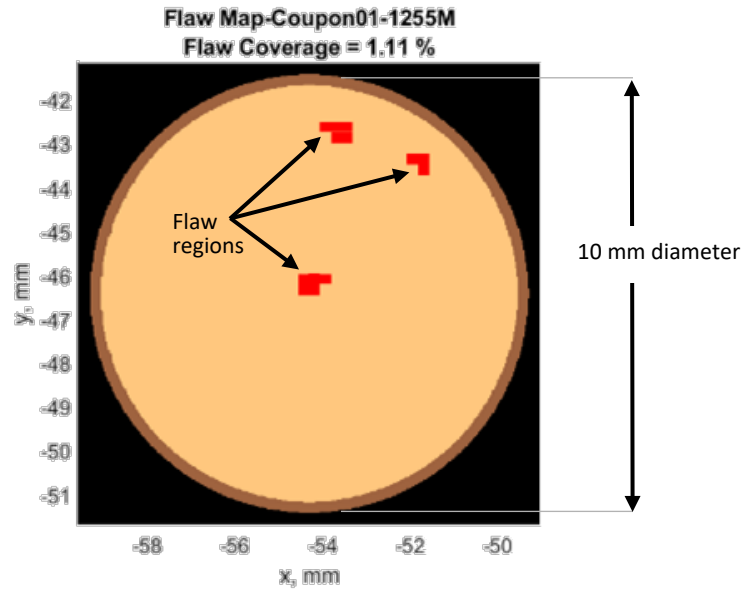


Figure 22 – Flaw maps are generated to define sections of the layer area that are flawed

Once the Flaw map is created as shown in Figure 22, the Flaw boundary is determined and exported to an STL file. This is performed so that the DMC operating software for the AM2 printer can read the flaw map for use in the Repair cycle. We used an existing MATLAB routine to generate the STL files from our 2D maps because it was convenient (minimized development time). However, this code is not very efficient (i.e., it operates slowly) and would need to be rewritten for faster real time operation.

9 Closed Loop Control

Closed Loop control has three elements:

- Define Flaws regions to be repaired (as described in [section 8](#) above).
- Establishing the Repair process
- Automatically repair those regions using the predefined Repair process

9.1 Repair Process Definition

Build 3 was used to establish a Repair process using a similar approach to that used to define the Nominal and Flaw processes as described in [section 6.3](#). Twenty-five (25) coupons were produced in this Build, and all featured a total of 82 intentional (or seeded) flaws distributed throughout. These flaws had a range of flaw type (lack of fusion and keyhole porosity), two levels of flaw intensity, and five different flaw ranging from 1 to 7 mm diameter for a total of 20 different flaw types. On average each flaw type had 4 replicates of any one flaw type to be better able to identify statistically meaningful trends using analysis of variance (ANOVA).

Six of the 25 coupons were not repaired at all, which served as our control. The remaining 19 coupons each used a different Repair process. The resulting porosity data from CT scans of these coupons was used to select an optimum Repair process from the 19 Repair candidates that resulted in the great degree of Flaw reduction over all 20 flaw types.

Test results are described in [section 13.3](#).

9.2 Automatic Repair Process Concept

A simplified conceptual description of the closed loop control logic is shown in Figure 23.

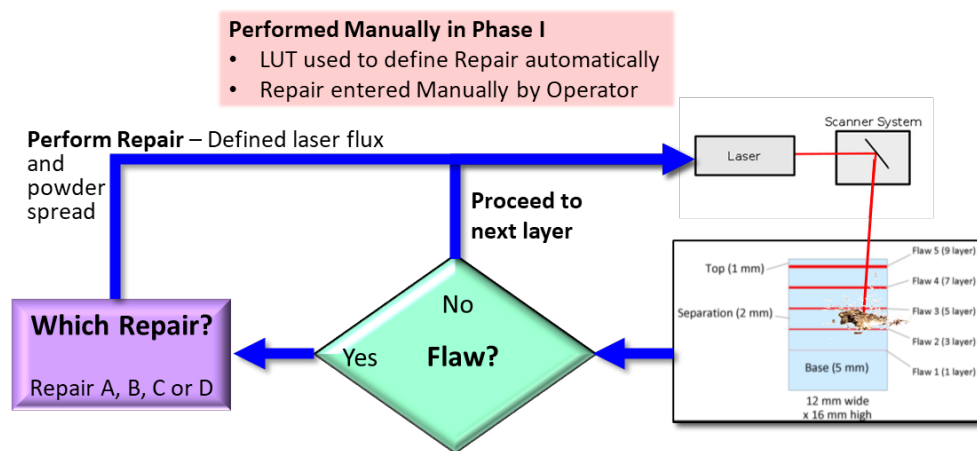


Figure 23 – Block diagram for closed loop control

This requires that three software codes interact to exchange information:

- Real time (RT) LTM software controls software generates the height map data
- Flaw map software defining which regions of the current layer to Repair
- DMC powder spread and laser control software to generate machine motions to perform the Repair

A more detailed view of the various steps and data file sharing is shown in Figure 24, where the software blocks are color coded. This required considerable effort to assure the communication protocols and timing worked properly as the three codes were developed in separate locations by different firms.

Code Elements Completed

DMC Code

IAP Code

RT LTM Code

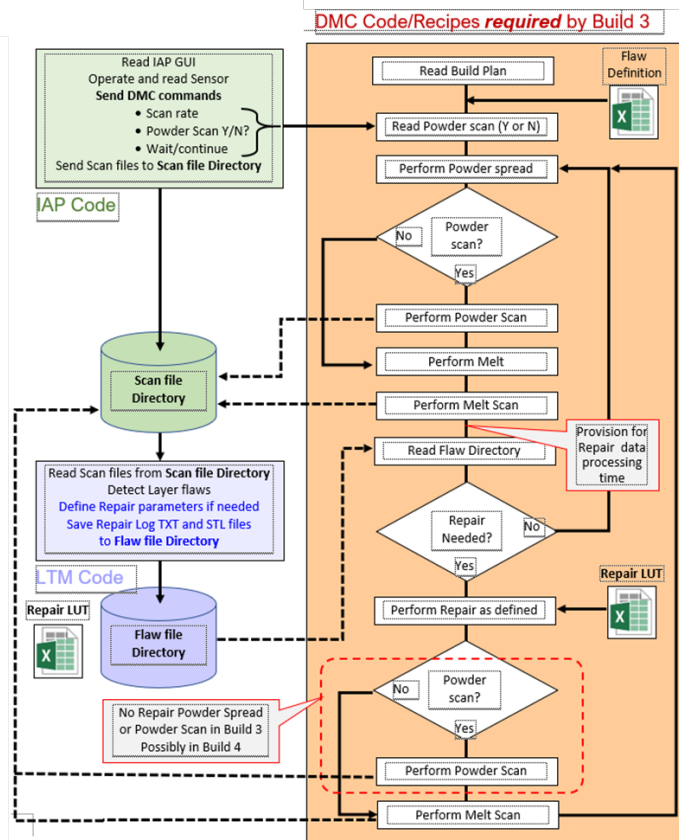


Figure 24 – Detailed flow chart for closed loop control data exchange

9.3 Automatic Repair Process Operation

Two changes were made to allow the DMC code to perform real-time Repair:

- Change the Build “recipe” (or instructions) to include logic instructions how to perform a Repair if one was needed. This itself had two parts: perform the layer re-melt with the laser and then rescanning the repaired layer to assure the repair was properly made.
- Wrote a new Repair plug-in for DMC

The plug-in was needed to perform several functions:

- Identify that a Repair is needed in one or more of the 25 coupons produced. This was defined by continuously reading a common Flaw file directory to detect when any new file was added. When the layer was inspected ((as described in [section 8](#) above) all Flaw files were saved in this directory. Therefore, this scheme allowed the inspection software to “notify” DMC that a new flaw was found for repair.
- Read the Flaw boundary from the Flaw STL file.
- Perform the flaw repair within the flaw boundary only using the established Repair process.
- Record the Repairs made to a separate Repair Log file.

10 LPBF Coupon Fabrication

10.1 Coupon material

All coupons were produced from titanium T16Al4V alloy. The PSD of the virgin powder used was **xxx**.

10.2 Coupon Layouts

Twenty-five (25) coupons, each 10 mm in diameter, were located on the 150 x 150 mm print bed as shown conceptually in Figure 25. This layout was used to determine if the lateral X,Y location on the bed affected flaw formation or flaw repair. Coupons were 139.2 mm (approximately 5.5 inches) tall, made using 3,480 layers each 40 μm thick. In this manner, most of the 150 x 150 x 150 mm build volume of the AM2 was used effectively to generate coupons and data of interest.

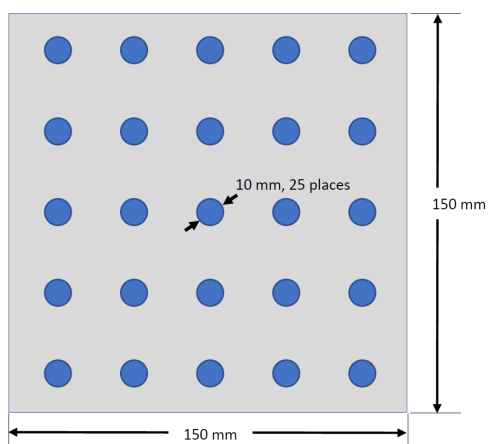


Figure 25 – Nominal layout of 25 coupons on the AM2 print bed

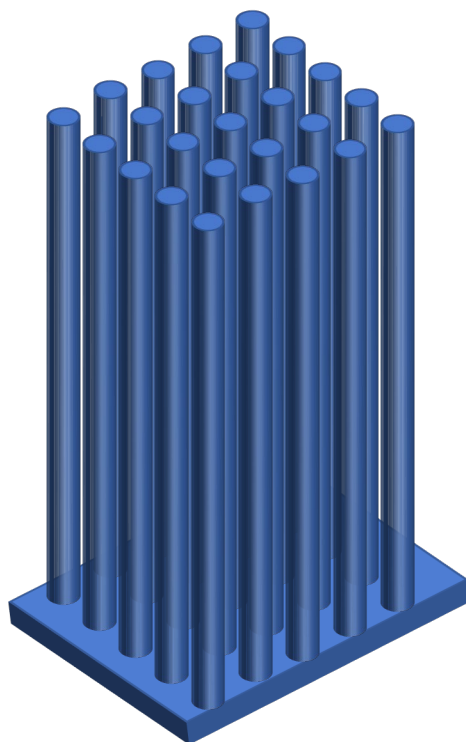


Figure 26 - 3D view of the 25-coupon layout on the AM2 print bed

A photograph of a partially completed coupon build is presented on Figure 28.

10.3 Detailed Coupon Geometry

A closeup view of a single coupon is shown in Figure 27. Several features are included in each coupon:

- **Bottom cone** – The bottom section of the coupon, where it attaches to the build plate, features a cone that transitions from the 10 mm coupon cylinder at the top to only 2 mm at the bottom, where it connects to the build plate. This geometry allows the coupon to be simply snapped off the Build plate by hand, compared with cutting the coupons off using EDM which is more costly and time-consuming.
- **Fiducial sections** – There are six fiducial portions of the coupon where the diameter tapers down to 9.5 mm as shown in Figure 29. The fiducials allow determination of the precise location of any layer within the CT scan. We know the layer numbers of the six minimum diameter layers, and these can also be located from examination of the CT cross section. We plot both parameters and use the resulting linear fit to extract a layer number for any arbitrary CT location. Typically, this fit was very precise (>0.99999) as further described in [section 13](#).
- **Flaw layers** – By default all layers of the coupons are printed with Nominal process conditions as defined in [section 6.3](#). However, each coupon also contains many seeded (i.e., intentional) flaw layers. For these layers, process parameters were used to generate flaws in the center of the circular layer as shown in Figure 27. Many different flaw types are produced encompassing the following flaw variations:
 - Flaw type (lack of fusion and keyhole porosity)
 - Flaw diameter
 - Flaw severity

Furthermore, multiple replicates of each Flaw type are included in each coupon. These replicates were randomly distributed throughout the coupon height to prevent biasing results associated any build height sensitivity. The exact details of the flaw variations changed slightly from build to build as further discussed in [section 10.4](#).

Since the effect of off-process conditions in any given layer can extend several layers above and below the defined Flaw layer, it is important to sufficiently thermally isolate each Flaw from each other. Therefore, Flaw layers we spaced every 30 build layers from each other.

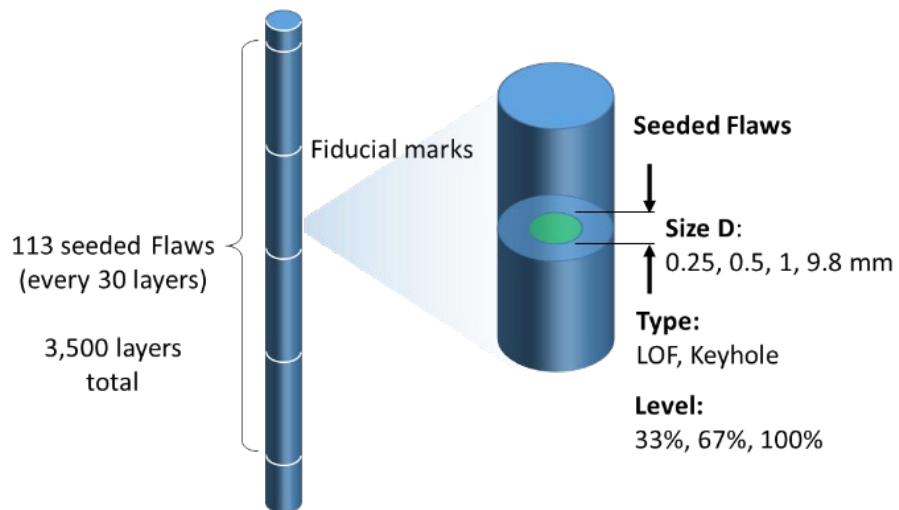


Figure 27 – Coupon Cone, Fiducial and Flaw Regions

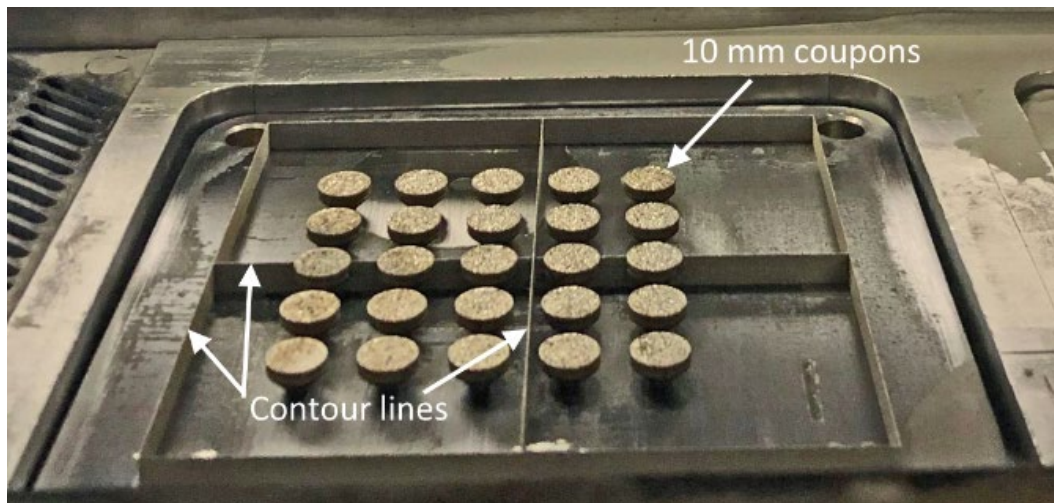


Figure 28 – Partial build of coupons in the print bed (with all powder removed) also showing contour lines used for IAP calibration

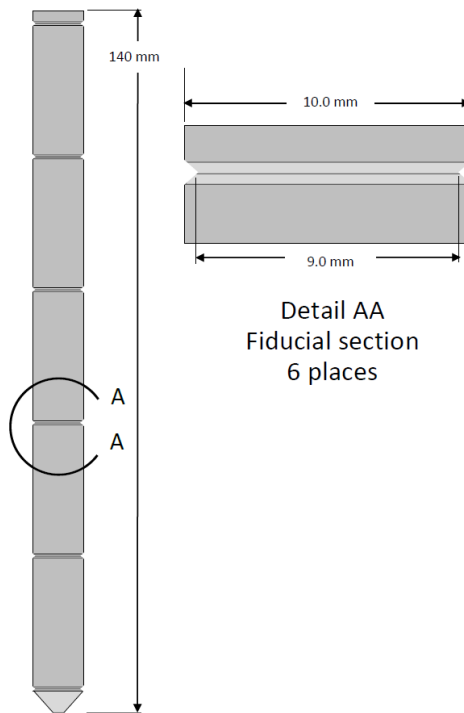


Figure 29 – Geometry of the Fiducial region (one of six in the coupon)

10.4 Build Plan Details

Details of the four Builds produced during the program are presented here.

10.5 Build 1

In Build 1 our objective was to validate our approach to creating a wide range and number of flaws in one Build. This data was intended to be used to tune the LTM algorithm parameters to obtain optimum accuracy.

Seeded flaw variations included:

- Two flaw conditions (lack of fusion and keyhole porosity)
- Three flaw severities (which we labeled as 33%, 67% and 100%, as discussed in [section 6.3](#))
- Four flaw sizes were used - 10, 1, 0.50 and 0.25 mm.

This generated a total of 24 different discrete flaw types. Every flaw type had about 5 replicates for a total of about 100 discrete flaws distributed within the 3,480 layers in each coupon. Besides the roughly 100 flaw layers, all other layers in the build used Nominal process conditions.

