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-Technical Report-

TARDEC Direct Energy Deposition Technical Analysis
Design of Experiments, Part 1, Phase 2

Ian J. Toppler

Dan Schleh

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Ian J Toppler
Dan Schleh

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Materials Characterization & Failure Analysis Group - U.S. Army TARDEC
6501 E. 11 Mile Road (MS 267), Warren, MI 48397 - 5000

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14. ABSTRACT
TARDEC Production Lifecycle Engineering (PLE) Group is conducting a Design of Experiments (DOE) to determine a standard process to optimize parameters settings to validate coatings and repairs conducted with Direct Energy Deposition (DED) technology. Phase 2 is a continuation of the phase 1 of the TARDEC DED Design of Experiments to complete the fundamental understanding of pattern effects on deposition quality. Materials used in the deposition were Stellite 21 powder and an ASTM A514 steel plate. Four patterns were selected, two of which had been created by TARDEC personnel. Each of the patterns were designed to evaluate the changes in porosity within the material cores. Two patterns were modified from the initial recipes in phase 1 of the DOE to narrow each pass's line spacing. The other two patterns consisted of different in-plane layer offsets. These offsets allowed for the line passes of the layer being deposited to be placed between the line passes of the layer below it in an effort to eliminate the pores.
After analyzing the resulting surfaces and cores for quality and defects, the offset recipes demonstrated the best results. The Longitudinal/Transverse pattern of recipe 19 showed an increase in porosity at the fusion zone and between the layers. The Longitudinal pattern of recipe 21 showed both a significant increase and decrease in porosity between the layer line passes.

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DEPARTMENT OF THE ARMY
US ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
6501 E. 11 MILE ROAD
WARREN, MI 48397-5000

REPLY TO
ATTENTION OF

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MEMORANDUM FOR: TARDEC PLE A.D., Jason Middleton

TARDEC Direct Energy Deposition Technical Analysis

Design of Experiments, Part 1, Phase 2

Ian J. Toppler
Materials Engineer, US ARMY TARDEC
Materials Characterization and Failure Analysis Team

Dan Schleh
Mechanical Engineer, US ARMY TARDEC
Application & Integration Team

Lewis Marshall
Undergraduate Materials Researcher
Michigan Technological University

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

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Abstract

TARDEC Production Lifecycle Engineering (PLE) Group is conducting a Design of Experiments (DOE) to determine a standard process to optimize parameters settings to validate coatings and repairs conducted with Direct Energy Deposition (DED) technology. Phase 2 is a continuation of the phase 1 of the TARDEC DED Design of Experiments to complete the fundamental understanding of pattern effects on deposition quality. Materials used in the deposition were Stellite 21 powder and an ASTM A514 steel plate. Four patterns were selected, two of which had been created by TARDEC personnel. Each of the patterns were designed to evaluate the changes in porosity within the material cores. Two patterns were modified from the initial recipes in phase 1 of the DOE to narrow each pass's line spacing. The other two patterns consisted of different in-plane layer offsets. These offsets allowed for the line passes of the layer being deposited to be placed between the line passes of the layer below it in an effort to eliminate the pores.

After analyzing the resulting surfaces and cores for quality and defects, the offset recipes demonstrated the best results. The Longitudinal/Transverse pattern of recipe 19 showed an increase in porosity at the fusion zone and between the layers. The Longitudinal pattern of recipe 21 showed both a significant increase and decrease in porosity between the layer line passes. Areas of the deposition were almost free of porosity, while others were heavy with porosity. These areas of increased porosity for both patterns suggested an unknown variable may have affected the depositions. The pattern of porosity also indicated a repeated error may have occurred during the DM3D 405D operations. The two off-set Longitudinal patterns, recipes 22 and 23, showed significantly less porosity in both cross sectioned specimens when compared to the original Longitudinal pattern, of recipes 17 and 21.

Background

This report details the analysis of the TARDEC design of experiments (DOE) results from part 1, phase 2. Part 1, phase 1, of the DOE focused on determining the initial pattern effects of depositing Stellite 21 powder onto an A514 substrate, and to establish a baseline for resulting material properties. Phase 2's focus was to analyze the results of modifying the deposition patterns of the two depositions from part 1, phase 1, of the DOE. The two Phase 1 deposition patterns were modified to bring the lines within each layer closer together to reduce or eliminate the existing porosity between each line pass. The modified pattern paths were labelled Sample Numbers 19 and 21 within this report. Sample numbers and recipe numbers of part 1, phase 2, specimens were designated the same for ease of reference. Two additional patterns were produced with the line passes of each layer being placed slightly offset in the transverse direction to determine effects of offset deposition layers on the material properties and level of porosity. Each deposition layer was offset parallel to the passes of the prior layer by 50% (0.625 mm) for Sample 22, and offset by 33.3% (0.42 mm) for Sample 23. See Figure 1 for a depiction of each of the deposition patterns from phase 1 and phase 2.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

Sample 19 was the modified pattern of the longitudinal/transverse depositions (Sample 1). Sample 21 was the modified pattern of the longitudinal only deposition (Sample 2). All of the deposition were designed to be 101.6 mm (4 inches) long and 6 mm wide. A total of six layers were deposited. Samples 2 and 21 were deposited so that each of the lines would be stacked one on top of the other.

The completed depositions were sectioned into XZ-plane cross sections, every 12.7 mm (0.5 inch) along the Y axis. Selected cross sections were measured to determine the effects of the current parameters on the final height, width, deposition penetration into the substrate, penetration of the second layer into the first, and penetration of the third layer into the second. Hardness mapping was conducted to further evaluate the deposition results. Every line represent a line pass in a layer.

