Registration No.

OPSEC1115

-Technical Report-

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

Ian J. Toppler

Dan Schleh

Michael Nikodinovski

DISTRIBUTION STATEMENT A: Approved for public release; Distribution is unlimited.

1 May 2017

U.S. Army Tank Automotive Research,
Development, and Engineering Center
Detroit Arsenal
Warren, Michigan 48397-5000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
1 May 2017

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*
12-6-2016 - 05-01-2017

4. TITLE AND SUBTITLE
TARDEC Direct Energy Deposition Technical Analysis
Design of Experiments, Part 1, Phase 1

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ian J Toppler
Dan Schleh
Mike Nikodinovski

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Materials Characterization & Failure Analysis Group - U.S. Army TARDEC
6501 E. 11 Mile Road (MS 267), Warren, MI 48397 - 5000

8. PERFORMING ORGANIZATION REPORT NUMBER
OPSEC1115

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
TARDEC Product Life-cycle Engineering Group - Application and Integration Team.

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release; Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
TARDEC Production Lifecycle Engineering (PLE) Group began 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. For this DOE, TARDEC used the DM3D 405D laser deposition equipment. The purpose of this DOE is to evaluate the capabilities of this technology to be used in three areas within the US Army; surface repairs for cracks and wear, surface repair of corrosion damage, and surface coatings for corrosion prevention. A secondary role of this DOE is to evaluate the current state of the DM3D 405D and to determine what upgrades and modifications would be necessary for this equipment to function in a parameter validation role. Three primary parameters were identified in this DOE as having the most significant effects on the quality of a deposition pattern above all others; laser power, powder flow rate, and head feed speed. These parameters have the greatest effects on build height, porosity, fusion, and a wide range of other deposition properties. Since this team conducting the DOE was not provided with any optimal parameter settings or ranges to begin with, this DOE was designed around figuring out how to determine an optimal range for each parameter, and which parameters held the greatest effects over the others for future optimization efforts. Effectively laying the ground work for additional powdered materials to

15. SUBJECT TERMS
Direct Energy Deposition, Additive Manufacturing, Material, Characterization, Failure Analysis, Validation and Qualification of AM

16. SECURITY CLASSIFICATION OF: UNCLASSIFIED			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Ian J Toppler
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	15	**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED			563-594-8911

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

RDTA-SIE-ES-PLE-MCFA Date: 1 May 2017

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

TARDEC Direct Energy Deposition Technical Analysis

Design of Experiments, Part 1, Phase 1

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

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

Michael Nikodinovski
Mechanical Engineer, US ARMY TARDEC
PLE Application & Integration Team

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

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

Abstract

TARDEC Production Lifecycle Engineering (PLE) Group began 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. For this DOE, TARDEC used the DM3D 405D laser deposition equipment. The purpose of this DOE is to evaluate the capabilities of this technology to be used in three areas within the US Army; surface repairs for cracks and wear, surface repair of corrosion damage, and surface coatings for corrosion prevention. A secondary role of this DOE is to evaluate the current state of the DM3D 405D and to determine what upgrades and modifications would be necessary for this equipment to function in a parameter validation role. Three primary parameters were identified in this DOE as having the most significant effects on the quality of a deposition pattern above all others; laser power, powder flow rate, and head feed speed. These parameters have the greatest effects on build height, porosity, fusion, and a wide range of other deposition properties. Since this team conducting the DOE was not provided with any optimal parameter settings or ranges to begin with, this DOE was designed around figuring out how to determine an optimal range for each parameter, and which parameters held the greatest effects over the others for future optimization efforts. Effectively laying the ground work for additional powdered materials to come. This DOE was created with two parts in mind, the first designed to create stable deposition line builds and identifying optimal trends. The second part of the DOE was designed to take the optimal parameter settings developed in the first part, and create standardized specimens to determine material and mechanical properties as they related to the intended function of that specific powder material to be deposited an a specific substrate. Before any of these activities could begin, a fundamental understanding of the DM3D 405D and its available pattern settings was required. This report covers part 1, phase 1, of the DOE. Two deposition lines were made using the two different pattern types provided in the DM3D software. A parameter set used in a prior application was used as a baseline for future depositions. A Military Standard has been developed around this DOE as the framework work for developing a uniform system for validate DED operations within the Army for on-vehicle use.