The Build Plan specified alternating 0° and 90° fill hatch angles vs. the 67° incremental fill hatch angles as originally specified in the Build Plan.

In Build 1 each coupon was isolated by only printing one Flaw per layer of 25 coupons. This complicated the Build plan somewhat because it was necessary to randomly distribute all flaws through the Build volume. The Build volume was classified in three planar regions (near, mid and far from the center of bed) and three vertical or height regions (bottom, mid and top heights). This created a total of nine volume regions as shown in Figure 30.

This was changed because our approach to flaw thermal isolation in Build 1 (only one flaw per layer) was unnecessarily conservative. Each 10 mm diameter coupon is thermally isolated from the adjacent coupons by 20 mm of powder (which is a very poor thermal conductor). However, since each coupon used the same build sequence, programming the Build was greatly simplified.

In Build 1 we learned that it was difficult to detect 1 mm flaws, so we broadened the range and number of flaws. Seeded flaw variations included:

- A fifth flaw size (3 mm) was added to better determine the limits of flaw detection, so the full range of flaw sizes were 10, 3, 1, 0.50 and 0.25 mm)
- Two flaw conditions (lack of fusion and keyhole porosity) – no change
- Three flaw severities (which we labeled as 33%, 67% and 100%, as discussed in [section 6.3](#)) – no change.

This generated a total of 30 different discrete flaw types. Every flaw type had about 4 replicates for a total of about 120 discrete flaws distributed within the 3,480 layers in each coupon. Besides the roughly 120 flaw layers, all other layers in the build used Nominal process conditions.

The Build 2 Plan again specified alternating 0° and 90° fill hatch angles.

10.7 Build 3

Build 3 was made to the same general Build Plan as Build 2 because Build 2 failed as described further in [section 12.2](#). However, there were also other some changes based on items learned in Build 2.

As further discussed in [section 12.2](#) we observed a large amount of ball-like porosity in Build 2. Subsequent discussion with Open Additive identified two possible sources for this.

With the 0° hatch orientation used, the laser hatch and gas flow direction are aligned in parallel. Open Additive had previously observed that in this case the gas flow can blow powder ahead of the melt pool and build up a growing “snowball” of molten material which eventually deposits on the melt surface as a large spatter particle. Open Additive calls this phenomenon “spatter porosity” and apparent avoid using fill angles close to 0° in this programming for this reason. Unfortunately, we were only made aware of this after Build 2 was completed. Accordingly, we changed the fill hatch strategy once again to a 67° incremental hatch in Build 3. Although we were not sure how this would affect LTM results we wished to obtain clear (porosity free) Nominal layers. The 67° incremental hatch strategy is also widely used in industry.

A second possible source for the excessive porosity in Build 2 identified by Open Additive may have been relatively high Nominal laser fluence level used. Recall that the Nominal process condition has been selected based on numerous density cubes and microscopy examination, as described on [section 6.3](#). Upon closer examination, however, we were informed that the coupon polishing technique that had been used may have been less ideal and, instead of highlighting small pores, may have essentially hidden them by smearing the polished surface. By that point, Open Additive had installed better polishing equipment so it was decided to repeat some of the Nominal process trials. As a result of this work the Nominal process was changed from 0.44 watt-sec/mm to 0.33 watt-sec/mm. This was achieved using a laser power of 330 watts and a laser scan speed of 1,000 mm/sec as seen in Figure 32 and Table 4.

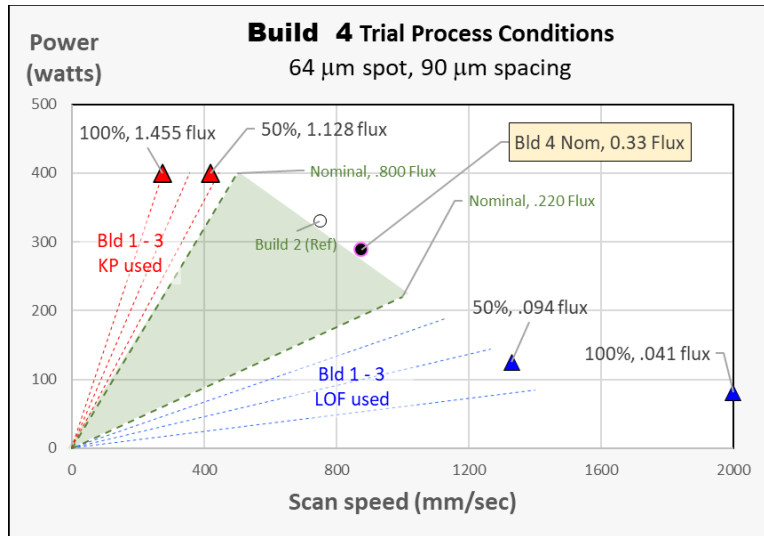


Figure 32 – Revised Nominal process parameters used in Build 3

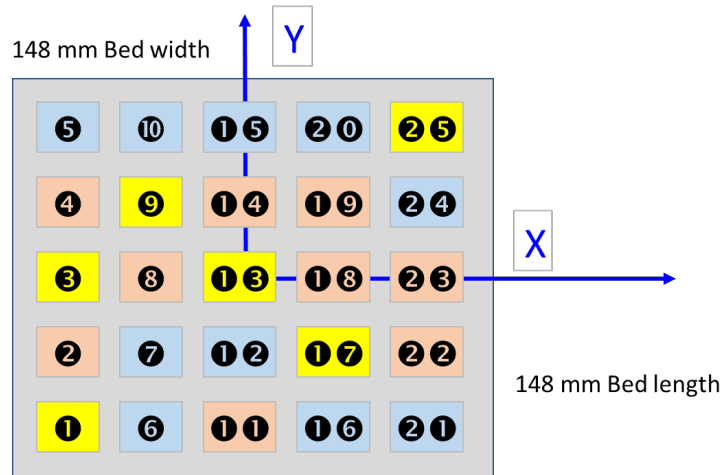
Table 4 – Repair parameters used in Build 3

Flaw Type	Severity	Power	Speed
	%, watt-sec/mm	watt	mm/sec
Nominal	0.330 flux	330	730
KP	100%, 1.455 flux	400	275
KP New	50%, 1.128 flux	400	420
LOF New	100%, .041 flux	81	2000
LOF New	50%, .094 flux	125	1329

We also observed several other trends in Build 1 and 2 which informed changes in Build 3. First, we did not see much evidence of lack of fusion and concluded that we need to reduce the laser flux of the 100% severity LOF condition. This was reduced from 0.061 watt-sec/mm in Build 1 and 2 to 0.041 in Build 3.

In addition, we noted in Build 1 that porosity was not highly sensitive to the degree of flaw severity, so instead of using three levels (33%, 67% and 100%) we reduced to two severity levels – 50% and 100%. This helped to offset the size of the DOE created when we increased the flaw sizes from four to five.

The objective of Build 3 was to identify the optimum Repair process used in closed loop control. The Build Plan was identical to the Build 2 plan, except that six (6) of the coupons were not repaired after a Flaw layer was produced and nineteen (19) of the 25 coupons were repaired with unique Repair parameter set. This shown in Figure 33, where the yellow coupons are Not Repaired and the blue and orange coupons used experimental Repair conditions after each flaw was produced. The ten (10) blue coupons used Repair conditions intended to Repair lack of fusion flaws while the nine (9) orange coupons used Repair conditions intended to Repair keyhole lack flaws. As seen, the Nominal, LOF and KP Repair coupons were randomly distributed across the 5 row and 5 columns of the coupon grid to remove any location bias that be3d location might play in these results.



Coupons over largest practical area of the Bed

Figure 33 – Nominal (yellow), LOF repair (blue) and KP repair (orange) coupon locations on the Build 3 print bed

Specific Repair conditions used are noted in Table 5. The Skip Hatch count shown in Table 5 is illustrated in Figure 34, where the higher the skip hatch count, the higher the applied repair energy density achieved with overlapping laser passes on one area.

Table 5 – Repair parameters used in Build 3

	Repair Process By Coupon Number							
Coupon no.	Repair	Comments	Condition	Power	Spot dia	Hatch	Scan speed	Skip Hatch count
				watt	(μm)	(μm)	mm/sec	
1	No Repair							
2	1		KP	400	64	90	518	1
3	No Repair							
4	2		KP	400	64	90	518	2
5	3		KP	400	64	90	672	0
6	4		LOF	330	64	90	750	0
7	5		LOF	330	64	90	653	0
8	6		LOF	330	64	90	575	0
9	No Repair							
10	7		LOF	330	64	90	882	0
11	8		KP	400	64	90	672	1
12	9		LOF	330	64	90	518	1
13	No Repair							
14	10		KP	400	64	90	672	2
15	11		LOF	330	64	90	518	1
16	12		KP	225	64	90	437	0
17	No Repair							
18	13		KP	225	64	90	437	1
19	14		KP	225	64	90	378	0
20	15		LOF	330	64	90	518	1
21	16		LOF	330	64	90	466	1
22	17		KP	225	64	90	378	1
23	18		KP	225	64	90	378	2
24	19		LOF	330	64	90	427	1
25	No Repair							

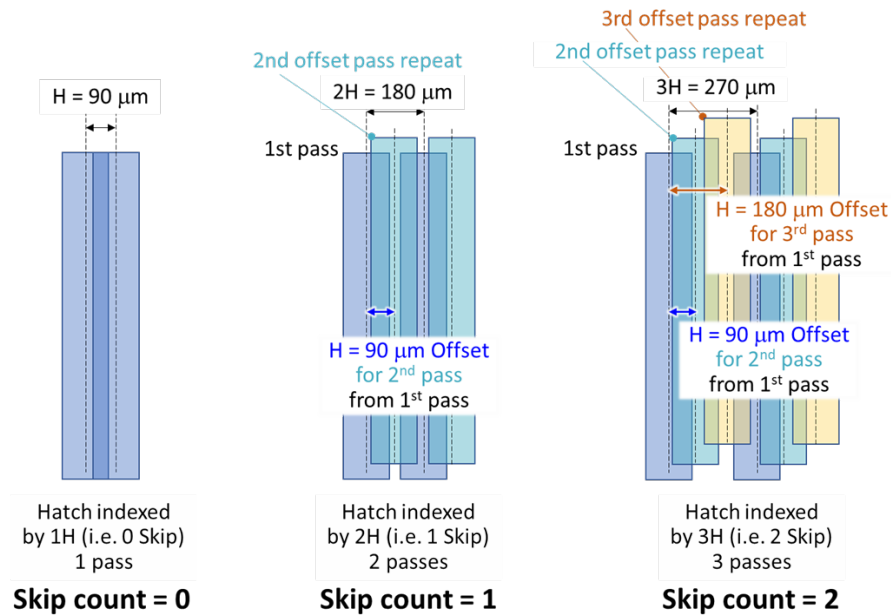


Figure 34 – Description of Skip Count nomenclature for Repair processes used

10.8 Build 4

Based on lessons learned in Build 3 as described in [section 12.3](#), the Flaw types were changed as follows:

- Two flaw conditions (lack of fusion and keyhole porosity)
- Two flaw severities (which we labeled as 50% and 100%)
- Five flaw sizes (1, 2, 3, 5 and 7 mm)

The reduction in flaw severity levels was made because the data did not show a strong severity level effect. Flaw sizes were changed because earlier data indicated that 1 mm was close to the minimum detectable flaw size.

11 CT Inspection

11.1 CT Considerations

CT is currently the highest quality nondestructive method available to assess internal melt quality and therefore was used to establish defect or flaw ground truth. Destructive methods like microscopy of polished sections can provide higher resolution but are much more time-consuming and costly.

A nominal voxel size of 20 μm was selected, which is half the layer thickness of 40 μm (i.e., two voxel per layer thickness). This was a compromise between minimum flaw detection size (smaller voxels are better) and CT scanning cost (larger voxels means less costly CT scan).

11.2 CT Scanning

To minimize CT costs, coupons were scanned four at a time as shown in Figure 35. Using this approach, the maximum X-ray path length was 20 mm (fully penetrating two 10 mm diameter coupons) which provided acceptable X-ray absorption images in titanium.

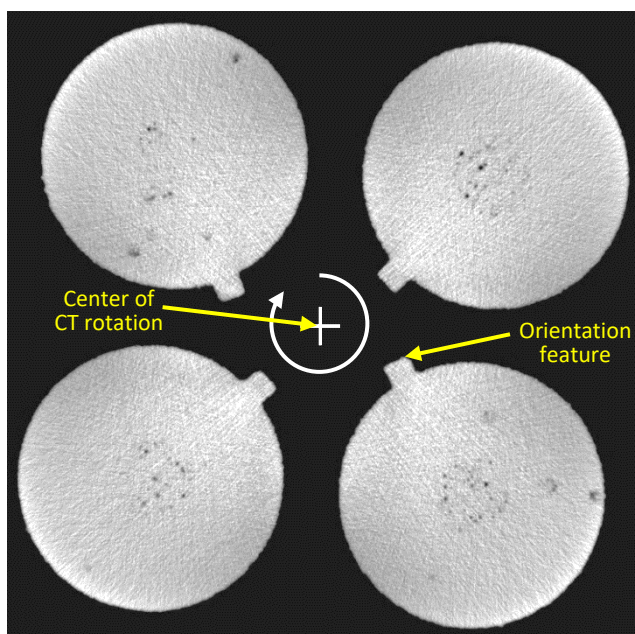


Figure 35 – Four coupons were scanned simultaneously for CT scans

While this approach creates some X-ray scatter artifacts (the beam that hits one coupon generates some scatter which is detected as noise in the other coupons), we removed significant noise in subsequent CT data processing as shown below.

To obtain the desired voxel size requires that the X-ray source, sample and detector are placed in specific geometric relationship that provides the desired magnification factor. This setup has a limited field of view as shown in Figure 36. With this magnification to capture the full 139 mm length of the sample required that five overlapping scans be taken as shown in Figure 37.

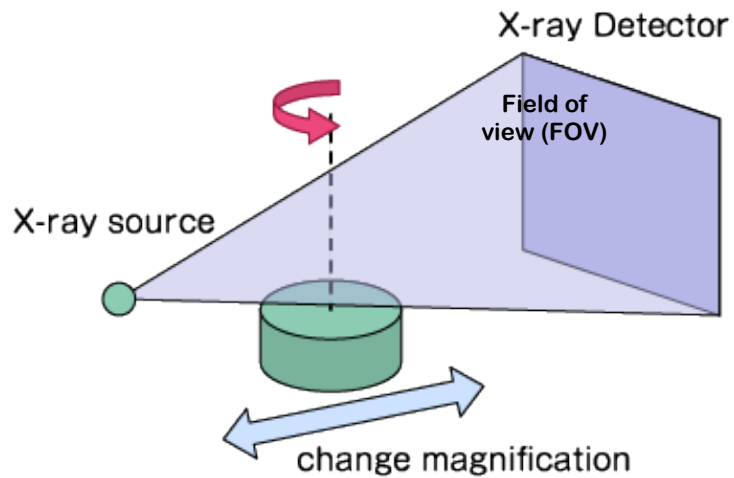


Figure 36 – The selected voxel size defines the X-ray field of view

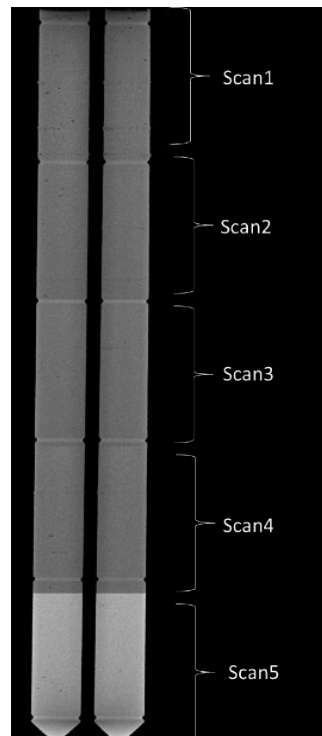


Figure 37 – Each group of four coupons were scanned in five overlapping vertical regions

11.3 CT Data Processing

The X-ray data collected during CT scans was processed to extract porosity as a function of layer number as described here.

- The data for each of the four coupons was segregated.
- The X-ray intensity (gray scale density) data for each of the five vertical segment of one coupon was normalized to account for scan-to-scan variability.
- Ring artifacts in the data were filtered out.
- Data from the five segments were aligned and stitched to form one data set for the coupon.
- The data was aligned with to its original print orientation using the physical orientation feature on the coupon (see Figure 35).
- The data was masked or cropped slightly to excise the orientation feature and external surface roughness (which was not of interest here).
- The gray scale images were converted to binary black and white images which permitted numerical computation of the porosity on a layer-by-layer basis.

This sequence of operations was performed as part of “CT post processing” and is summarized in Figure 38 below. Once performed, the stack of binary images through the coupon height illustrates regions or layers with porosity flaws, as seen in Figure 39. Note that this figure is for illustration only, and the images came from Phase I work, where square coupons were used.