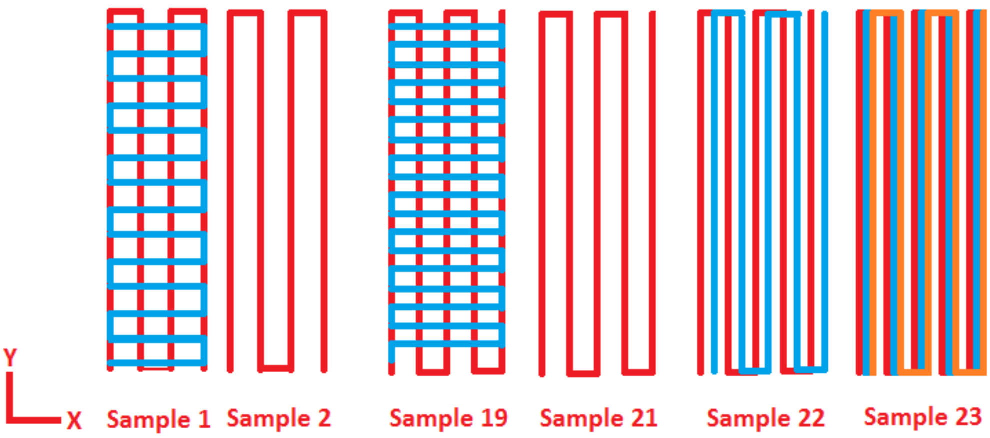

Figure 1: The following patterns are as viewed from above. Deposition patterns for layers one (red), two (blue), and three (orange). For those patterns that do not show the additional layers, the displayed pattern is then repeated over the first until six layers have been produced.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

Results and Observations

Samples 19, 21, 22, and 23 were sectioned every 12.7 mm from the same end of the deposition. See Figure 2. The cross sections at the 25.4 mm mark and 50.8 mm mark of the deposition and substrate were removed and mounted for microscopic analysis. The 12.7 mm deposition sections were then cross sectioned again down the center of the deposit line. This allowed for an “XZ” and “YZ” plane inspection of the materials’ cores.

Figure 2: Image of the surface and cross sections of Phase 2 deposition samples.

The parameter setting for each of the depositions can be seen in Table 1. These parameters are machine specific to the TARDEC DM3D 405D. Each recipe contains the specific process parameters, powder preparation, and ambient temperature/humidity during the deposition process. The substrate plate was bead blasted prior to the deposition to remove any oxidation build up on the surface. This prevents corrosion and inclusion build up between the deposition layers and the substrate surface.

A review of recipe parameters, in Table 1, was provided for the reader to understand the differences in each of the parameter sets. The phase 2 parameters used a decreased line pass separation, larger powder grain size, and a shorter bake time at a lower temperature to remove any moisture from the powder. The changes to the powder grain size were due to the limited amount of powder for this stage of the DOE. Changes in bake time and temperature were made to optimize the timeline of the process. The manufacturer only recommends a minimum pre-deposition bake temperature of 303 °F (150 °C) for one hour.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

Table 1: Parameter sets developed from Part 1, Phase 1, of the DOE.

Sample Number	**1**	**2**	**19**	**21**	**22**	**23**
Recipe Number	16	17	19	21	22	23
Powder Material	Stellite 21	Stellite 21	Stellite 21	Stellite 21	Stellite 21	Stellite 21
Substrate	A514	A514	A514	A514	A514	A514
Deposition Dimensions	5mm x 101.6mm x 6 layers	5mm x 101.6mm x 6 layers	5mm x 101.6mm x 6 layers	5mm x 101.6mm x 6 layers	5mm x 101.6mm x 6 layers	5mm x 101.6mm x 6 layers
Powder Feed Rate	1750 ~ 14 g/min.	1750 ~ 14 g/min.	1750 ~ 14 g/min.	1750 ~ 14 g/min.	1750 ~ 14 g/min.	1750 ~ 14 g/min.
Pass Separation	1.5 mm	1.5 mm	1.25 mm	1.25 mm	1.25 mm	1.25 mm
Pattern	Trans/Long. Alternate. Default	Longitudinal Stacked	Trans/Long. Alternate. Default	Longitudinal Stacked	Longitudinal, Layer Offset 0.625mm, Every 2 layers	Longitudinal, Layer Offset 0.4167mm, Every 3 layers
Head Speed	800 mm/min	800 mm/min	800 mm/min	800 mm/min	800 mm/min	800 mm/min
Laser Power Setting	1100 W	1100 W	1100 W	1100 W	1100 W	1100 W
Layer Step-Up Height	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm
Grain Sieving	<45micrometer	<45micrometer	<63micrometer, Mesh230	<63micrometer, Mesh230	<63micrometer, Mesh230	<63micrometer, Mesh230
Ambient Process Temperature	70 °F	70 °F	68 °F	68 °F	68 °F	68 °F
Ambient Process Humidity	NA	NA	45 %	45 %	45 %	45 %
Notes	Baked 1.5hrs @550F	Baked 1.5hrs @550F	sieved 30min., 40min. @500F	sieved 30min., 40min. @500F	sieved 30min., 40min. @500F	sieved 30min., 40min. @500F

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

1. Visual inspection:

Each of the cross sections were mounted and polished down to a 1 micron finish. An optical microscope, with measurement software, was used to evaluate the heights and widths of each cross sectioned specimen. Measurements of the phase 2 deposition penetration into the substrate, average deposition pass width, penetration of the second layer into the first, and penetration of the third layer into the second layer were compared to the phase 1 results. The averages of each measurement can be seen in Table 2. It should be noted that each of the specimens were deposited on the same day, and in order of numbering.

Table 2: Average cross sectional dimensions of completed depositions. The LT stands for Longitudinal/Transverse, the L stands for Longitudinal, and the OL stands for different types of Offset Longitudinal recipes. N/A represents measurements that could not be taken.