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

Background

This DOE began in November of 2016 with extensive literature reviews, program planning, and organization of necessary training, support, and equipment to conduct DED operations. The provided DM3D 405D equipment had received minimal use and upkeep prior to the start of this DOE, and required some maintenance from the manufacturer prior to beginning. No optimized parameters or testing had been conducted prior to this DOE and baseline information was unavailable. Within the DM3D software, two types of deposition patterns were available for use. The first deposition was an alternating Longitudinal/Transverse deposition 101.6 mm long and 5 mm wide. A total of six layers were deposited in an alternating fashion so that the deposition paths of each layer crossed each other. The second deposition was a Longitudinal only pattern of the same layers and dimensions. This deposition was deposited so that each of the lines would be placed one on top of the other. Each of these deposition paths were selected to determine the quality of the deposition, using the existing loaded parameters within the DM3D 405D equipment for Stellite 21 powder. The powder was deposited onto an 8 x 15 x 5/8 inch thick ASTM A514 steel plate. Analysis of the deposition build height, width, and depth of penetration were recorded. Hardness measurements were taken via Vickers hardness mapping across the cross sectioned surface of each deposition. Inspection and identification of cracks and porosity in the specimens were conducted using a microscope and scanning electron microscope (SEM).

Results and Observations

1. Visual inspection:

Visual inspection of the deposition can be seen in Figure 1. These depositions were cross sectioned every half inch, from one end to the other, to evaluate the cross sectional layer quality. See Figure 2. The surfaces were polished to a one micron finish, and then etched to evaluate the micro structure and to distinguish between the A514 and Steel interface. It was determined that the Stellite 21 requires a specialty etchant to reveal the microstructure of future depositions. However, this etchant was not available at the time of this report and not required at this point of the evaluations, as only identifying the interface was required.

The second part of the visual inspection was to determine the existence of defects such as cracks, pores, or inclusions within the deposition. In addition, an evaluation of the quality of the deposition paths, depth of penetration, and thickness of heat effected zone into the substrate was conducted. The targeted height of the deposition was 1 mm per layer, for a total of a 6 mm tall six layer deposition. It should be noted that due to the penetration of the deposition, it is assumed that the first and potentially second layer will not meet the 1 mm build height, and will have to be accounted for later in the DOE once an optimal range of the laser power (W) and powder flow rate (g/mm) are determined.

1.1 Longitudinal/Transverse Pattern

As seen in Figure 3, the deposition had a penetration depth of 0.5715 mm (0.0225 inches) from the surface of the A514 substrate. Total height of the deposition was roughly 3.1090 mm (0.1224 inches), including the overall depth of

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

penetration. The height of the deposition from the surface of the substrate to the top of the deposition was 2.7635 mm (0.1088 inches). A close inspection of the surfaces indicated one or two pores near the interface on one of the cross sections, as could be seen via microscopic inspection.

1.2 Longitudinal Pattern

As seen in Figure 4, the deposition had a penetration depth of 0.6452 mm (0.0254 inches) from the surface of the A514 substrate. Total height of the deposition was about 2.3876 mm (0.0940 inches). The surface was further noted to contain porosity between the corners of the deposition passes, as well as within the material between layers. Large pores were documented between the deposition passes.

2. Hardness:

Micro-hardness mapping was conducted with the use of Vickers hardness measurements (HV 0.5). Each deposition cross section was polished to a one micron finish and left unetched to ensure indent visibility. A mapping function was used to inspect the changes across the surface from each deposition, heat effected zone (HAZ), and substrate. Each indent was visually verified after program mapping was complete to ensure data accuracy.

2.1 Longitudinal/Transverse Pattern

In Figure 5 and 6, Vickers hardness data was collected and analyzed to determine the quality of the deposition. The hardness measurements for the deposition were compiled and the average hardness was determined to be 376 HV. The average hardness of the substrate was determined to be 274 HV.