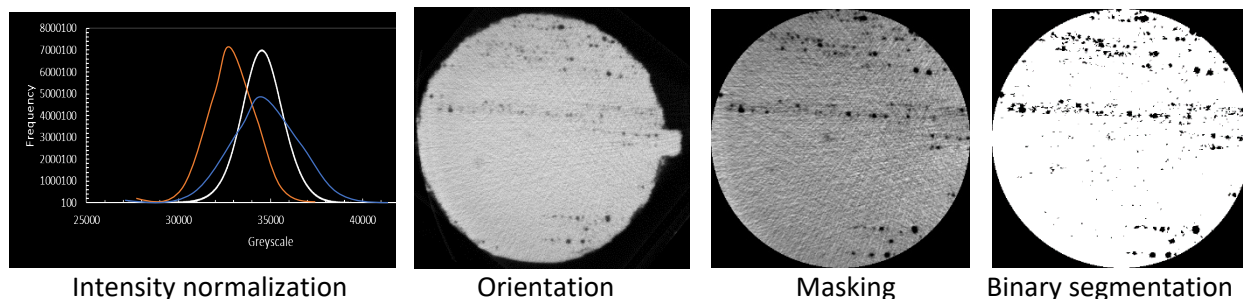


Figure 38 – CT post processing steps

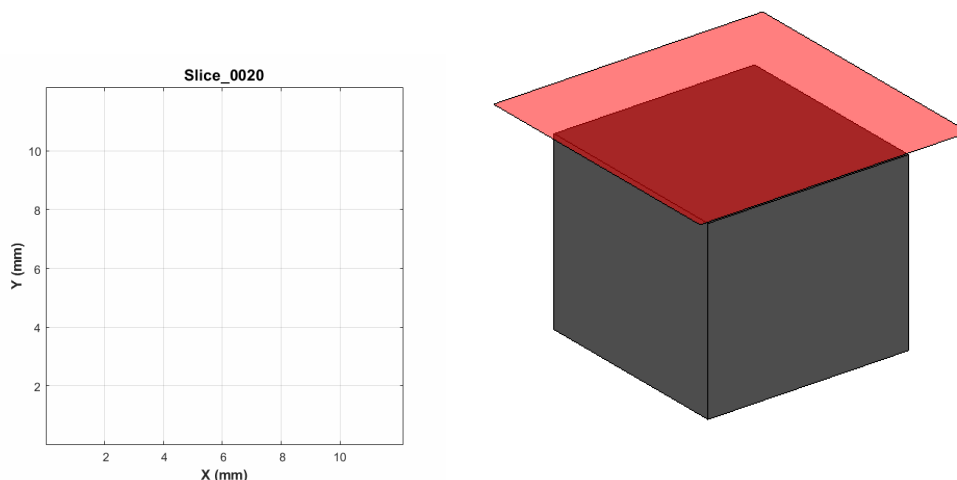


Figure 39 – Conceptual “fly-through” of a CT scan illustrating porosity variation along the coupon Z dimension

MATLAB software was written to read the stack of binary CT images and extract the percent porosity value for each “slice” of CT data, where a slice is a one-voxel thick portion of the 3D CT model. The porosity was calculated as:

$$P = \frac{A_p}{A_t} \quad \text{where}$$

P = Porosity (%)

A_p = number of pore (white) pixels in the slice

A_t = total number of pixels (white + black) in the coupon

Furthermore, the software enabled not only the calculation of porosity for the total area of the coupon, but also as a percentage of the total *flaw diameter* cross-section. This is illustrated in Figure 40 which shows a nominal 2.5 mm diameter flaw produced in a 10 mm diameter coupon. As expected, the number of flawed pixels (i.e., pores) is highest in the central seeded flaw region as shown in the notional bar chart. Therefore, to calculate porosity level based on the full 10 mm diameter section would improperly reduce the apparent porosity level. Rather, a more accurate porosity assessment is obtained calculating the percentage of pore pixels within the 2.5 mm diameter flaw area.

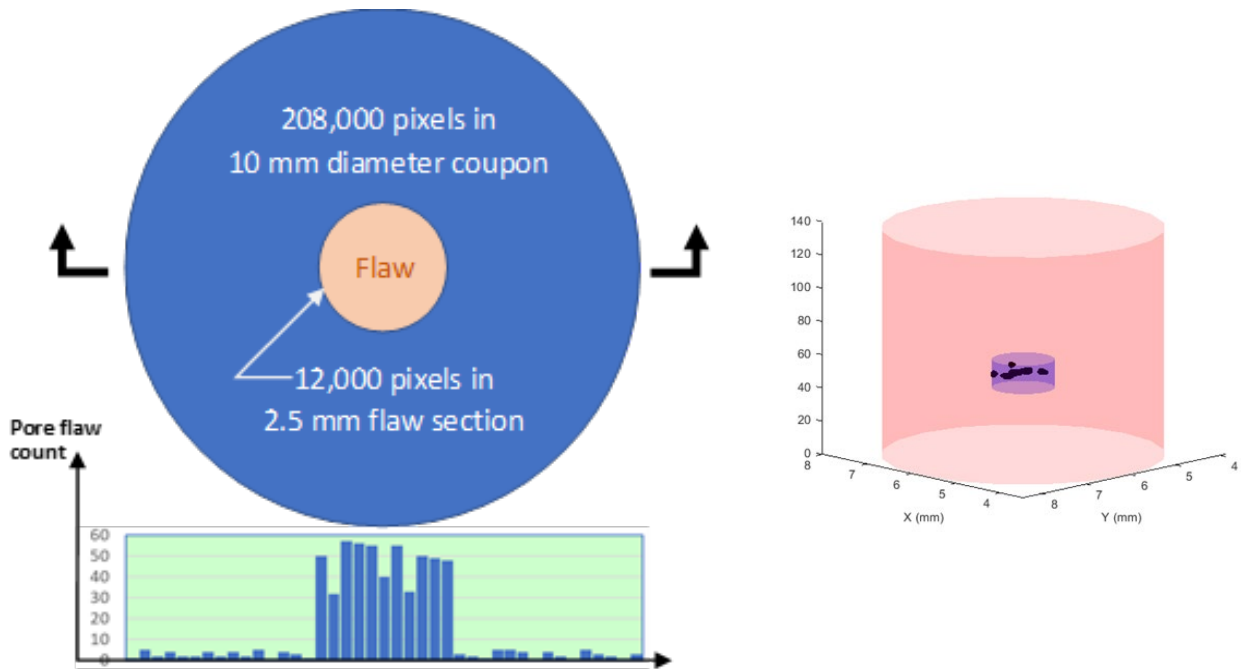


Figure 40 – Porosity calculation from binary pore image

Using this approach, the full stack of CT slices (about 7,000 voxel slices for one coupon) was imported and the porosity (as a percentage of the flaw area) was calculated and plotted throughout the thickness, as shown in Figure 41. In the plot the Z height within the coupon is plotted as the X axis of the plot. There was some noise in the plots, so the data was slightly smoothed using a first order Savitzky-Golay filter with a frame length of 9.

The red and blue bars in Figure 41 represent the layer locations where seeded flaws were created. **Red** represents a keyhole porosity (KP) flaw and **blue** represents a lack of fusion (LOF) flaw. This shown in more

detail in Figure 42, which presents the data for a small portion of the full coupon height. Here the flaw size (diameter) and flaw severity are noted for each of the 11 flaws within the plot.

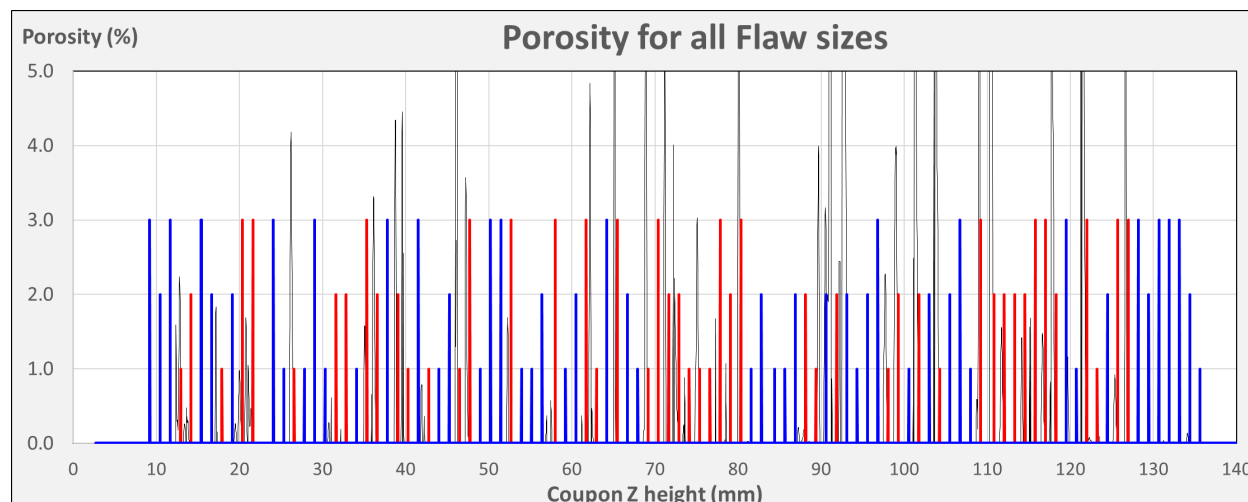


Figure 41 – Porosity values (black line) exacted from CT images

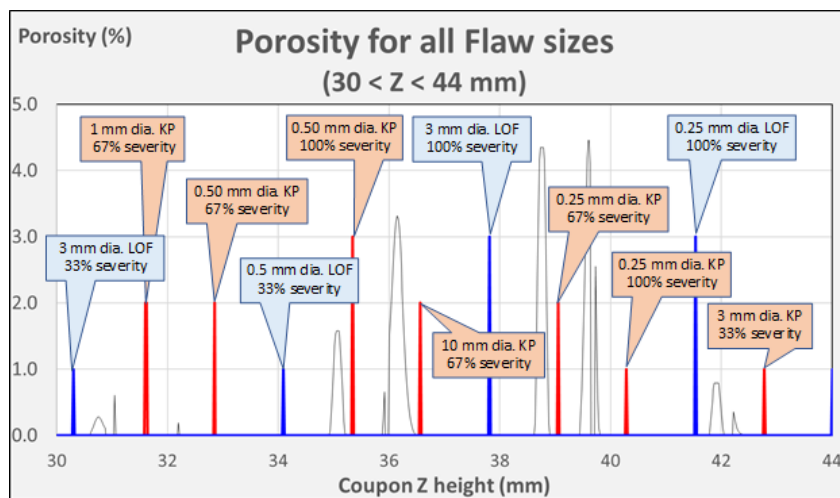


Figure 42 – More granular view of porosity plot

As previously discussed, the plotted porosity value is relative to the corresponding flaw diameter region. For example, the peak porosity associated with the 10 mm diameter flaw at $Z = 36.56$ mm is about 3.2%, peaking below the flaw layer. At this location 3.2% of the 10 mm diameter area were pores. By contrast, the peak porosity associated with the 0.50 mm diameter flaw at $Z = 35.32$ mm is about 1.6%, also peaking below the flaw layer. In that case 1.5% of the 0.50 mm diameter area were pores.

Porosity associated with any flaw occurs both below or above the layer where the flaw was generated but that this porosity generally does not exceed more than 10 layers above or below. By plan, seeded flaws were located every 30 layers (1.2 mm) to assure adequate isolation between flaws so they could be treated and analyzed separately. Also note that many of the Nominal layers between flaws showed absolutely no porosity, as intended.

12 Results

12.1 Single Cube Results

Initial trials were performed of the Build and sensing system using a single square coupon 10 x 10 mm. The color-coded profile map for the melt layer is shown in Figure 43. The plotting code automatically scales ("autoscales") the Z or height values to the minimum (blue) and maximum (red) observed values.

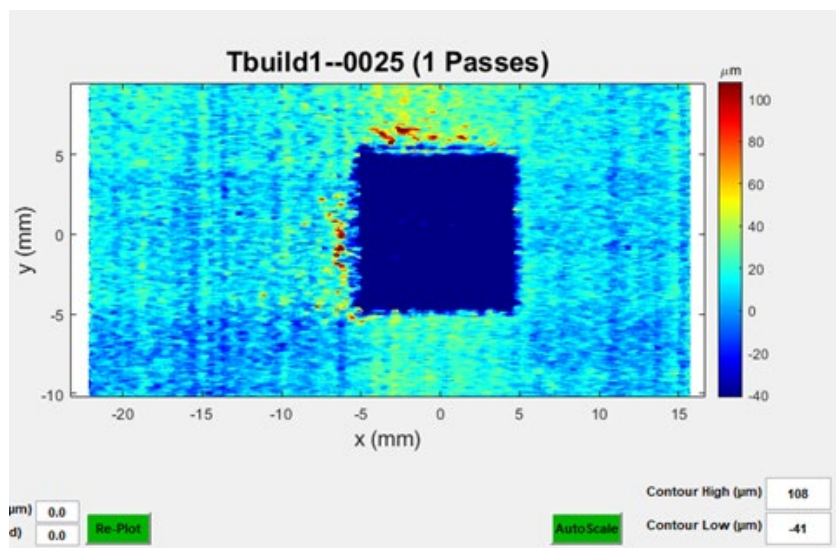


Figure 43 – More granular view of porosity plot

These upper and lower autoscale limits were plotted for the first 25 layers in the Build for both the melt layer height and the powder bed layer height as seen in Figure 44. From this data the difference between the powder height (before melt) and the melt surface (after melt) were determined

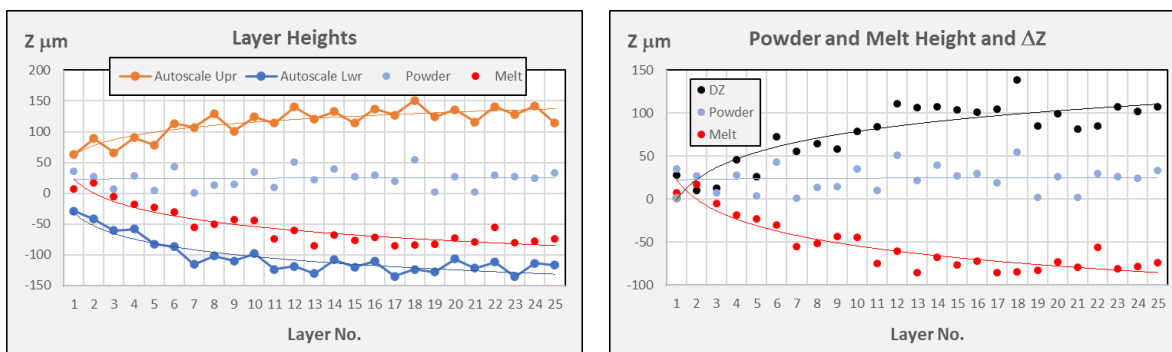


Figure 44 – Powder and melt thickness during initial layer fabrication

From this data it can be seen that:

- The powder layer height is stable immediately, as this is directly controlled by the position of the powder Recoater blade and the bed platform height .
- Melt layer height and thickness values stabilize over the first 25 layers or so. This period occurs when the melt addition process transitions from zero (melt Z = 0) to the stable melt layer thickness for powder provided.
- The stabilized melt layer thickness is 40 μm , which is controlled by the amount of programmed Z motion decrement of the bed platform.

- The difference between the powder bed height and the melt height (labelled DZ) stabilizes at about 100 μm . In other words, the effective powder density is 100/40 or 2.5 times less than the density of the 100% solid metal melt.

12.2 Build 1

12.2.1 Coupon fabrication results

Build 1 was produced as described in [section 10.5](#), but encountered several problems.

Instead of printing the full 139 mm height, the build failed at 107 mm as shown in Figure 45. This occurred because of an error in the way the Build had been programmed to read from the Build Plan spreadsheet in DMC as described in [section 10.5](#).

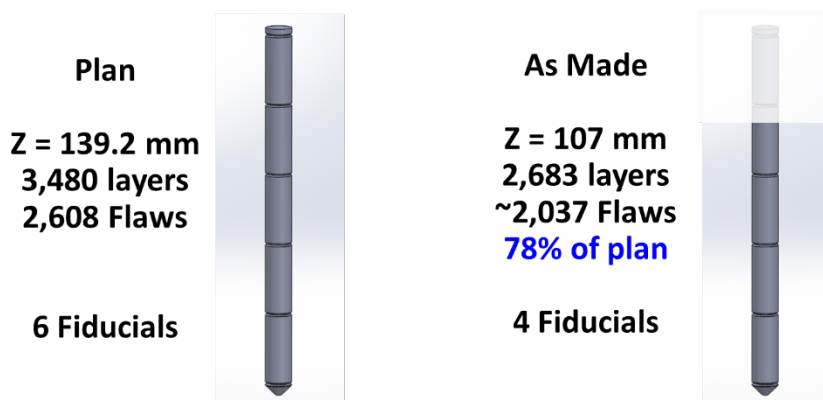


Figure 45 – More granular view of porosity plot

Instead of using Nominal parameters with a laser flux of 0.440 watt-sec/mm as defined in Build Plan, a greatly reduced laser flux (0.167 watt-sec/mm) was accidentally used as shown in Figure 46. This occurred due to a miscommunication – this lower flux had previously been determined as the *lower bound* of Nominal condition as described in [section 6.3](#). As a result of this error, there was little difference between porosity seen in Nominal regions and lack of fusion flaws.

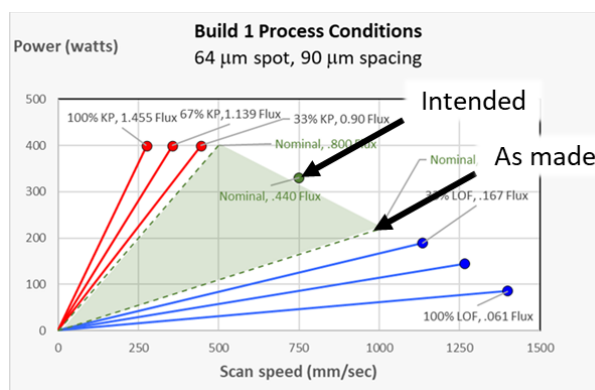


Figure 46 – Nominal laser flux used in Build 1

A third problem was that the fill hatch angle specification in the Build Plan was not followed. The Build Plan specified an alternating 0° and 90° hatch be used. This is also sometimes referred to a 90° incremental hatch scheme, consisting of cycles of 0° , 90° , 180° and 270° fill hatch patterns (note that a 180° hatch is the same as a 0° hatch and a 270° hatch is the same as a 90° hatch).