	Sample 1 (LT)	Sample 2 (L)	Sample 19 (LT)	Sample 21 (L)	Sample 22 (OL)	Sample 23 (OL)
Deposition Height (mm)	2.82	2.31	2.69	2.26	2.32	2.28
Deposition Width (mm)	5.83	5.79	6.07	6.11	5.97	7.78
Average Substrate Penetration (mm)	0.57	0.55	0.63	0.60	0.63	0.64
Average Deposition Pass Width (mm)	0.94	1.07	0.96	1.00	0.92	0.93
Penetration of 2nd layer into 1st layer (mm)	N/A	N/A	N/A	0.31	0.36	0.33
Penetration of 3rd layer into 2nd layer (mm)	N/A	N/A	N/A	0.32	0.29	0.33

1.1 Sample 19:

Sample 19 used an alternating longitudinal and transverse layer deposition pattern. The first layer was deposited in the longitudinal (Y axis) direction and the second in the transverse (X axis) direction. A total of six deposition layers were produced. The height and width of Sample 19 were measured using cross sections of the deposition along the XZ plane, as seen in Figure 3. The average height and width of the completed deposition was 2.69 mm and 6.07 mm. This was a decrease in height compared to Sample 1's averaged height of 2.82 mm from part 1, phase 1, of the DOE. See Figure 4.

To improve overall depth of penetration and fusion of the deposition, Sample 1's deposition pattern was modified to bring the deposition line passes, in each layer, closer together. Each line pass was modified from 1.5 mm apart to 1.25 mm apart. This had a varied effect on the deposition. Porosity in Sample 1 was primarily limited close to the outer surface, with a few exceptions. However, Sample 19 demonstrated random porosity between the layers in the core

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

material as well as within the fusion zone of the powder and substrates. Those pores appeared to be localized to the area between the first and third layers, and were roughly 0.09 mm in diameter. The average width between the deposition line passes could only be measured from the first layer deposited into the substrate surface. Each measurement was taken from center to center of each neighboring pass. The average deposition pass width of Sample 1 was 0.94 mm and the deposition consisted of four passes per longitudinal layer. The average deposition pass width for Sample 19 was 0.96 mm and five passes per longitudinal layer. The average depth of substrate penetration was 0.57 mm for Sample 1 and 0.63 mm for Sample 19.

The lack of uniformity in the finished surface can be seen in the right image of Figure 3. This dip in the surface runs repeatedly with this pattern and would require additional surface removal during finishing operations.

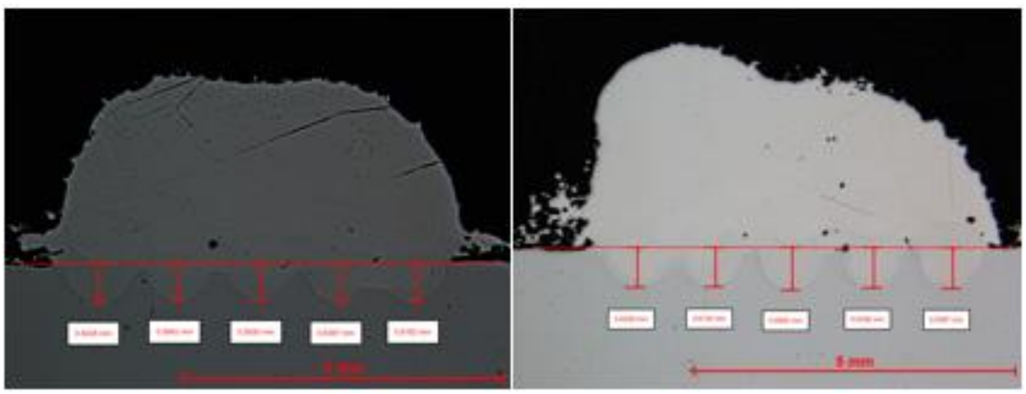

Figure 3: Image of Sample 19's XZ plane cross section. The cross section taken at the 50.8 mm (2 inch) mark can be seen on the left, and the cross section taken at the 25.4 mm (1 inch) mark can be seen on the right.

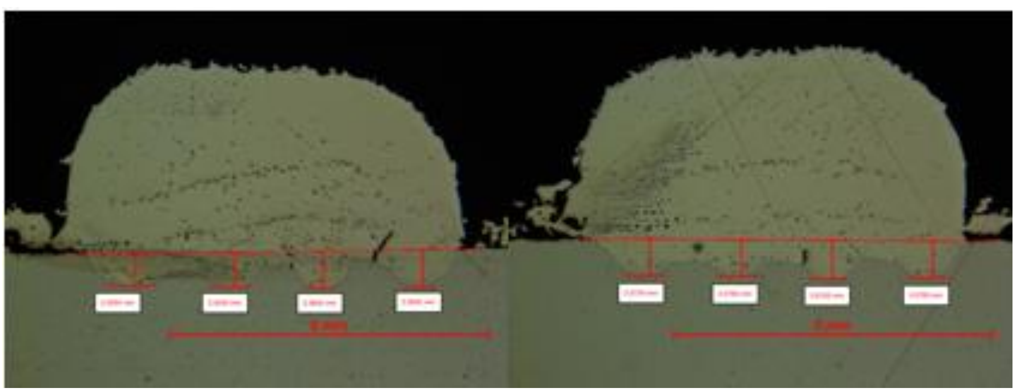

Figure 4: Image of Sample 1's XZ plane cross section. The cross section taken at the 63.5 mm (2.5 inch) mark can be seen on the left, and the cross section taken at the 38.1 mm (1.5 inch) mark can be seen on the right.