2.2 Longitudinal Pattern

In Figure 7 and 8, Vickers hardness data was collected for the Longitudinal deposition, and the average hardness was determined to be 400 HV. The average hardness of the substrate was determined to be 276 HV.

3. Scanning Electron Microscope (SEM) Analysis:

SEM analysis was conducted and found micro pores in both the Longitudinal/Transverse and Longitudinal depositions. These pores were found to be roughly 25 micrometers in diameter. However, the Longitudinal/Transverse deposition had very few pores in the bulk material of the deposition. See Figure 9. The vast majority of pores were located around the deposition surface (away from the bulk material), which would otherwise be removed during CNC finishing operations.

The micro-pores in the Longitudinal deposition appeared to be in less numbers than the Longitudinal/Transverse deposition, but contained more pores and what appeared to be some inclusions within the bulk of the deposited powder. See Figure 10. This was in addition to the visual pores (Figure 4) already identified by microscopic analysis.

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

4. Energy Dispersive X-Ray Spectroscopy (EDS) / Compositions:

Line scans were conducted across the surface interfaces of each deposition line, as well as some of the defects. The transition from the A514 steel and the Stellite 21 can be identified by the drop in the Fe content and increase in the Cobalt and Chromium, as seen in Figures 11 through 16. A close look at the images on the left of these figures will allow the observer to identify the steel/stellite interface by the slight change in shading.

4.1 Longitudinal/Transverse Pattern

Figures 11 and 12 demonstrated a change in chemical composition as the scanning line crossed the A514/Stellite 21 interface. As can be seen from these images, the surface had little to no defects, and the interface was clearly bonded. Figure 13 shows a line scan of the defects near the deposition surface. Large spikes in carbon are observed, which may be a residual surface coating from polishing medium that was trapped in the pore.

4.2 Longitudinal Pattern

Figures 14, 15, and 16 demonstrate the change in chemical composition as the scanning line crosses the A514/Stellite 21 interface for the Longitudinal deposition. As can be seen from these images, the surface has a large number of defects in the deposition and near the fusion zone of the two materials.

Discussion:

The Longitudinal/Transverse deposition came the closest to passing the porosity requirement. Little porosity was found during microscopic evaluation and only micro pores were found near the surface. The build heights for both depositions were less than half that of the targeted height. Both demonstrated an extensive amount of powder waste on the sides and around the deposition sites. The Longitudinal stacking deposition proved to be a failure in its current configuration. Pores were found to exist between deposition lines and the penetration of the deposition into the substrate was not uniformly achieved for the deposition. This result was expected to some degree, though the experiment was conducted to determine to what extent the Longitudinal deposition would contain porosity. Despite the existence of the pores, the Longitudinal deposition path would provide a faster deposition rate of material and less finishing required. Which would allow for faster turnaround of coatings and repairs. This is due to the top surface of the deposition being more uniformly flat, compared to the Longitudinal/Transverse deposition surface.

The hardness data demonstrated that the deposition path can have an effect on the resulting hardness of the material. This indicates that the properties of a deposition are not isotropic and can be effected by the deposition pattern.

In part 1, phase 2, of the DOE, the deposition patterns will be modified and reattempted. A third line pattern will be applied to see if the Longitudinal deposition can achieve a structure without porosity. The third line pattern will consist of layers of longitudinal lines with each layer slightly offset from the ones above or below it such a manner that the lines should fill in the spaces between the prior layers deposition lines.