The 0/90 hatch scheme was defined because it had been used in Phase I and we had observed that the LTM algorithm results were sensitive to the hatch angle, as seen in Figure 47. We did not wish to introduce the complication of hatch angle variation in this first Build.

Unfortunately, however, the 0/90 hatch scheme was not used and a 67° incremental hatch angle was accidentally used instead as depicted in Figure 48. This is a typical or standard approach in AM, where the hatch angle increases by 67° for each incremental layer. This scheme is used because any given hatch angle only repeats itself after 360 layers and this is believed to generate more uniform results. In fact, the 67° incremental hatch angle is the default setting in the DMC slicing software and that is how it was inadvertently used for Build 1.

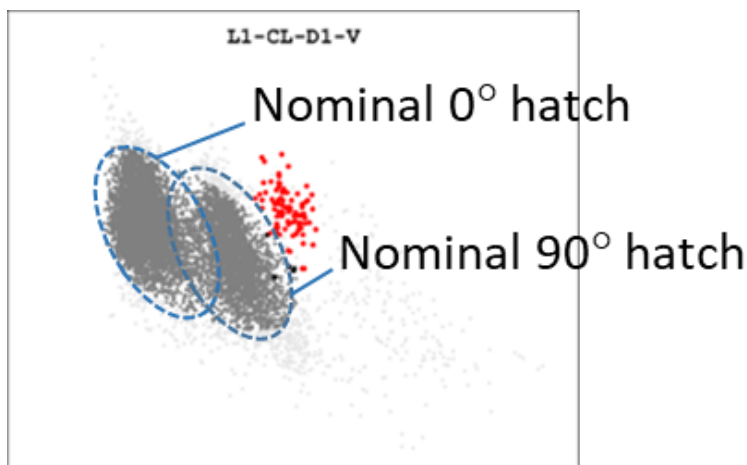


Figure 47 – LTM output was sensitive to hatch angle as seen in Phase I

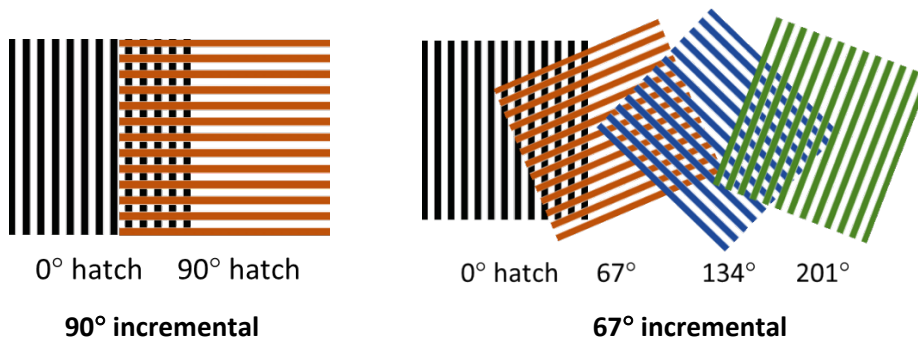


Figure 48 – 90° vs. 67° incremental hatch schemes

12.2.2 Profilometry results

The raw height map of a single melt layer is shown in Figure 49, where the 25 melted circular sections are clearly visible from the surrounding powder. This occurs because the spaces between powder particles before melt no longer exist after melting. Therefore, the melt region has a higher density and the top surface of the melt is reduced in height. Lower Z height is shown in the color height plot as towards the

blue end of the height scale while higher Z values (i.e., the powder bed) appears more towards the red end of the color scale.

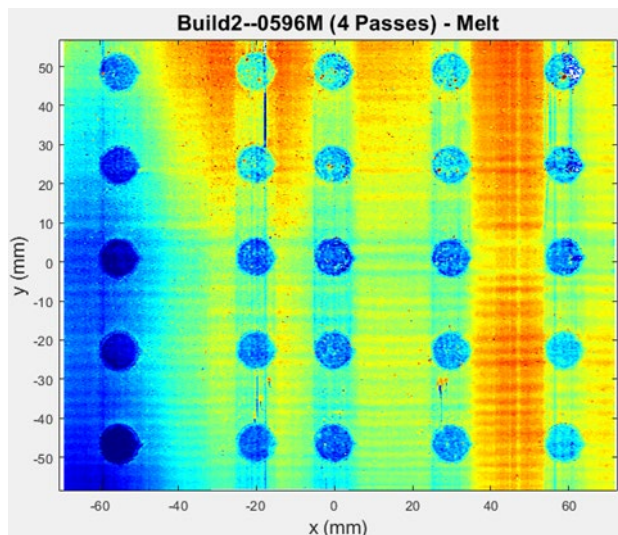
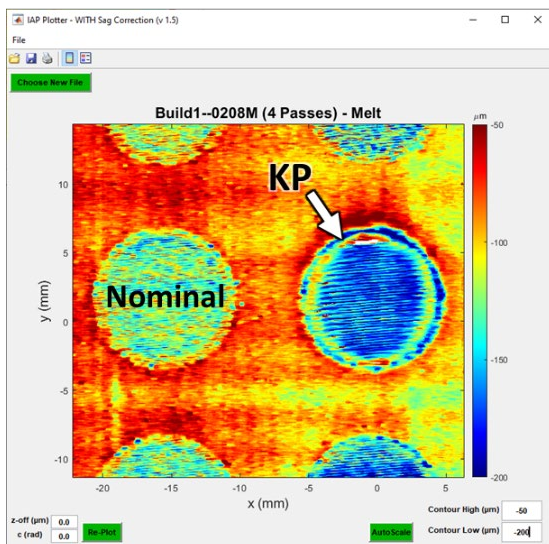


Figure 49 – 90° vs. 67° incremental hatch schemes

Keyhole porosity (KP) was easily distinguished from Nominal melt as shown in Figure 50 even in the raw profile data, exhibiting a smoother surface (lower roughness). Similarly, lack of fusion (LOF) flaws showed a higher roughness than Nominal melt. The degree of flaw severity, as previously described, had a relatively small effect on the profile as shown in Figure 51 for a 10 mm keyhole porosity type flaw.

Keyhole Porosity



Lack of Fusion

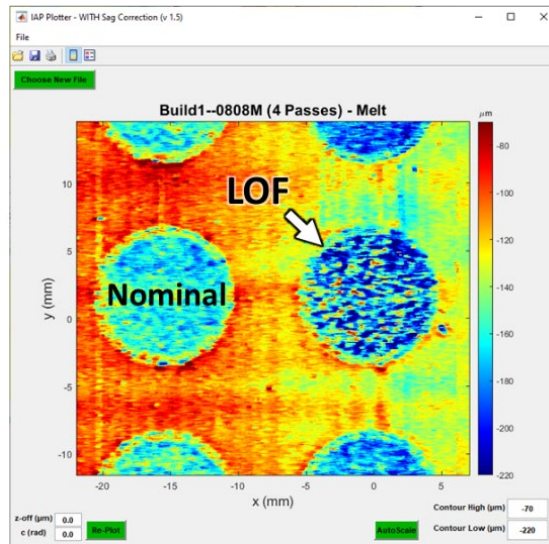


Figure 50 – KP and LOF flaws exhibit clearly differentiated surface topologies

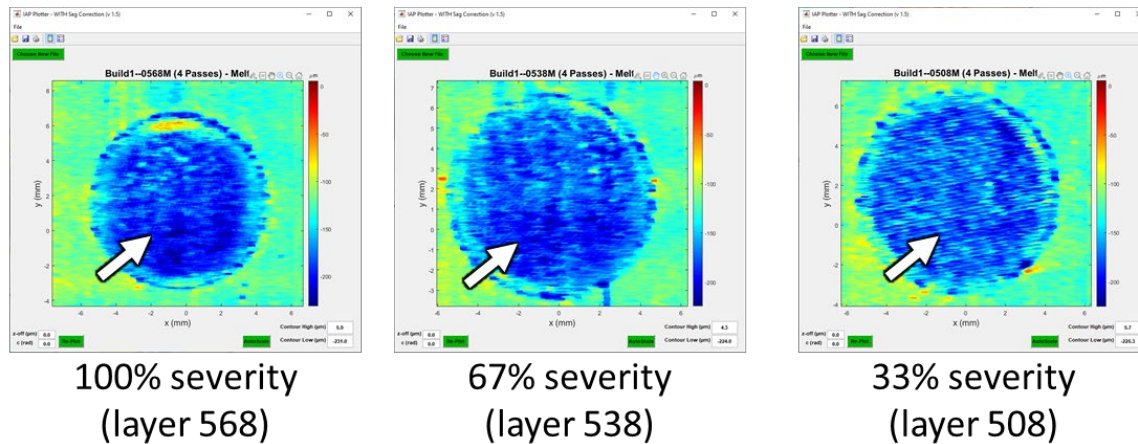


Figure 51 – Flaw severity has a relatively small effect on the surface profile or roughness

The flaws examined in Build 1 were full area (10 mm diameter) as well as 1.00, 0.50 and 0.25 mm diameter. As seen in Figure 50 the surface roughness difference (from Nominal) for a 10 mm flaw is very apparent, However, this difference is much less apparent for smaller flaws as seen in Figure 52. The difference (to the human eye) is difficult and subjective to discern for a 1 mm flaw and not distinguishable for 0.50 and 0.25 mm size flaws.

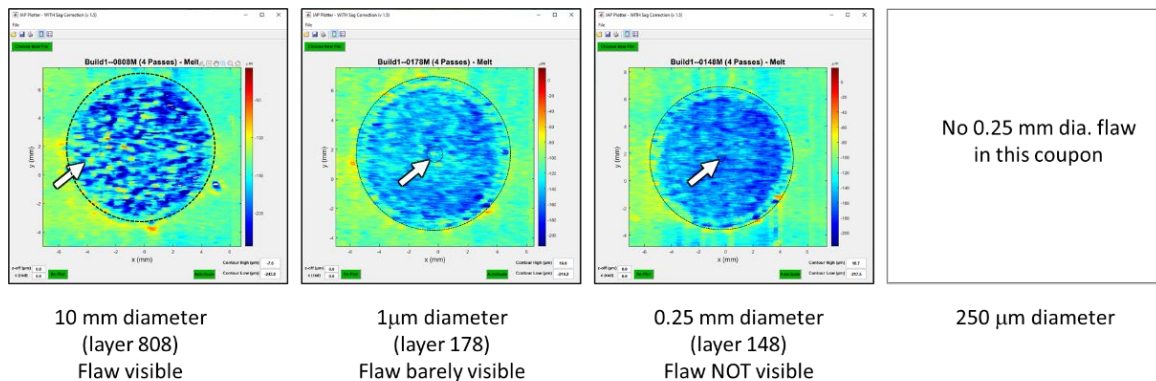


Figure 52 – 1 mm LOF flaws were barely visible in the profile data

12.2.3 LTM algorithm results

AS previously discussed in [section 8.2](#), the profile height map is subdivided into many smaller windows and the statistical values k and λ are determined for each window. These k and λ values determine whether that window is assessed as a flaw or not, based on the Nominal/Flaw boundary as described.

However, windows are intentionally overlapped to generate a more granular determination of flaw location. Any one X,Y location on the bed can be captured in multiple windows, therefore we define a flaw detection index for each location that describes how many of the overlapping windows at that location define it as flaw. The greater the number of windows calling the location a flaw, the higher the detection index. The detection index for a Nominal layer in Build 1 is shown on the leftmost image of Figure 53.

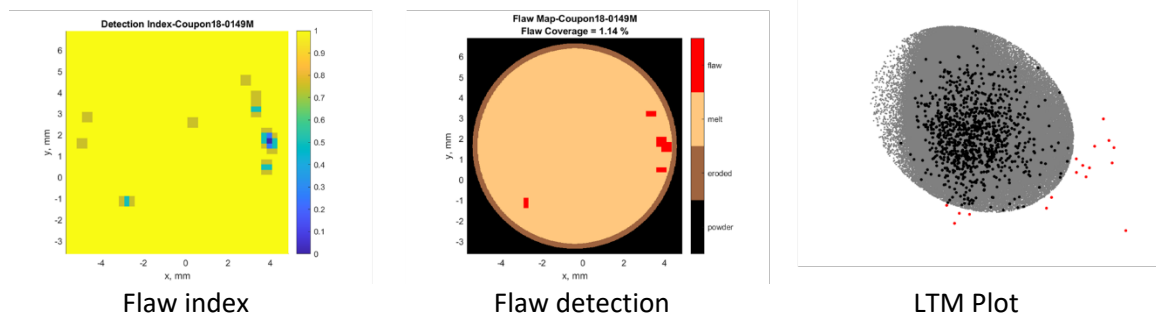


Figure 53 – Typical flaw detection results for Nominal layer

We then establish a threshold for the detection index to generate a binary Flaw map. Every index location above the threshold is deemed a flaw, while all other locations are deemed Nominal or no flaw. This is seen in the middle image in Figure 53, where flawed locations are shown in red and Nominal regions are shown in tan. The rightmost image in Figure 53 is the Mohalanobis plot for the entire layer, where every red dot in the plot corresponds with a flaw location in the flaw index plot.

As seen, Nominal layers generally exhibited few detected flaws. Large flaws, however, showed a large percentage of flaws as seen in Figure 54 for a lack of fusion (LOF) flaw and Figure 55 for a keyhole porosity flaw.

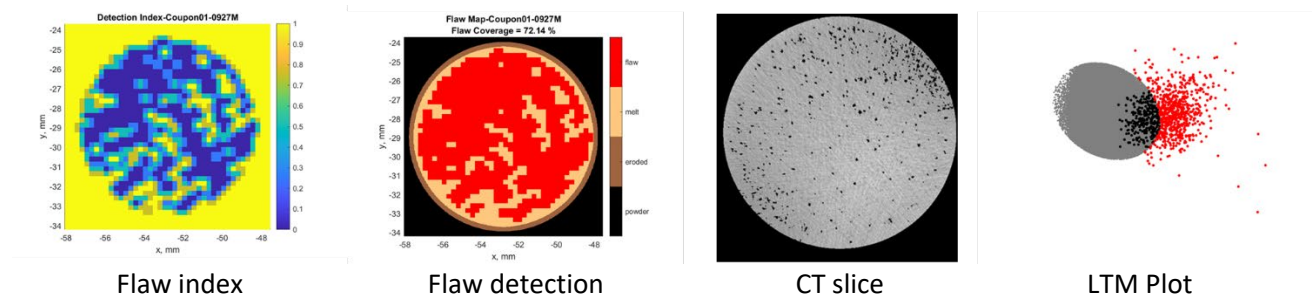


Figure 54 – Typical flaw detection results for 10 mm Lack of Fusion flaw

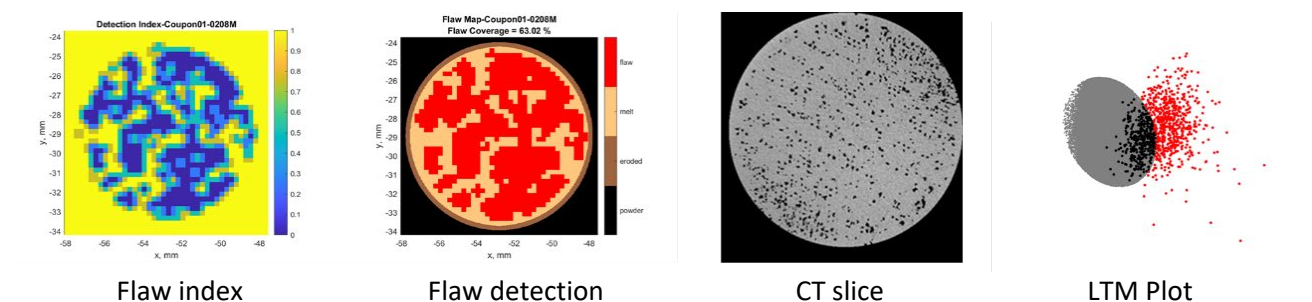


Figure 55 – Typical flaw detection results for 10 mm Keyhole flaw

While flaw detection results for 3 mm flaws were also visible, they were not as clear as the 10 mm flaw results, and 1 mm flaws were not clearly visible. Given the problems with this Build it was decided to focus LTM algorithm refinement on a subsequent Build.

12.2.4 CT Results

CT scans from Build 1 were processed and porosity values were extracted from all coupons. A typical porosity plot from one coupon showing only full size (10 mm diameter) flaws is shown in Figure 56. Seeded flaw locations are shown in **red** for keyhole porosity and **blue** for lack of fusion. Porosity results are only plotted for 20 voxels above and 20 voxels below the seeded flaw location, corresponding to +/- 10 layers. Although not plotted here, it should be recognized that flaws of other sizes exist between the plotted flaws and are not shown in this plot for clarity.