Sample 19 was inspected in the center of the deposition along the YZ plane. This cross section was inspected to determine how the structure was affected by the transverse deposition layers. See Figure 5. It was noted when

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

inspecting these cross sections that porosity was identified in groupings of the cross section. At one end there appeared to be minor porosity and uniform deposition layer patterns. However, groupings of large pores can be seen on on the left side of Figure 5. It was unclear as to what caused this porosity.

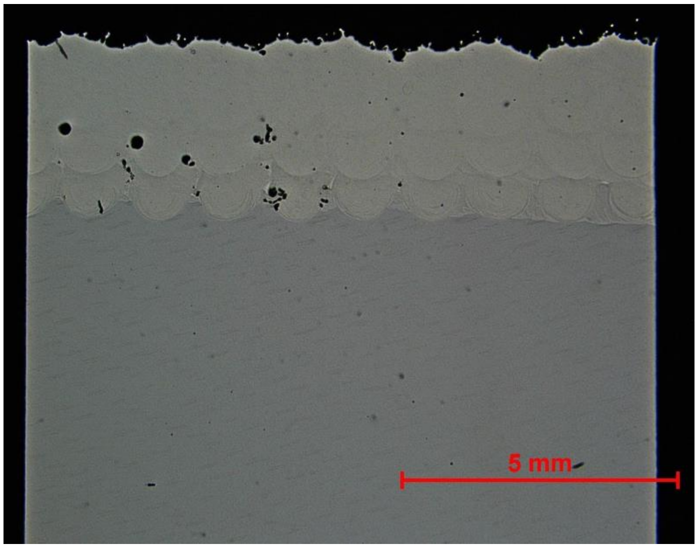

Figure 5: Image of Sample 19 YZ plane cross section. The cross section taken between 25.4 mm to 38.1 mm (1 - 1.5 inch) along the X axis.

1.2 Sample 21:

Sample 21 originated as a modified version of the Sample 2 longitudinal stacking pattern, from part 1, phase 1, of this DOE. This pattern was found to provide a more uniform distribution of powder on the completed outer surface. The pattern appeared to a better fit for reducing the necessary amount of surface finish after the deposition was complete. Just as in Sample 2, Sample 21 used a longitudinal pattern that placed each layer and line pass directly on top of the other. In Sample 2, pores were readily identified between the line passes. It was believed that a reduction in the distance between the line passes might reduce or remove those voids. Each of the line passes were separated by 1.5 mm from center to center in Sample 2. This distance was modified to 1.25 mm for Sample 21.

The reduction of the line pass width to 1.25 mm did reduce the amount of porosity in some areas, but did not remove it in others. Analysis of the low porosity cross sectioned areas indicated that the amount of porosity decreased and the size of the pores decreased as well. As can be seen in Figure 6, there are two large pores between line passes 2 and 3 and four large pores between line passes 4 and 5. The pores appear to have formed between the first four layers of the deposition. This is seen throughout the deposition. Figure 7 shows the cross sections for Sample 2, which were used for comparison.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

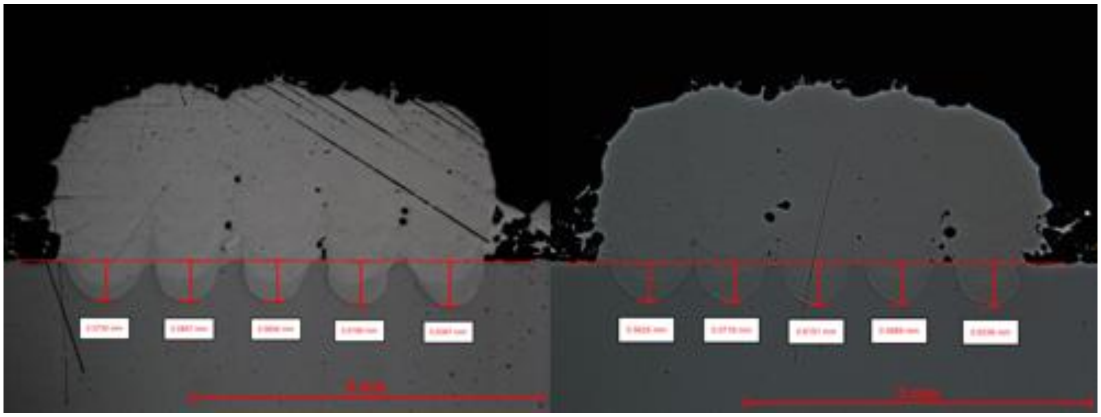

Figure 6: Image of Sample 21 XZ plane cross sections. The cross sections were taken at the 25.4 mm (1 inch) mark as seen on the left, and 50.8 mm (2 inch) mark can be seen on the right.

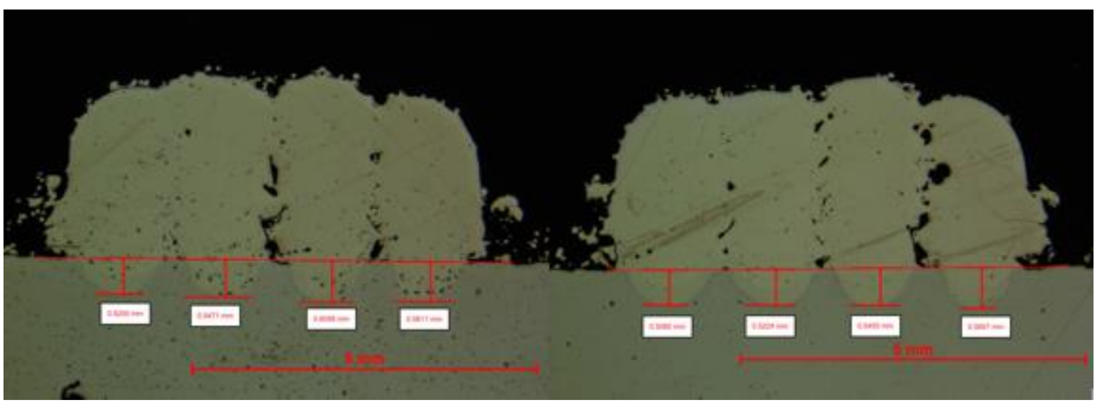

Figure 7: Image of Sample 2 XZ plane cross section. The cross section taken at the 63.5 mm (2.5 inch) mark can be seen on the left, and the cross section taken at the 38.1 mm (1.5 inch) mark can be seen on the right.