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 appendices materials, the following conclusions were made:

1. The Longitudinal/Transverse deposition produced a deposit with no porosity at the interface or within bulk deposition. Small amounts of micro-porosity was identified near the surface, but would otherwise be removed during finishing operations. Surface indents from the pattern suggest a larger amount of material removed during finishing may be required.
2. The longitudinal deposition pattern resulted in failure with numerous pores found within the bulk material and at the interface. This indicates most or all parameter settings are too low to achieve a uniform deposition.
3. The hardness data demonstrated that the deposition path can have an effect on the resulting hardness of the material. It also indicated that properties are directionally dependent, and would require consideration during application selection.
4. TARDEC's Material Characterization & Failure Team recommend:
    a. Moving forward with second phase of depositions by moving the deposition lines close to one another. Reduction of the line spacing within the Longitudinal and longitudinal/transverse layer passes.
    b. Adding an additional Longitudinal deposition consisting of an offset layer pattern. Such that the pass lines in a given layer are placed between the deposited pass lines of the preceding layer.

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

Appendices:

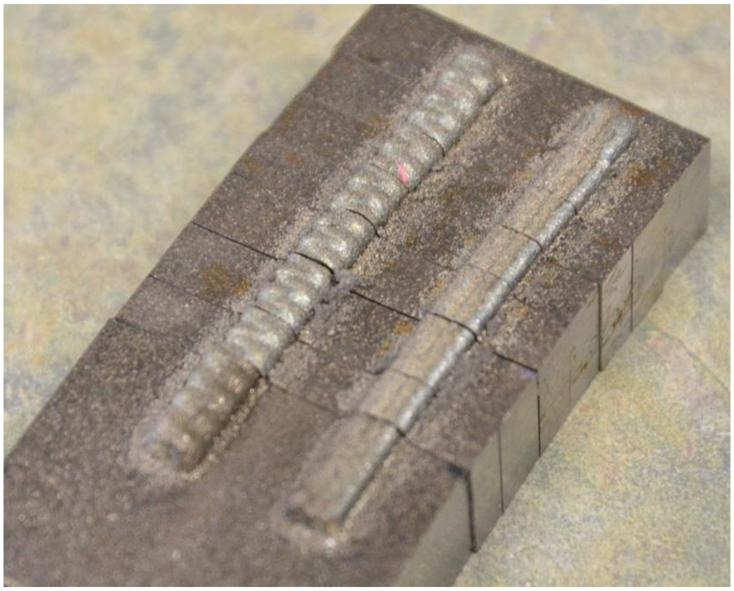

Figure 1: Sectioned deposition lines. On the left can be seen the Longitudinal/Transverse deposition pattern, and on the right Longitudinal deposition pattern.

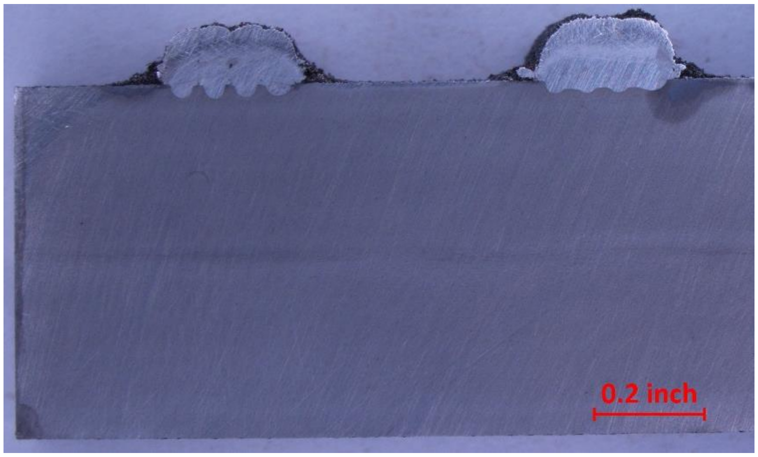

Figure 2: Cross sectioned deposition lines. On the right can be seen the Longitudinal/Transverse deposition pattern, and on the left Longitudinal deposition pattern.