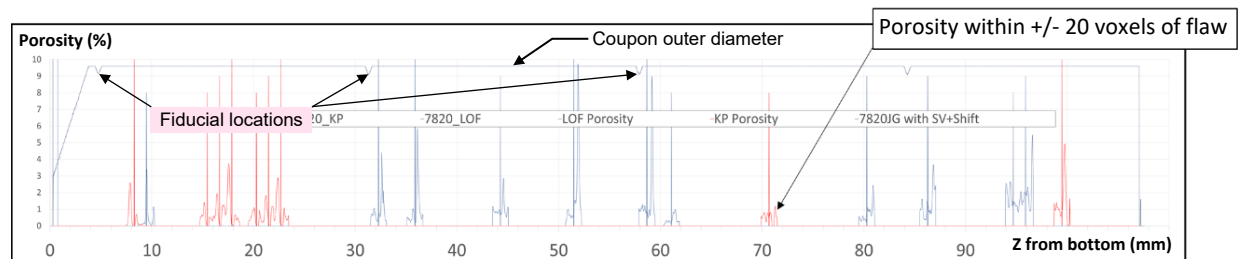


Figure 56 – Porosity extracted from regions surrounding 10 mm diameter flaws

Typical porosity curves surrounding flaw layers are shown on more detail in Figures 57. Generally, the maximum or peak porosity for a keyhole flaw occurred below the seeded flaw layer as noted by the black peak arrows. This is consistent with how keyhole porosity is created, where gas pores below the melt surface are trapped as the melt cools. For LOF flaws, peak porosity tended to occur above the flaw layer as shown in Figure 57. This may occur because the LOF conditions create a very rough surface and subsequent melt layers (i.e., layers above the flaw) do not fully intermix with lower layers due to this roughness.

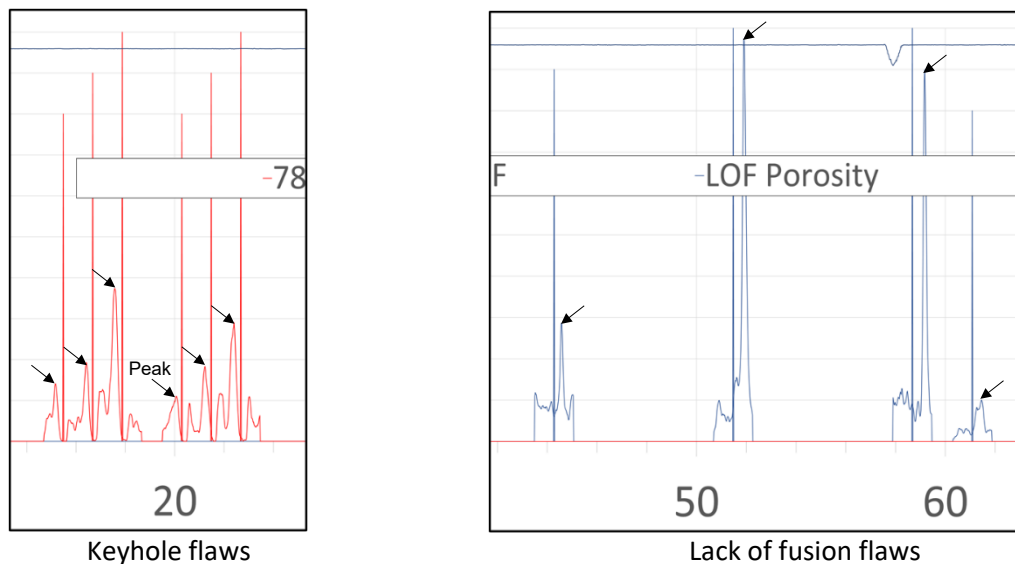


Figure 57 – Detail of porosity surrounding seeded Flaw layers

It was also learned in Build 1 that more careful attention was required to effectively process the CT data than our CT provider (Jesse Garant) was able to provide using their standard CT processing software (Volume Graphics). Another firm (Simplevoxel) who specializes in CT data processing was retained as a subcontractor to Jesse Garant and developed the CT processing procedures described in [section 11.3](#).

12.3 Build 2

In Build 2 we implemented several lessons learned from Build 1 to improve results:

- The DMC programming error that caused premature Build failure was fixed.
- The originally defined Nominal laser flux (0.440 watt-sec/mm) was used
- The fill hatch angle was changed to a 90° incremental scheme.
- X-ray data was processed into a CT reconstruction model by Simplevoxel using the procedures defined in [section 11.3](#).

This is further described below. We saw very unusual CT results and most of our effort was expended trying to understand what we were seeing and why it had occurred as described in more detail below.

12.3.1 Coupon fabrication results

The Build fully completed without interruption as shown in Figure 58. One powder bin refill was required approximately halfway through the Build.

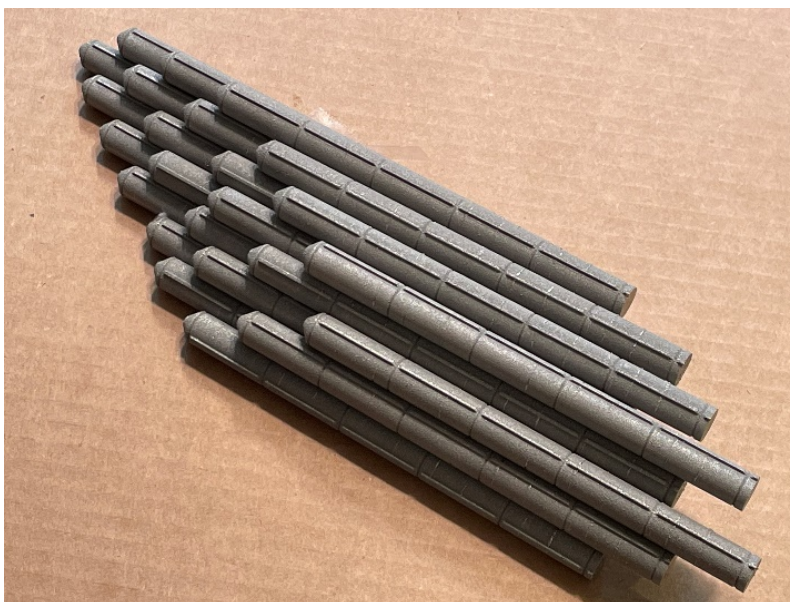


Figure 58 – Build 2 Coupons

12.3.2 Profilometry results

We immediately noted a large number and size of flaws in the CT scans as further described [section 12.3.4](#) below. We did not analyze profilometry data here because we knew from the CT scan that we had not properly created Nominal quality material.

12.3.3 LTM Algorithm results

We did not analyze profilometry data here because we knew from the CT scan that we had not properly created Nominal quality material or Nominal profilometry scans from which useful LTM data could be derived.

12.3.4 CT Results

We immediately noted a large number and size of unusual flaws which can be seen in the CT porosity models of almost all coupons. Typical 3D views of a section of one coupon are shown in Figure 59 and typical CT slides are shown in Figure 60.

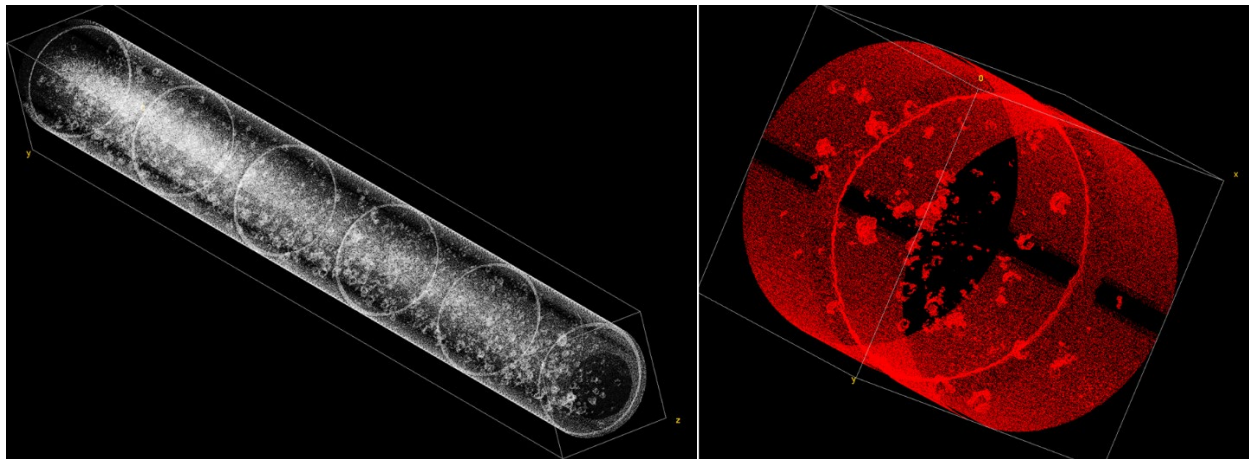


Figure 59 – 3D CT scans of a section of a Build 2 coupon showing numerous ball-like porosity regions

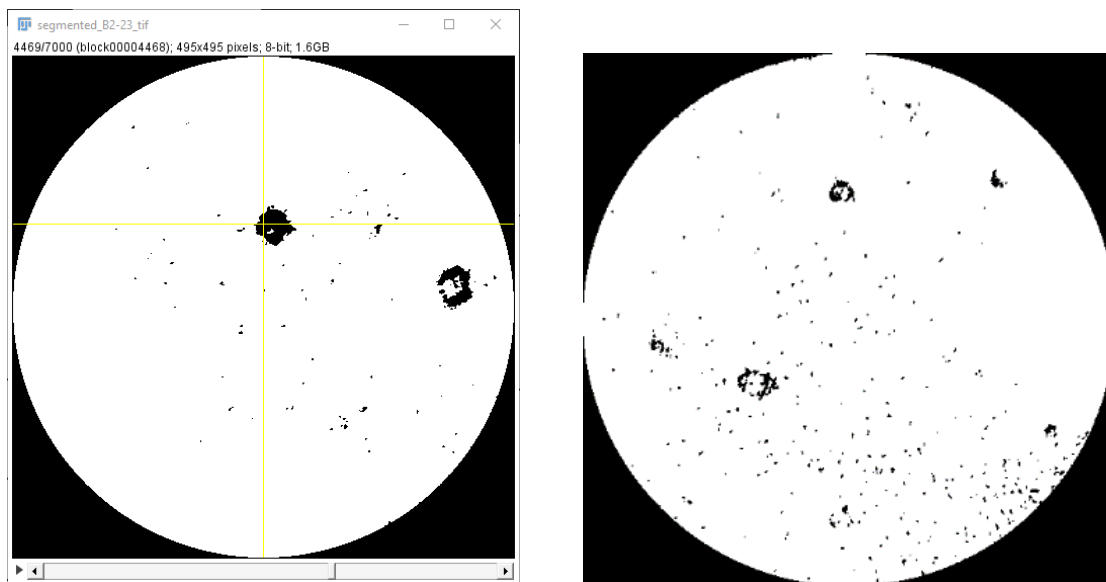


Figure 60 – 2D CT slices sections showing cuts through ball-like porosity regions

These ball-like regions of porosity were roughly 0.8 to 0.9 mm in diameter and sometimes consisted of a solid metal core (shown in white) surrounded by poorly consolidated powder (shown in back).

Upon discussion with Open Additive, two explanations for this behavior were proposed.

1. First, the melt laser optics in the AM2 had been problematic for some time and a repair to the optic train had recently been performed by replacing a collimator with a new part. Unbeknownst to Open Additive, this collimator was defective and had been contaminated with debris that cause the system to lose focus, heat up, expand and lose further focus.
2. The porosity characteristic observed had been observed by Open Additive previously in a phenomenon they labeled “spatter porosity” as previously discussed in [section 10.6](#). The images in Figure 61 were provided by Open Additive from other parts they had produced where similar spatter porosity was formed and observed.

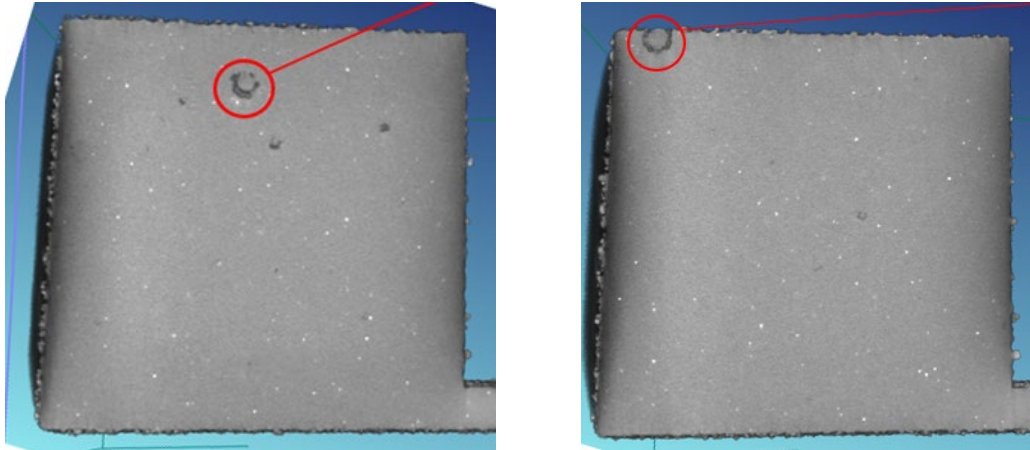


Figure 61 – Spatter porosity observed in other parts produced by Open Additive

Based on these results we decide to remake Build 2 and call it Build 3, together with other changes designed to improve results as described in [section 10.7](#).

12.4 Build 3

Build 3 was a repeat of Build 2 together with other changes designed to improve results as further described in [section 10.7](#).

12.4.1 Coupon fabrication results

The Build printed successfully without issue.

12.4.2 Profilometry results

Profile data was collected for all 3,480 print layers. This comprised 14,412 files (4 scan files per layer) and 1.01 terabytes. This data was used to refine LTM algorithm parameters to achieve the most accurate flaw detection results.

Here again we observed that the seeded flaws were quite visible in the raw profile (height) data. For example, the data from the full 10 mm flaws in Figure 62 clearly shows that the surface roughness is maximum for the lack of fusion (LOF) flaw and minimum for the keyhole porosity (KP) flaw, with the Nominal layers showing surface roughness between the two flaw conditions. This is like what was observed as describe in [section 12.2.2](#) except that the profile maps are shown here in 3D vs. 2D where the differences are more apparent.

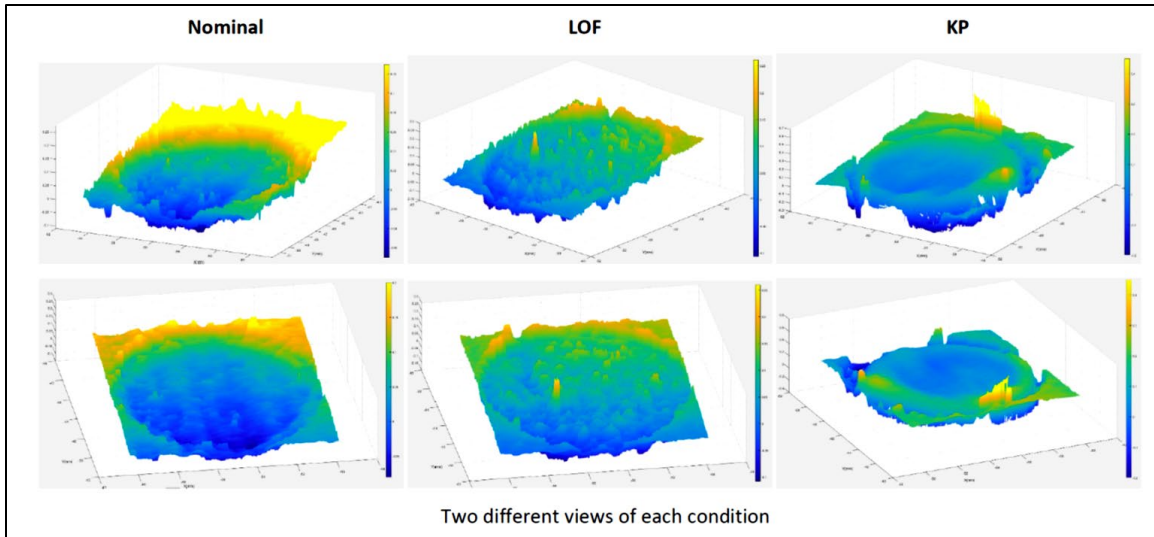


Figure 62 – Surface profiles (height maps) for three different flaw states

Similarly, the 3 mm central flaws clearly are visible in the raw profile data shown in Figure 63.

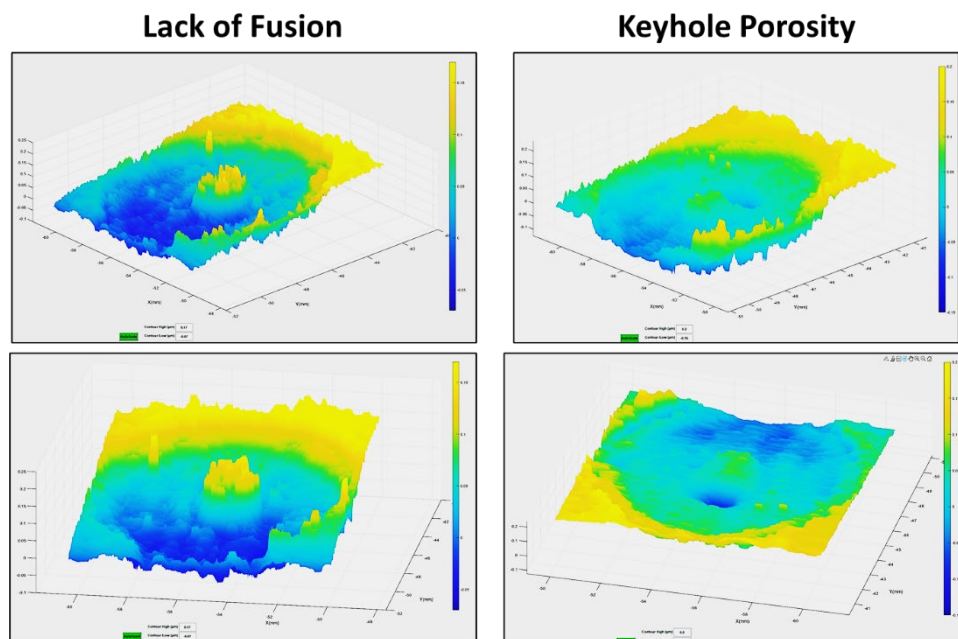


Figure 63 – Surface profiles (height maps) for the two 3 mm flaw types

12.4.3 LTM algorithm results

The LTM algorithm is defined by several parameters that can affect detection accuracy:

Window size: Recall that the overall profile image is subdivided into much smaller window and all algorithm processing occurs for the height data within that window as described in [section 8.2](#) . For example, a window that measures 0.5 mm x 0.5 mm contains 40 data points in the X direction (at 12.5 μm spacing) and 52 data points in the Y direction ((at 9.5 μm spacing). At this size, the widow contains 2,080 height data points and this data is used to generate the k and λ Weibull parameters that define where on

the Moholanobis plot this window is located. If it is inside the Nominal boundary, the window is labeled “Nominal” and if it outside the boundary the window is labeled a “Flaw”.