The areas of significant porosity can be seen in Figure 8. This areas of the deposition showed a significant increase in porosity, which was repeated with every pass and layer. The depth of penetration can be seen to have significantly dropped in this area, indicating a loss of heat input. This suggests that the laser power may have temporarily decrease, due to some unknown issue with the equipment.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

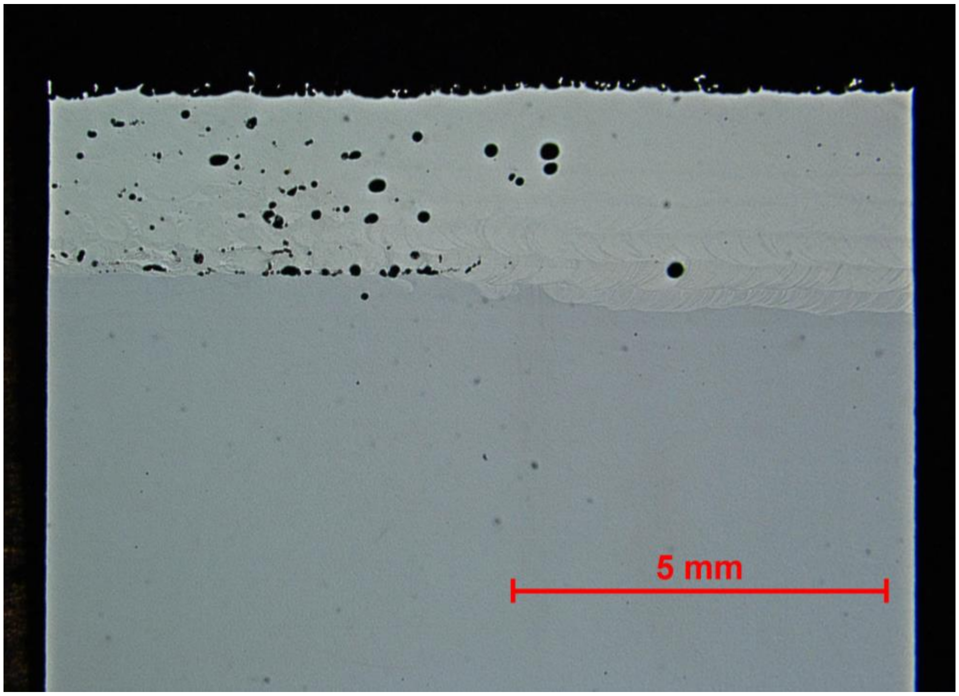

Figure 8: Image of Sample 21 YZ plane cross section. The cross section taken between 25.4 mm to 38.1 mm (1 - 1.5 inch) along the X axis.

1.3 Sample 22 and 23:

Due to the porosity identified in Sample 2 during the initial phase, two longitudinal offset patterns were selected to determine if porosity could be removed with a pattern change while maintaining the lowest amount of surface finish and removal required. Sample 22 was the first modified pattern tested by offsetting each line pass by 0.625 mm (50% of pass width) in the X axis direction for each layer. Sample 22 demonstrated a significant reduction in porosity. Sample 22 demonstrated little variation in deposition height, but had a less consistent width. Inspection of the material's 25.4 mm XZ plane cross section showed no porosity in the core. Inspection of the 50.8 mm XZ plane cross section showed a pore/crack between the second and third line pass and one pore/crack between the third and fourth line pass. See Figure 9.

Sample 22 was sectioned down the length of the deposition and inspected for porosity. Some larger pores were located near the substrate interface, while small pores were located near the top surface. The deposition showed a consistent depth of penetrations and fusion in the YZ-plane specimens.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

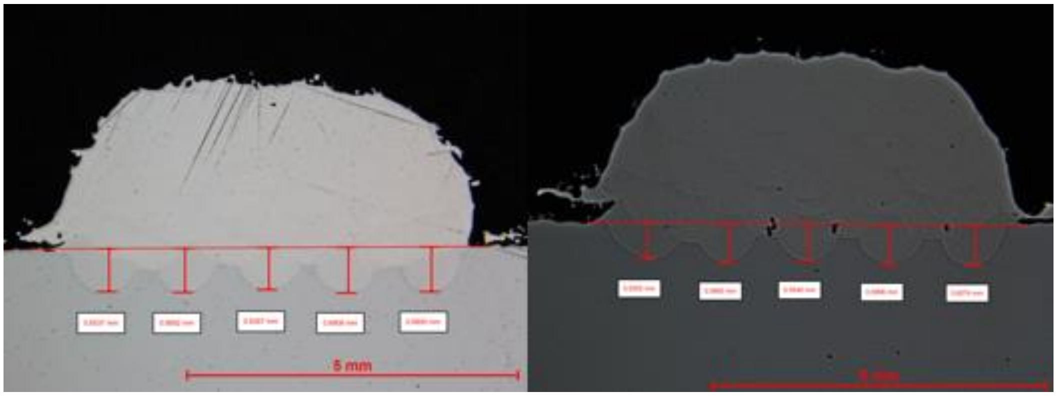

Figure 9: Image of Sample 22 XZ plane cross section. The cross section taken at the 25.4 (1 inch) mark can be seen on the left, and cross section taken at the 50.8 mm (2 inch) mark can be seen on the right.