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

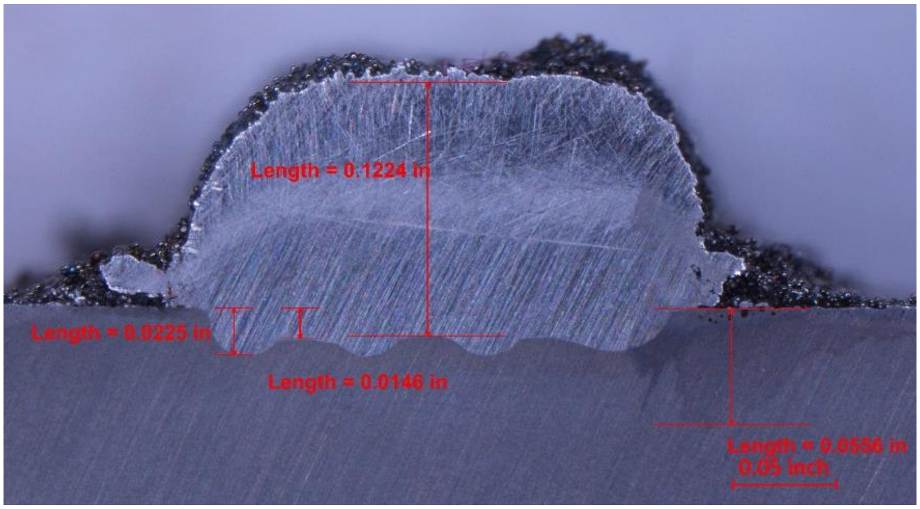

Figure 3: Cross sectioned deposition lines. On the right can be seen the Longitudinal/Transverse deposition pattern, and measurements of the deposition penetration depth and height.

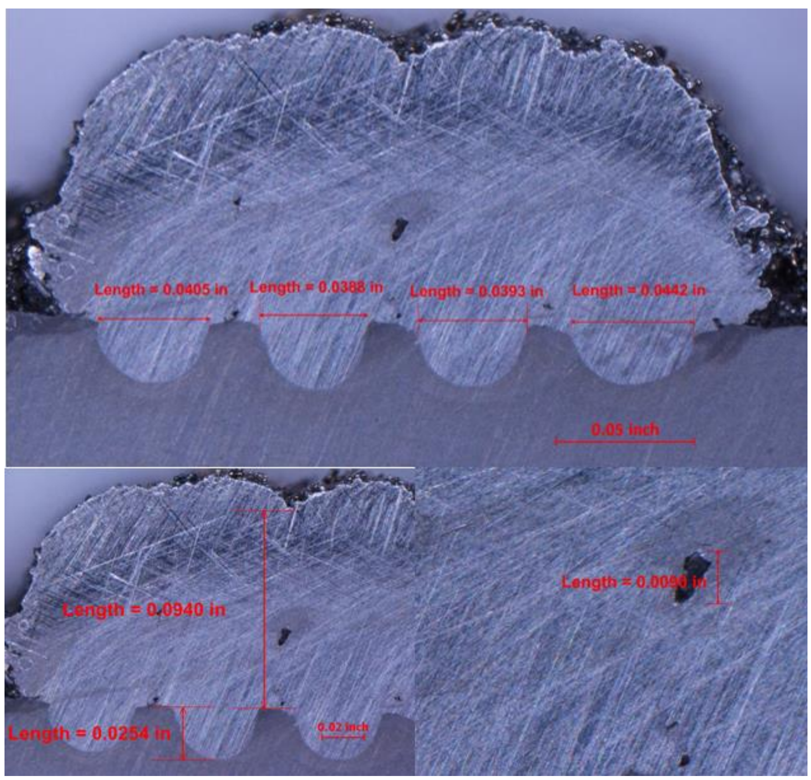

Figure 4: Cross sectioned deposition lines. On the right can be seen the Longitudinal deposition pattern, and measurements of the deposition penetration depth and height.