The larger the window, the more points it contains which is assumed to provide greater accuracy. However, the larger the window the larger the detected flaw, which reduces its usefulness. So, the window size is subject to tradeoffs that can be optimized.

Window overlap: To overcome widow size limits, we define sample profilometry data with overlapping windows. Therefore, any bed location is present in multiple overlapping windows and we use this to better localize the flaw. We use the concept of flaw damage index as described in [section 8.3](#). Therefore, the amount of window overlap is another parameter that needs to be optimized. More overlap provides more granular location data, but at the cost of more computation time, which is undesirable.

Sigma: The sigma value represents the amount of blurring or averaging performed by the gaussian derivative filter used in the LTM algorithm. Here again, the sigma value affects LTM accuracy and can be optimized.

Kernel size: The LTM algorithm is based on statistical variations of the gaussian filtered slope of the surface profile. In practice, the gaussian filtered slope value is calculated by a matrix operation of Z height values surrounding the point of interest. The matrix used in this calculation is called a kernel and the larger the matrix, the more accurate the slope calculation becomes. This is offset by the time required to perform the calculation (the larger the kernel, the higher the computation cost).

We used the Build 3 calibration data to investigate how these parameters changed the Nominal/Flaw boundary, as seen in Figure 64. An additional variable examined here was the fill hatch angle (recall we used the 67° incremental hatch in this Build). We separated the 360 different hatch angles maps into 10° increment groups - 0° to 10°, 10° to 20°, etc. – and then evaluated whether it was valid to lump various Nominal hatch angle ranges together or not.

Based on this effort, the following LTM parameters were found to provide the best results:

- Nominal/flaw boundaries for hatch angles of 0° to 10° and 10° to 20° found to be significantly different than the remaining hatch angle groups.
- Window size: 1.0 mm
- Window overlap: 75%
- Sigma: 0.1 mm
- Kernel size: 0.25 mm (or 20 x 26 matrix with the 12.5 µm by 9.5 µm height data grid)

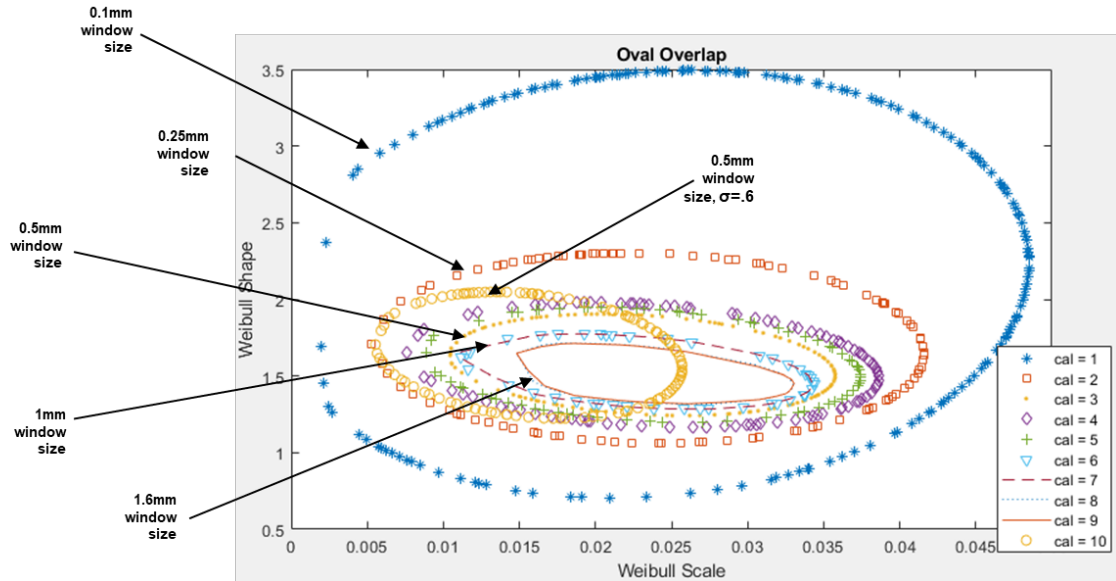


Figure 64 – The effects of LTM parameters was evaluated to determine optimum settings

12.4.4 CT Results

Porosity values were extracted from the Build 3 CT scans by flaw type, severity and size, where the porosity value reported here is the average of replicates of the same flaw type, severity and size.

Unrepaired coupons (#1, 3, 9, 13, 17 and 25) porosity levels for keyhole porosity are plotted in Figure 65 for all sizes where the flaw size code is F = 7 mm diameter, X = 5 mm L = 3 mm, M = 2 mm and S = 1 mm. A total of 636 flaws were produced without Repair with an average porosity of 2.10%. Fitting these results to a normal distribution indicates that 75% of keyhole porosity was at or above 1.07%. Similarly, for LOF flaws the average porosity was 1.81% and 75% of the porosity measured exceeded 0.63%.

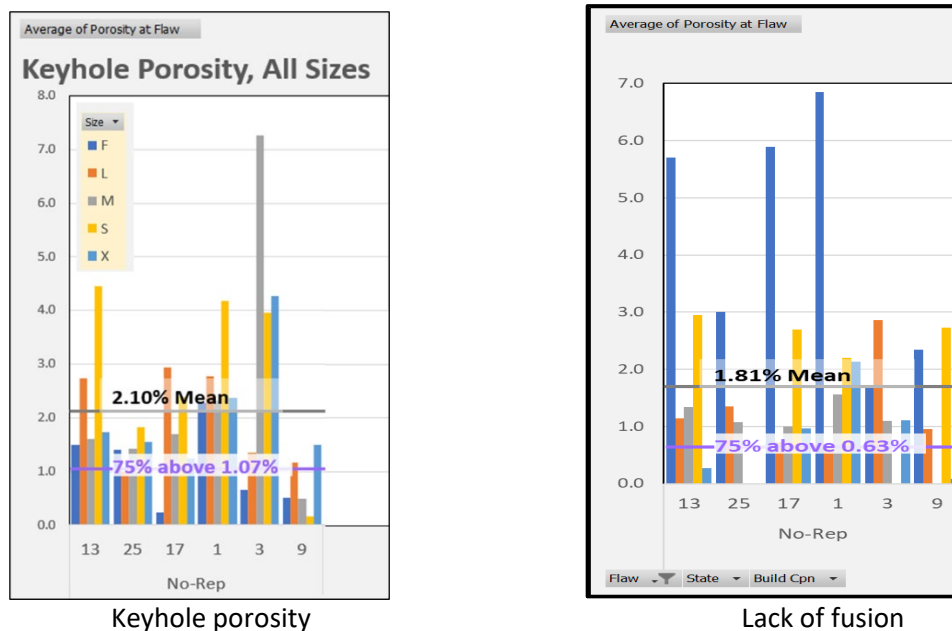


Figure 65 – Porosity for unrepaired (control) Flaws

A statistical approach was used to assess Repair effectiveness, as illustrated in Figure 66. For each Repair process the repaired porosity level mean and standard deviation were calculated (for all flaw types, sizes and severity levels). This allowed the projected overlap between the Repaired porosity and Unrepaired or control porosity to be calculated.

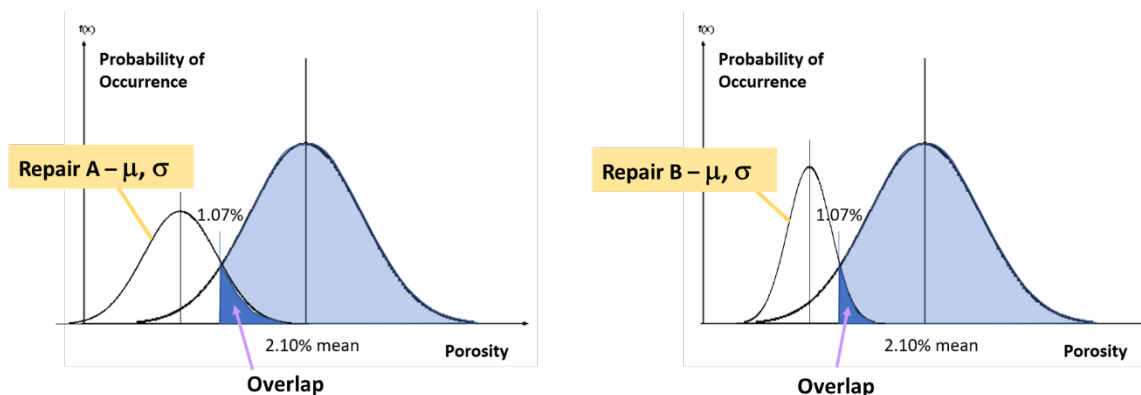


Figure 66 – Overlap of Repaired and Unrepaired (control) Flaws

The figure shows two different notional repair processes, A and B, each with its own mean and standard deviation. This permits determination that the overlap region for Repair B is smaller than for Repair A. The overlap area represents the portion of Repaired parts that might be expected to exceed the lowest 25% of pre-existing porosity in a flawed part without Repair. The smaller the overlap the better (lower porosity after Repair). In this notional example (in this case for keyhole porosity flaws), Repair B is expected to be more effective repairing flaws than Repair A.

Porosity results for the 6 Unrepaired and 19 Repaired coupons are plotted in Figure 67 for Keyhole Porosity and Figure 68 for Lack of Fusion.

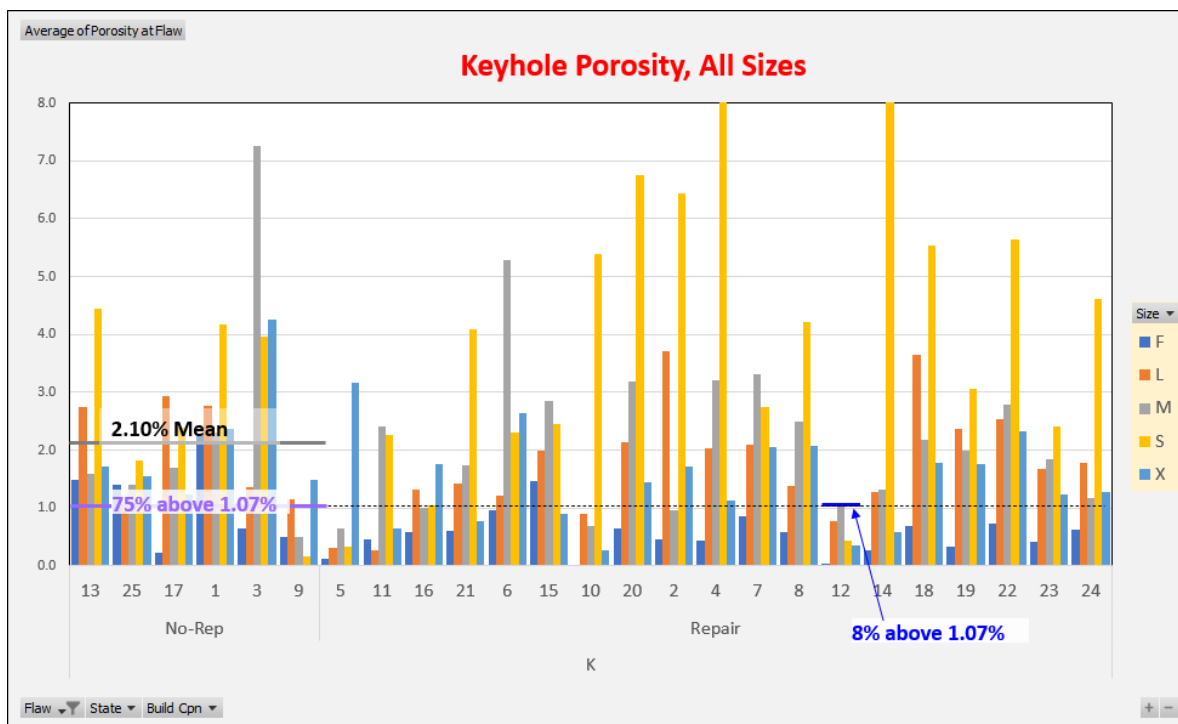
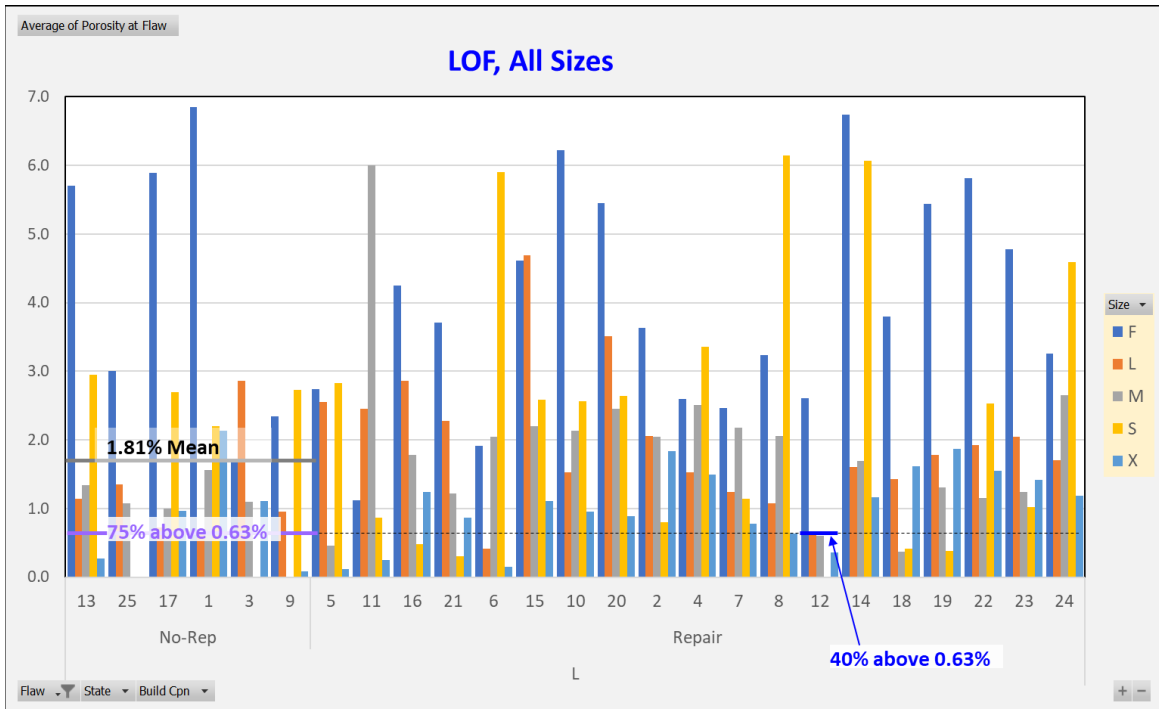


Figure 67 – Porosity for repaired Keyhole Porosity flaws



Repairable	Rank	Cpn
68%	2	5
61%	4	11
31%	7	16
30%	8	21
23%	19	6
32%	6	15
76%	1	10
25%	18	20
28%	13	2
30%	9	4
29%	12	7
28%	14	8
66%	3	12
34%	5	14
29%	11	18
27%	16	19
28%	15	22
29%	10	23
27%	17	24

Keyhole

Repairable	Rank	Cpn
20%	6	5
26%	1	11
19%	8	16
19%	10	21
19%	9	6
18%	16	15
20%	7	10
18%	13	20
18%	17	2
18%	12	4
21%	4	7
21%	5	8
21%	2	12
18%	14	14
21%	3	18
18%	15	19
18%	19	22
19%	11	23
18%	18	24

LOF

Figure 69 – Rank stacking of the 19 Repair processes used in Build 3

12.4.5 Optimum Repair Process Definition

Our LTM algorithm is not currently able to reliably determine flaw type, so we had to use a single Repair process as a compromise to best repair either Keyhole or LOF flaws. We averaged the Repair process parameters for Coupons 10 and 11 as shown in Table 6. We averaged the laser fluence level as shown in Figure 70, retained the laser power used for Coupon 10, and calculated the scan speed to provide the target laser fluence. This single Repair process was used to repair both detected LOF and Keyhole flaws.