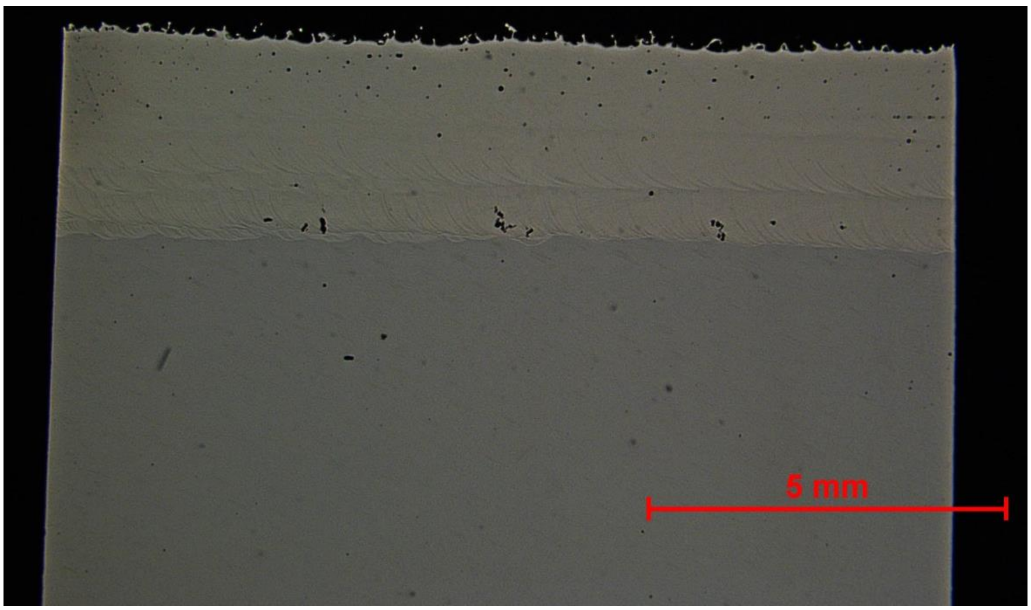

Figure 10: Image of Sample 22 YZ plane cross section. The cross section taken between 25.4 mm to 38.1 mm (1 - 1.5 inch) along the X axis.

The pattern of Sample 23 was further modified from Sample 2 by offsetting the layer passes by roughly 0.42 mm (33.3% of the pass width), as seen in Figure 11. It appeared that a single pore/crack was identified within the core of both the 25.4 mm and 50.8 mm cross section. After evaluating the thickness of the entire deposition, it was concluded that the layer coding of the passes needed to be adjusted to meet the 6 mm thickness requirement set at the beginning of the DOE.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

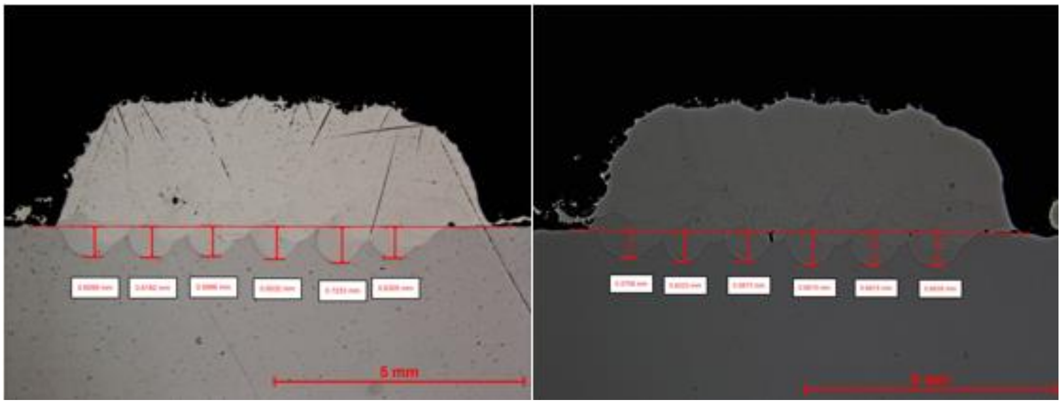

Figure 11: Image of Sample 23 XZ plane cross section. The cross section taken at the 25.4 (1 inch) mark can be seen on the left, and cross section taken at the 50.8 mm (2 inch) mark can be seen on the right.

Minimal porosity was identified with the YZ plane cross sectioned specimens of Sample 23. One large pore can be seen in Figure 12 below, roughly located between the second and third layer. Based on the shape of the pore, it may have formed as a trapped air bubble. Depth of penetration into the substrate material is relatively consistent.

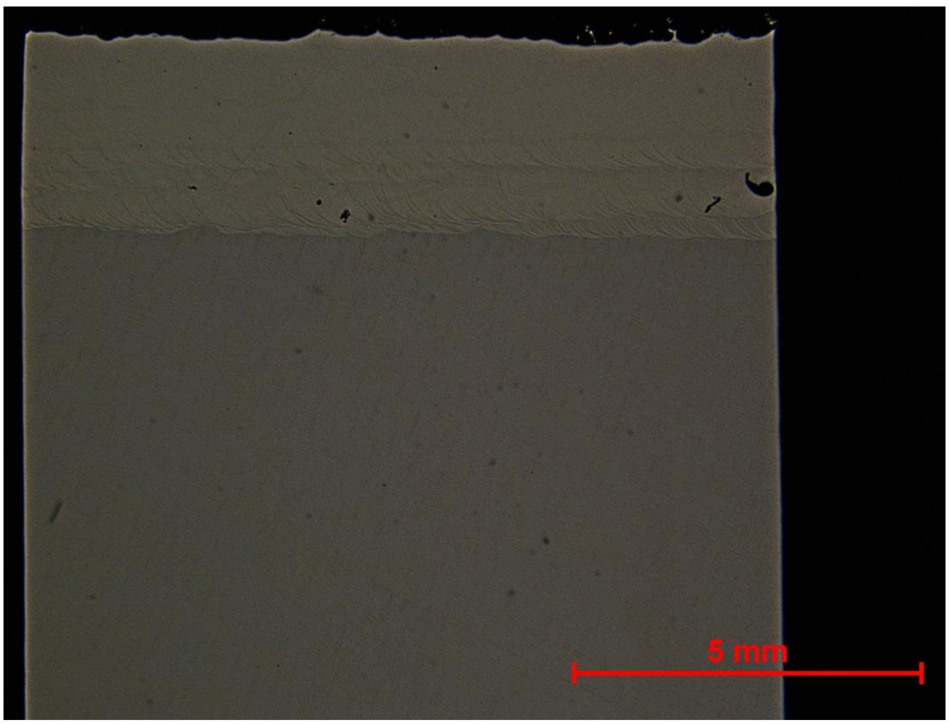

Figure 12: Image of Sample 23 YZ plane cross section. The cross section taken between 25.4 mm to 38.1 mm (1 - 1.5 inch) along the X axis.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

2. Hardness:

Hardness data was collected through the use of a Vickers hardness tester. Both the XZ (perpendicular plane to the longitudinal line passes) and YZ (parallel plane to the line passes) planes were cross sectioned and hardness mapped. The XZ plane cross sectional surfaces were inspected at the 25.4 mm and 50.8 mm mark from the deposition end along the Y axis. The YZ plane cross sectional surfaces were inspected between the 25.4 and 38.1 mm mark, and the 50.8 and 63.5 mm mark from the deposition end along the Y axis.

Table 3 shows the average Vickers hardness values for each of the samples. The deposition hardness averaged between 381 and 404 HV. There was little variation between the deposition XZ plane surfaces and the deposition YZ plane surfaces. Figure 13 uses a color coating system to map the hardness values across the cross sections of the core.

Table 3: Average Vickers hardness mapping measurements of DED XZ and YZ (side) cross sectional planes of the deposition samples. Vickers hardness color table included for Figure 10 below.

	Deposition	Substrate
Sample 19	387	282
Sample 19 side	381	276
Sample 21	400	284
Sample 21 side	404	291
Sample 22	397	280
Sample 22 side	394	278
Sample 23	395	276
Sample 23 side	403	285

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
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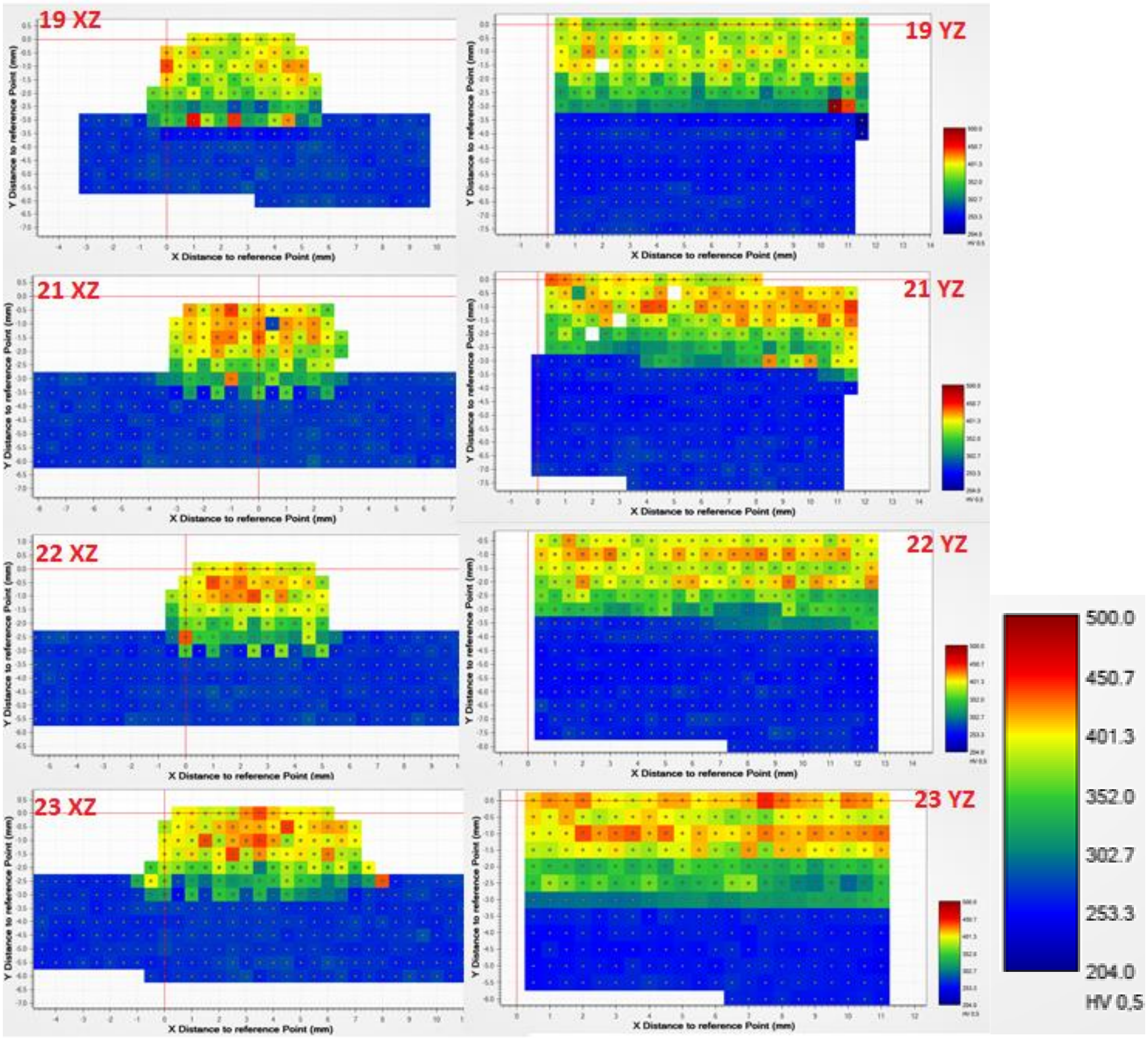