Table 6 – Compromise Repair Process Determination

Flaw type	Best Repair Coupon	Power (watts)	Scan speed (mm/sec)	Fluence (w-sec/mm)
KP	10	330	750	0.60
LOF	11	225	378	0.37
Repair	All	330	680	0.49

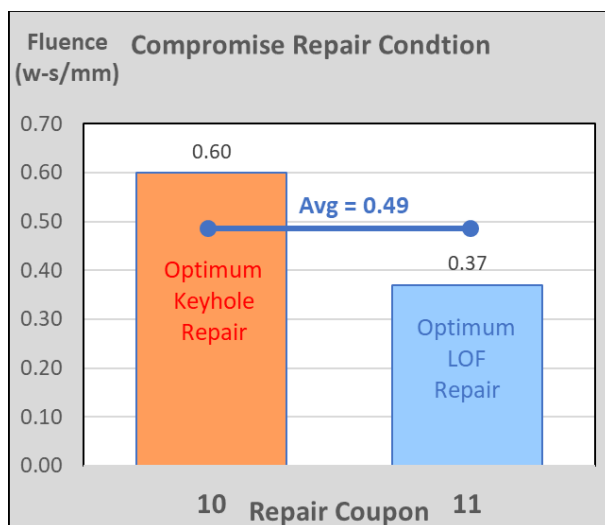


Figure 70 – Single repair process used the average laser fluence from optimum Keyhole and LOF repairs

12.5 Build 4

12.5.1 Coupon fabrication results

The closed loop control scheme was implemented using the software develop as noted in [section 9.3](#). It worked exactly as intended. A video showing the operation of the closed loop system can be seen [here](#).

To clarify, the determination of whether a flaw was present and where it was located was made completely by the automated in-situ inspection system. This information was provided to the printer without human intervention and the machine performed the Repair exactly where and how it was directed.

Build 4 had 3,480 layers and each layer contained 25 circular print regions, for a total of 87,000 circular melt areas. Excluding the cone base and fiducial regions, 2,571 of these layers were examined for Flaws. Within these layers 82 layers contained seeded or intentional flaws.

12.5.2 LTM algorithm results

12.5.2.1 Total Flaw Indications

Nineteen (19) of the 25 coupons contained a Repair - the remaining six coupons had No Repair as a control. 2,571 layers in each coupon contained either a Flaw or Nominal melt region. Therefore, a total of 48,849 melt regions were created and interrogated for the presence or absence of a Flaw.

The LTM system detected 15,451 Flaw indications within these 48,849 circular melt areas. The distribution of detected flaws by Coupon number is shown in Figure 71 (in absolute number) and Figure 72 (per Melt layer). The control coupons where no Repair was performed (#1, 3, 9, 13, 17 and 25) were not interrogated for Flaws to save Build time.

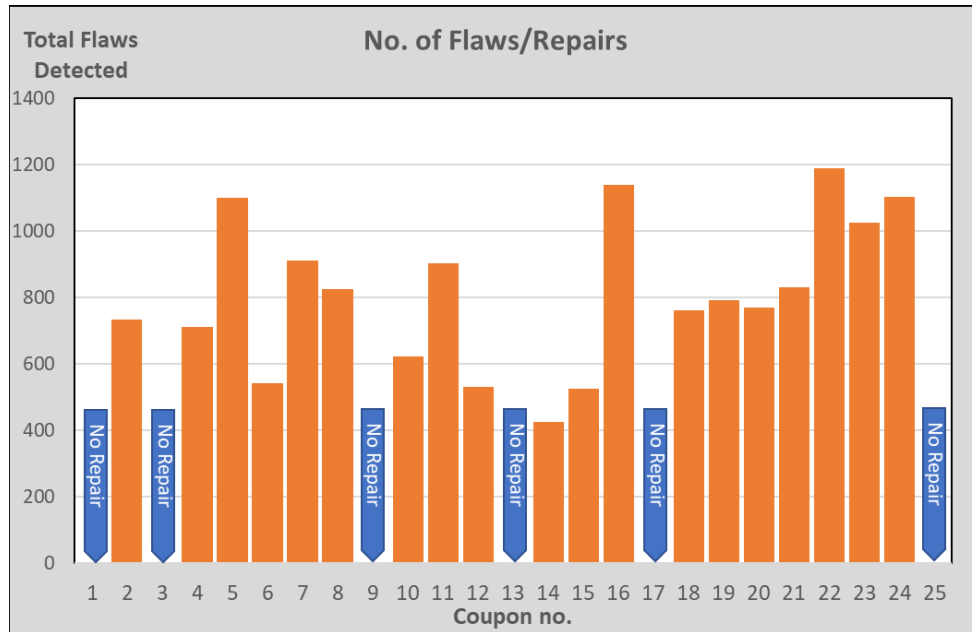


Figure 71 – Total detected flaws by coupon number

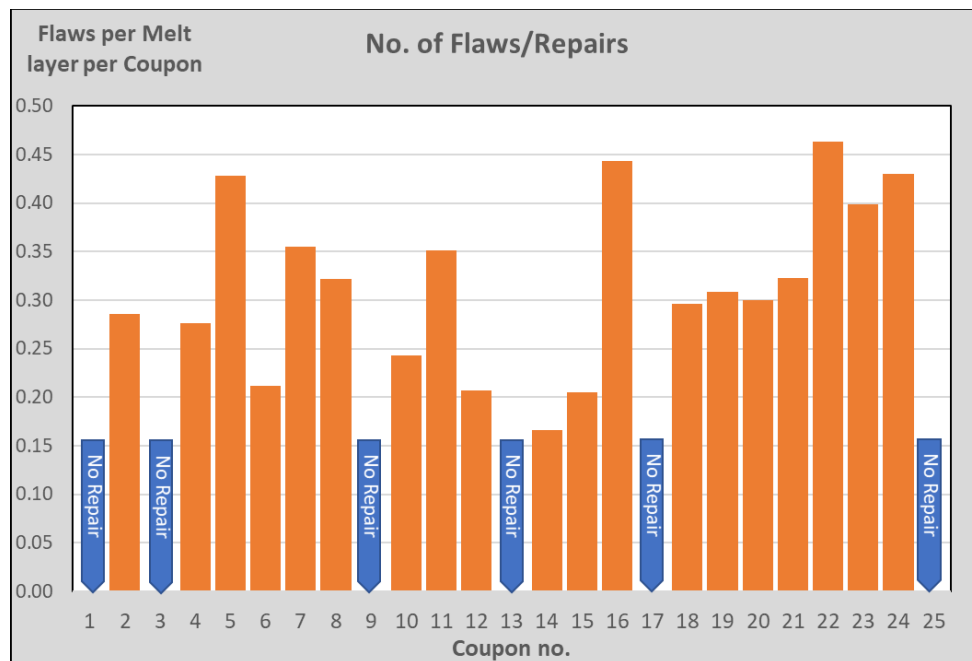


Figure 72 – Detected flaws per Melt layer by coupon

On average across all coupons and Melt layers about 32% of Melt layers indicated the presence of a Flaw. Seeded flaws were created only every 32 layers, meaning that if Flaws were created only on those layers, we might expect a Flaw detection rate only 3.1% of the time (1/32). Two possible explanations for the higher actual flaw detection rate are:

- The seeded flaw created flaws not only in the layer where it was produced, but also extending to adjacent layers.
- The Flaw detection algorithm has a high false positive rate.

12.5.2.2 Flaw Detection on Seeded and Nominal Layers

Detected Flaws were further segregated between those detected on layers with seeded Flaws and those detected on Nominal layers (i.e., where no seeded Flaw was intentionally created). These detections are shown in Table 6.

Table 7 – Detected Flaw Statistics

Layer type	No. Lyrs	No. Flaws	Mean Flaws/cpn	Std Dev Flaws/cpn	% of Coupons
Flaw	82	1,350	16.5	4.4	87%
Nominal	2,489	14,101	5.7	3.4	30%
Total	2,571	15,451			

For the 82 seeded Flaw layers, 1,350 Flaws were detected or on average in 16.5 coupons of the 19 coupons inspected. In other words, a Flaw was detected 87% of the time on layers where Flaws were intentionally created.

By contrast, on the 2,489 layers where Flaws were not intentionally made (i.e., Nominal layers), on average 5.7 of the 19 coupons examined or 30% indicated the presence of Flaws.

This data is also shown graphically in Figure 73 where the mean detected Flaws per layer is plotted as well as the +/- one sigma band. Assuming Flaws were created on the Flaw layers as intended, the true positive detection rate of 87% is reasonable, though there is certainly room for improvement. It is encouraging that the detection rate is about 3 times higher for Flawed layers than Nominal layers. However, if we assume that Nominal layers were made as intended (i.e., without Flaws), the false positive detection rate of 30% is very high.

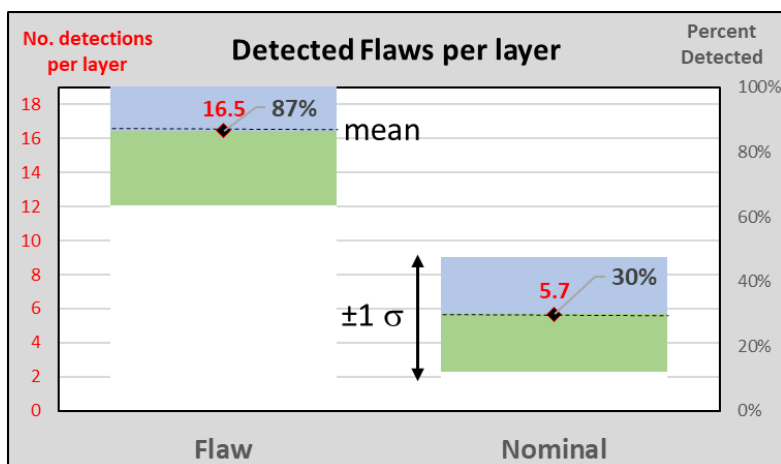


Figure 73 – Flaw detection in Seeded Flaw and Nominal Layers

These statistics and observations are assumptions only because the true or actual flaw state is not based on *intended* flaws, but rather what was *actually produced* in these melt layers. This information is embedded in the CT data, as discussed below.

12.5.3 CT Results

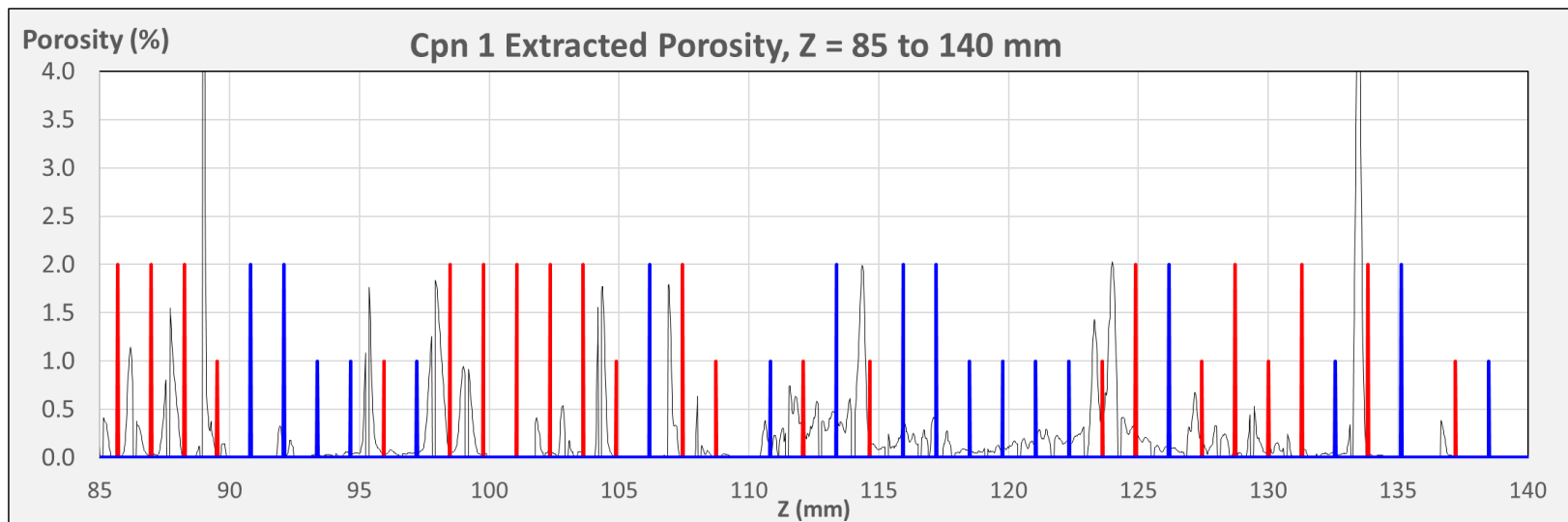
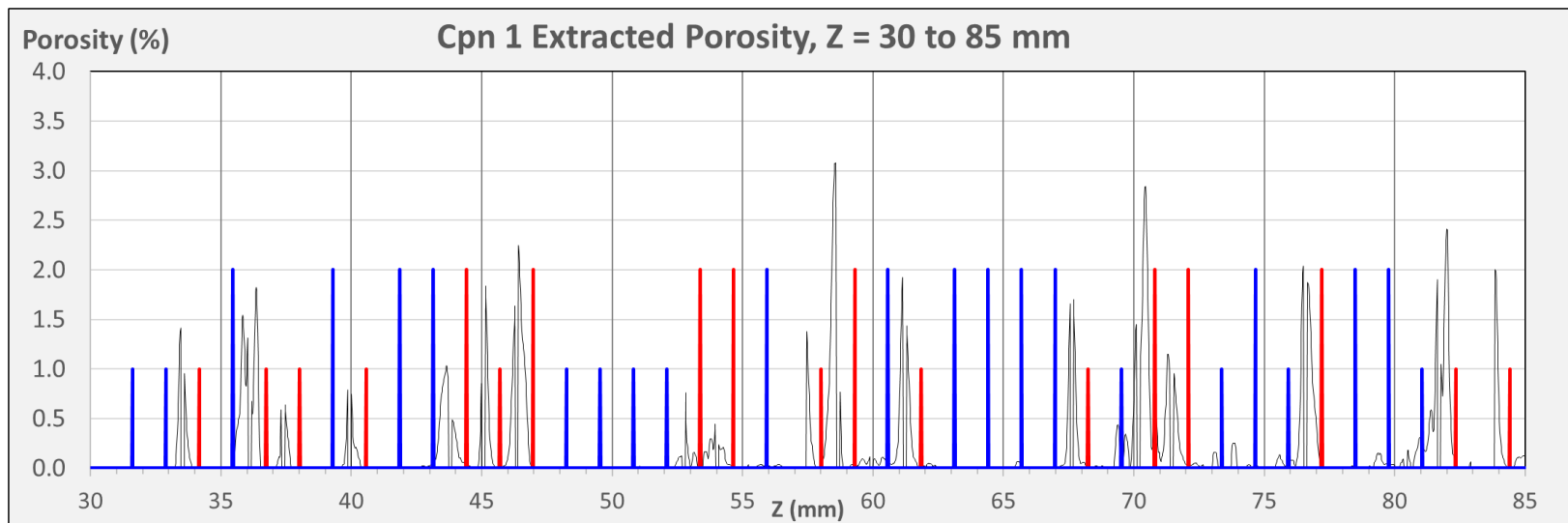
12.5.3.1 Unrepaired Coupons

Porosity values were extracted from each of the 25 coupons in the Build 4 CT scans by flaw type, severity and size and plotted as shown in Figure 74. The blue and red lines in the plots define the layer locations where lack-of-fusion (LOF) and keyhole porosity (KP) flaws had been seeded, respectively. As previously described in section [12.2.4](#), the magnitude of each porosity peak was extracted and value and logged to together with the description of the corresponding Flaw (flaw type, severity and size).

Peak porosity values were then organized in a table by Flaw type, size and coupon location. The porosity magnitude is color coded as shown in Table 7, where the higher the porosity, the redder the table cell. Also note that reported porosity values are the average of all replicates of the specific flaw condition and flaw size within each coupon (typically 4 replicates per coupon). For all 258 seeded LOF Flaws in the coupons, the mean peak LOF porosity was 0.89% with a standard deviation of 0.54%.

Table 8 – Peak LOF Porosity for Control Coupons (i.e., not Repaired)

		LOF	Mean	STD		
			0.89	0.54		
		Flaw Size (mm)				
Coupon No.	10.00	5.00	3.00	2.00	1.00	
	0.47	1.23	1.30	0.80	0.67	← Average
13	0.18	1.56	1.10	0.69	1.28	
25	1.15	1.57	1.40	0.05	0.64	
17	0.17	1.29	1.68	0.16	0.29	
1	0.33	0.41	0.68	0.60	0.78	
3	0.57	1.77	1.47	2.42	0.86	
9	0.42	0.76	1.45	0.87	0.14	



It is interesting to note that the porosity magnitude varies by flaw size, even though the flaw calculation procedure was designed to be independent of flaw size as described in section 11.3 and Figure 40. The 3- and 5-mm diameter LOF flaws had the highest average porosity at 1.30% and 1.23% respectively. Conversely, the 1- and 10-mm diameter LOF flaws had the lowest average porosity at 0.67% and 0.47% respectively.

This variation may be attributable to the melt laser scan paths used to create these flaws. We used alternating scan passes with "skywriting". Skywriting turns the laser On and Off at the beginning and end of each directional scan pass so that the laser path turnaround occurs outside or beyond the Melt region to avoid overheating in this region due to longer laser residence time as the scan path decelerates and accelerates while reversing direction.

While the laser spot *velocity* is constant in the Melt area, the local laser *exposure time* is not constant (i.e., varies) as a function of Flaw size as illustrated in Figure 75. A smaller Flaw size experiences a shorter local laser exposure time, and therefore a higher melt temperature, heating and cooling rate than a larger flaw. This may help explain the porosity differences seen in Table 7.