Figure 13: Vickers Hardness mapping of XZ and YZ cross sectioned planes of the DED sample 19, 21, 22, and 23. Each color coating is uniformly scaled to the reference bar

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

Discussion:

This report has provided a baseline to move forward with parameter optimization of the DED technology. After analyzing the cross sectional surfaces for cracks and porosity, it was determined that the geometry of the deposition pattern plays a significant role in the final quality. At the current parameter settings, it would be optimal to move the line spacing closer together. However, observations of the DED process have demonstrated that there is an excessive amount of powder that gets directed away from the melt pool and blown about the chamber. This is an effect of the head moving too far from the work piece, resulting in the powder flow tube coming out of alignment. This also suggests that the parameter settings are too low. By increasing the powder flow and laser intensity, the build rate can be maintained and the time required to build a specimen can be reduced. Otherwise the z off set parameter that dictate how high the head is elevated after each layer would have to be decrease. Which would increase the time it would take to build a specimen.

The patterns from Sample 22 and 23 demonstrated an improved quality on the longitudinal pattern. It is possible that decreasing the line pass spacing to a shorter distance may eliminate porosity further. However, such a reduction would also result in a significant increase in deposition time, as additional passes would be required to maintain the targeted width of the deposition. A decrease in the line pass spacing for Sample 21 did remove the porosity in some areas. However, other areas of the deposition demonstrated a significant increase in porosity throughout the core. It is believed at this point that there may have been some repeating error in the DM3D 405D equipment or system that resulted in this inconsistent quality repeated throughout the entire deposition. Sample 19 also demonstrated a similar inconsistent increase in porosity within certain areas of the core of the deposition.

It should be noted from the provided parameter settings in Table 1 that the powder grain size, powder sieve time, and powder bake time and temperatures had changed from the prior phase. The change in powder grain size was due to the result of the limited amount of supplies allotted for this DOE. It was also discovered after the deposition of Samples 19 through 23 that the amount of powder in stock with a grain size under 45 microns had been incorrectly documented. The remaining available powder had been sieved before use and had a grain size of 45 and 65 microns, which had been used instead. The increased porosity may have been, in part, due to a requirement for an increased amount of energy (which had not been provided) to properly melt the larger Stellite 21 powder.

The change in grain size did not appear to effect the properties of the successfully deposited material itself. The average hardness of the deposition patterns were relatively the same. The Longitudinal/Transverse deposition hardnesses, on average, have a slightly lower hardness than the Longitudinal only patterns by about 10 to 20 HV, roughly equal to a 1 HRC difference. Comparison of the hardnesses from part 1, phase 1 and 2, indicated no differences in material properties as a result of moving the line passes closer together or increasing the powder grain size.

Efforts going forward shall be put in place to further control equipment outputs over the course of a deposition. Such equipment as Infrared (IR) cameras to record the temperature at the melt pool, heated plates to properly preheat test specimens, and other devises that can ensure every parameter is observed so that errors and failures can be identified.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567

Conclusions and Recommendations

Based on the analysis of the produced materials, the following conclusions were made:

1. Analyzing the cross sectional surfaces for cracks and porosity indicated that Sample 22's pattern may be the most effective method for longitudinal patterns, with regards to deposition time.
2. Due to the patterns of grouped porosity and the inconsistence of uniformity in the depositions, the DM3D 405D equipment will likely require a refurbishment and upgrades to provide continued use to TARDEC's additive manufacturing initiatives. The equipment currently lacks a number of necessary functions required to properly monitor and track a deposition's quality and parameters to perform proper fault identification.
3. TARDEC's Material Characterization & Failure Team recommend:
    a. Move forward with the third phase of the DOE.
        i. Start the parameter optimization process by determining the correlation between the powder feed rate (g/min) and laser power (W).
        ii. Develop the optimal parameter requirements to produce a consistent 1 mm layer build rate with a consistent build width.
    b. That the following upgrades and/or modifications be made:
        i. Interfaced deposition data logging software to track deposition parameter outputs during an application to assist in identifying errors and inconsistencies in depositions.
        ii. Upgrade DM3D 405D with Infrared and Optical Cameras to monitor the weld pool temperature, so that the equipment will be able to output the required parameter settings to be useable outside of the TARDEC equipment.
        iii. Obtain S or R type thermocouples and recorder to measure heat transfer in specimen plate. This could be used as a temporary alternative to IR cameras to be applied to the current DOE.
        iv. Obtain particle flow rate sensor to monitor increases or decreases in powder flow during operations.

References:

[1] Toppler, I. J., Schleh, D., and Nikodinovski, M., 2017, "TARDEC Direct Energy Deposition Technical Analysis, Design of Experiments, Part 1, Phase 1," Defense Technical Information Center.

POCs: Ian J. Toppler, Materials Engineer, ian.j.toppler.civ@mail.mil 563.594.8911
Dan Schleh, Mechanical Engineer, daniel.c.schleh.civ@mail.mil 586.282.6567