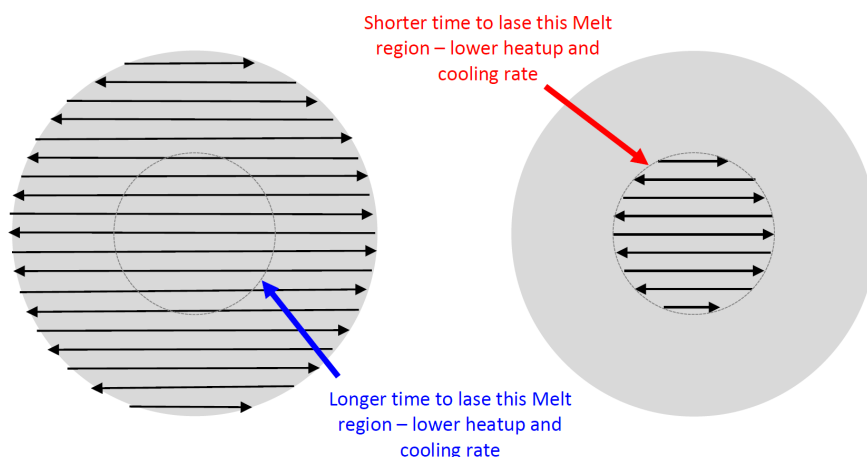


Figure 75 – Thermal exposure variation with Flaw size

Table 9 – Peak Keyhole Porosity for Control Coupons (i.e., not Repaired)

		KP	Mean	STD		
			0.98	0.31		
	Flaw Size (mm)					
Coupon No.	10.00	5.00	3.00	2.00	1.00	← Average
	0.86	1.05	0.72	0.90	1.39	
13	0.71	0.93	0.81	0.22	1.00	
25	0.65	0.81	0.00	0.65	1.65	
17	0.47	0.82	0.70	1.84	0.81	
1	1.89	1.07	0.73	0.97	1.96	
3	0.70	0.77	1.08	1.22	1.82	
9	0.74	1.87	0.99	0.51	1.12	

12.5.3.2 Repaired Coupons

A similar procedure was used to calculate porosity in the 19 coupons that were produced using the closed loop repair process. Results for repaired LOF porosity are shown in Table 9 and repaired Keyhole porosity are shown in Table 10.

There are a total of 630 repaired LOF Flaw regions, with a mean peak porosity of 1.00% and a standard deviation of 0.53%. The variation in peak LOF porosity with Flaw size in the Repaired coupons is similar that the trends noted in in the Unrepaired coupons as discussed in section [12.5.3.1](#) and [Table 7](#) above. The 3- and 5-mm diameter LOF flaws had the highest average porosity at 1.37% and 1.16% respectively. Conversely, the 1- and 10-mm diameter LOF flaws had the lowest average porosity at 0.43% and 0.94% respectively.

Table 10 – Peak LOF Porosity for Repaired Coupons

Coupon No.	Flaw Size (mm)				
	10.00	5.00	3.00	2.00	1.00
Avg	0.43	1.37	1.16	1.10	0.94
5	0.53	1.41	1.32	0.85	0.89
11	0.45	0.95	1.13	1.69	0.64
16	0.57	1.79	1.25	1.37	1.56
21	0.25	1.03	0.69	0.27	0.19
6	0.70	1.12	0.65	1.43	0.75
15	0.32	1.45	1.37	1.58	0.69
10	0.24	1.12	1.28	1.67	1.18
20	0.16	0.91	1.22	1.34	0.49
2	0.38	1.87	1.20	0.86	1.19
4	1.04	2.41	1.01	1.81	1.91
7	0.56	1.13	1.45	0.62	1.22
8	0.53	1.15	0.79	1.09	1.79
12	0.27	1.92	1.31	1.32	0.55
14	0.13	0.84	1.43	0.54	1.08
18	0.29	1.47	1.38	0.05	0.00
		LOF	Mean	STD	
			1.00	0.53	

[12.5.3.1](#) and [Table 8](#) above. Both data sets had the highest peak porosity with the smallest 1-mm Flaw size. The mid-size Flaws (3-mm and 5-mm) showed the lowest peak porosity values.

Table 11 – Peak Keyhole Porosity for Repaired Coupons

	Flaw Size (mm)				
Coupon	10.00	5.00	3.00	2.00	1.00
Avg	0.90	0.78	1.08	0.87	1.36
5	1.14	1.18	1.07	0.77	1.29
11	0.82	1.05	1.43	0.63	1.13
16	1.61	0.54	1.98	1.25	1.41
21	0.71	0.67	0.85	0.37	1.80
6	1.12	1.11	1.61	0.51	1.66
15	0.54	0.73	1.25	0.38	0.12
10	0.66	1.22	1.22	1.46	1.21
20	0.36	0.46	0.76	0.82	1.32
2	1.50	1.00	0.93	1.10	2.32
4	1.21	0.50	1.21	1.28	1.53
7	1.12	0.24	1.01	0.93	1.74
8	0.85	0.55	0.78	1.52	1.21
12	0.74	1.39	0.41	1.43	1.61
14	0.70	0.48	0.33	0.65	2.12
18	0.44	0.65	1.30	0.00	0.00
		KP	Mean	STD	
			1.00	0.49	

A comparison of the peak porosity in the Unrepaired (control) and Repaired coupons was performed to assess the effectiveness of the closed loop control scheme.

A comparison of the mean peak LOF porosity for Unrepaired and Repaired coupons as a function of flaw size is shown in Figure 76. A comparison of the mean peak LOF porosity for Unrepaired and Repaired coupons as a function of flaw severity is shown in Figure 77. As noted, the LOF porosity in the Repaired coupons was slightly *higher* than in the Unrepaired coupons, both with respect to Flaw size and Flaw severity level. Although the difference is small and within one sigma scatter, this results was disappointing.

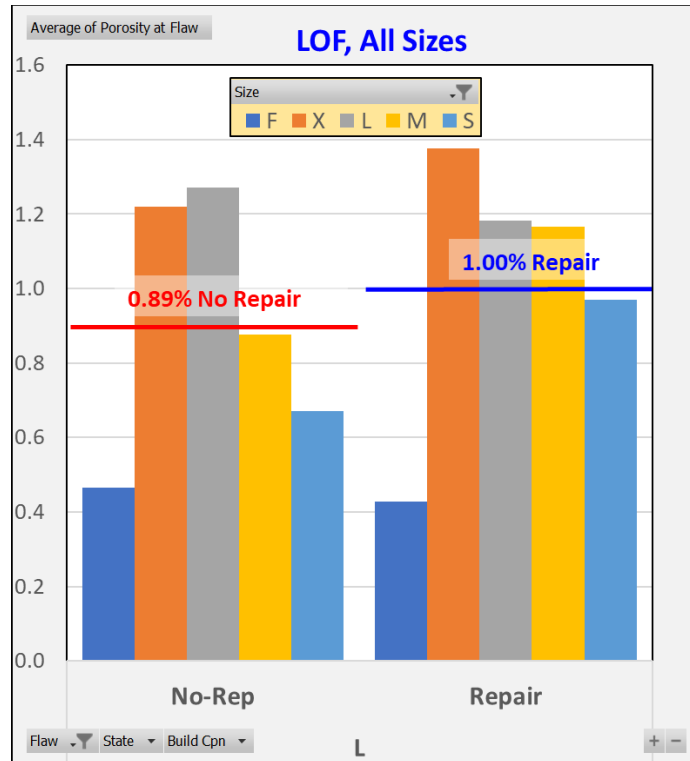


Figure 76 – LOF peak porosity as a function of Flaw size

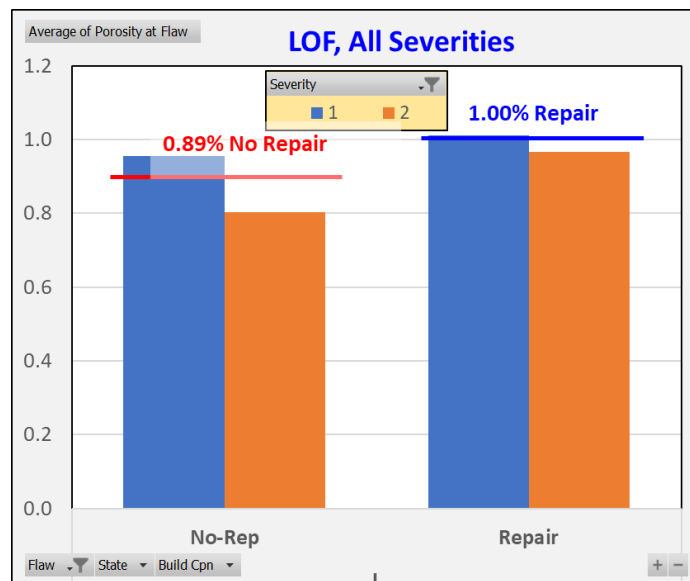
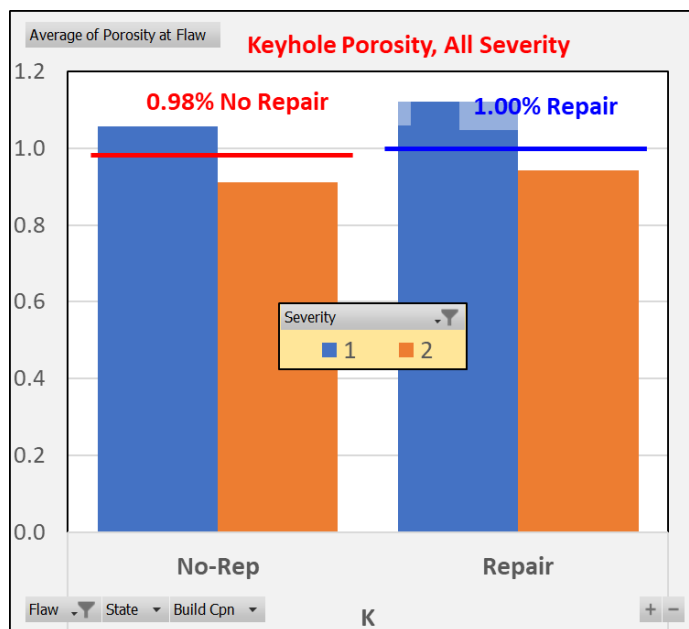
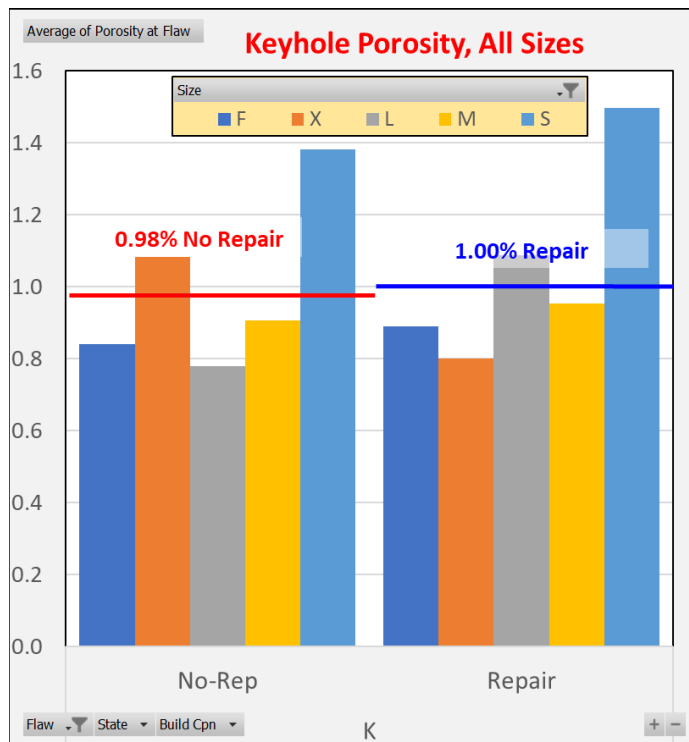


Figure 77 – LOF peak porosity as a function of Flaw severity

Similarly, a comparison of mean peak Keyhole porosity for Unrepaired and Repaired coupons as a function of flaw size is shown in Figure 78. A comparison of the mean peak Keyhole porosity for Unrepaired and Repaired coupons as a function of flaw severity is shown in Figure 79. Results were similar to LOF – the

Repaired Keyhole coupons had slightly higher porosity than Unrepaired, although within statistical data scatter.



13 Discussion and Conclusions

The following was demonstrated during this program:

1. A high resolution, high speed full bed profilometer (IAP) was designed, built, installed, debugged and calibrated in the Open Additive AM2 metal LPBF printer.
2. The system uses a COTS profilometer mounted on an X/Y gantry operating inside the printer chamber.
3. The IAP can measure 95 million height points over the 150 x 150 mm bed. Z height repeatability is 0.4 μm and the maximum X/Y spacing of data points is 12.5 μm by 9.5 μm .
4. At the highest point density, a complete bed profile can be captured and stored in 12 seconds.
5. LPBF process conditions for Ti6Al4V were established that provide Nominal condition material (i.e., very low porosity) as well as for controlled and varying severity levels for keyhole porosity and lack of fusion flaws.
6. Build plans were crafted and executed where several thousand seeded or intentional flaws were produced in one Build comprising two types of flaws, up to three flaw severity levels and up to five different flaw sizes.
7. Both keyhole porosity and lack of fusion flaws were apparent directly from the profile or topography data for larger flaws. Flaws of 1 mm and smaller were difficult or not possible to discern directly from profile data.
8. After optimization the LTM algorithm was able to detect and localize both keyhole porosity and lack of fusion flaws as small as 3 mm in diameter.
9. Optimum repair process was identified to restore both keyhole porosity and lack of fusion flaws to a more Nominal condition.
10. A single optimum Repair process was defined and used to repair both keyhole porosity and lack of fusion flaws in the Build 4 closed loop control demonstration.
11. A closed loop control demonstration of a 3,480-layer build was performed fully autonomously (i.e., no Operator intervention).
12. The LTM algorithm detected Flaws 87% of the time for melt regions that were created with a seeded Flaw. By contrast, the algorithm detected Flaws 30% of the time for melt regions that were created without a seeded Flaw (i.e., Nominal layers). This is analogous to a true positive rate of 87% which is reasonable, though can be improved. However, this is also indicative of a false positive rate of 30%, which is poor.
13. The detection rates are only analogous to actual detection rates because they *assume* Flaws do exist on the seeded Flaw layers and Flaws do not exist on the Nominal layers. This may not actually be the case, however. For example, if a Flaw is created on layer N, the presence of this Flaw may also create Flaws on the next few layers (perhaps up to the next 5 to 7 layers) *even though those layers were made with Nominal conditions* because of the disruption caused by the Flaw in melt layer N. Therefore, what was simplistically assumed as a false positive detection as noted in item 12 may be a true positive Flaw. Therefore, the actual false positive detection may be significantly less than the 30% estimate cited above.
14. There was considerable statistical scatter in the CT results. For example, the coefficient of variation for mean peak porosity associated with Flaws was between 31% and 61% as noted in Table 12 below.

This is relatively high and may reflect that porosity creation is a stochastic process and may not be highly reproduceable, even when identical process conditions are used.

Table 12 – Statistical Scatter of Mean Peak Porosity form CT data

Flaw Type	Repair State	Mean	Std Dev	CV
LOF	No Repair	0.89	0.54	61%
	Repair	1.00	0.53	53%
Keyhole	No Repair	0.98	0.31	31%
	Repair	1.00	0.49	49%

15. The degree of porosity generated associated with seeded Flaws varied with Flaw size, both for lack-of-fusion and keyhole flaws. This result was not anticipated, and may arise due to the scan path used, even though the scan parameters (laser power and the scan velocity) were the same for all Flaw sizes of given type. This suggests that more through consideration be given to the absolute melt temperature in the Flaw region, as this will change with Flaw size, all else held constant. This effect can be simulated using several commercially available software codes.
16. There was very little effect on porosity with the severity of the Flaw conditions used (i.e., how far from Nominal process conditions). There was a very slight porosity increase (5% or less) both for LOF and Keyhole porosity with increasing Flaw severity.
17. The closed loop control scheme did not achieve the desired result (i.e., a reduction in the level of porosity in Flaw regions). One reason may have been that a single Repair process was used, and the process conditions used were a compromise between the optimum Repairs for two different types of Flaws as discussed in section [12.4.5](#). There was a relatively large difference, roughly 23%, between the laser fluence selected for Repair (0.49 watt-sec/mm) and those found to be optimum for LOF (0.37 watt-sec/mm) or Keyhole porosity (0.60 watt-sec/mm). By seeking to achieve good repair results for both LOF and Keyhole flaws, we appeared to achieve neither. Put more eloquently by Tyrone Powers, a 19th century theologian,

“Compromise is but the sacrifice of one right or good in the hope of retaining another - too often ending in the loss of both.”

In hindsight, we may have had more success by focusing on one Flaw type only to better target our efforts.

14 Acknowledgements

This effort was performed by several people and organizations. Flightware wishes to acknowledge significant contributions from the following organizations and individuals:

Defense Logistics Agency – Sponsor Agency

Dr. Vaibhab Jain
Kristen Eads
Denise Price
Richard Follet

EWI - Development of the IAP sensor system

Connie Reichert LaMorte
Jacob Hay
Katie Harden

Open Additive (formerly ARCTOS) – Programming and generation of all AM coupons and parts

Joseph Walker
John Middendorf
Evan Harris
Ron Jacobson

Quartus Engineering – Development of custom software for LTM inspection, CT data processing and closed loop control

Eric Anstadt
Samantha Villers

Jesse Garant – CT scanning

Dylan Yazbeck

Simplevoxel - CT data processing

Rohini Marathe
Pradeep Bhattad

Their contributions are appreciated.