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

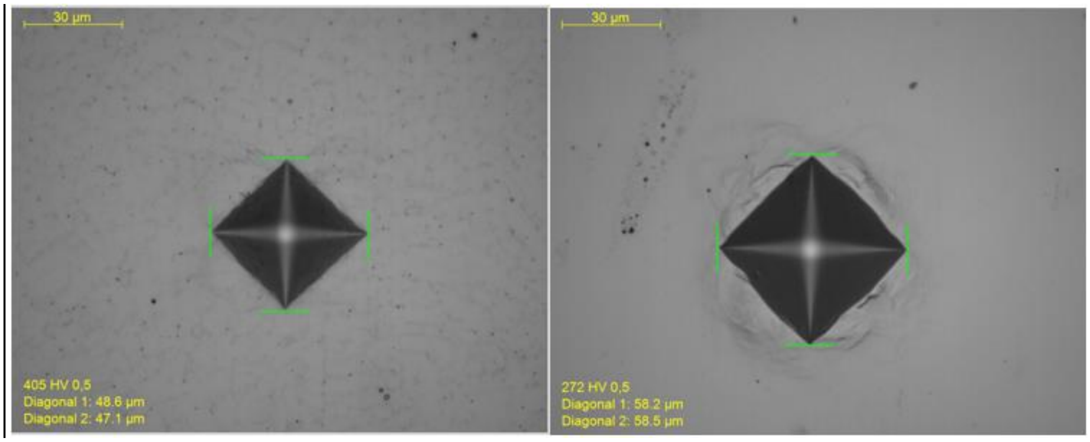

Figure 5: Longitudinal/Transverse deposition indents. On the left is a Vickers indent into the Stellite 21 deposition and on the right is an indent into the A514 steel. Note the difference in hardness of each material.

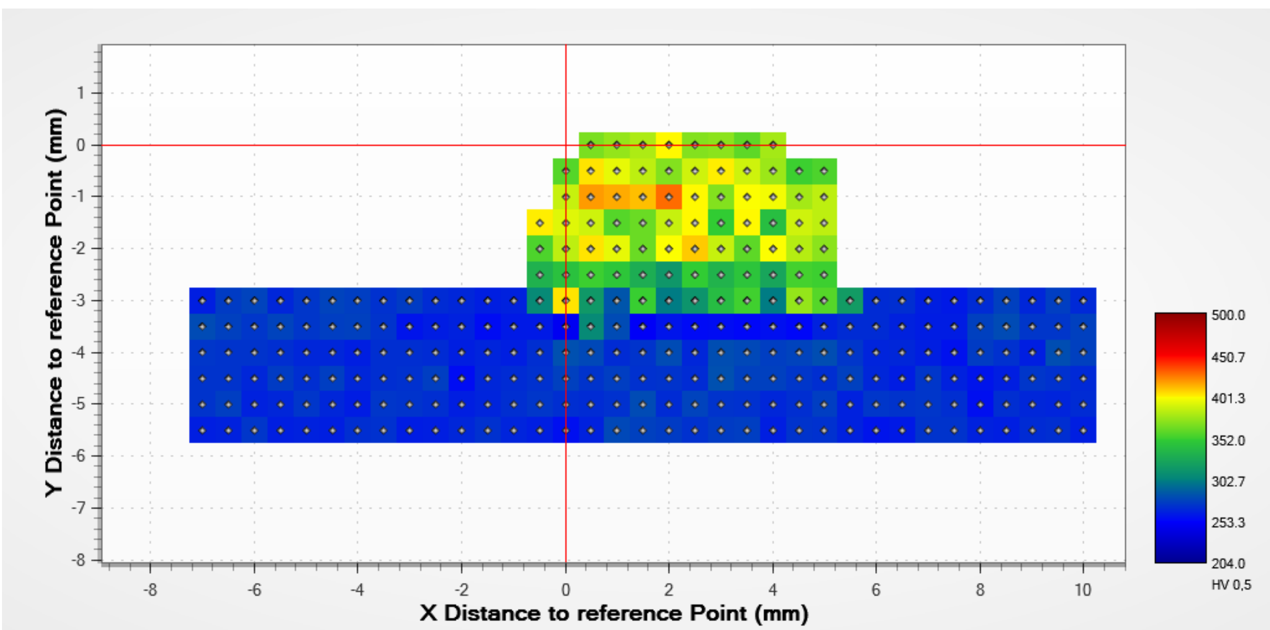

Figure 6: Longitudinal/Transverse deposition hardness mapping of the deposition, interface, and substrate.

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

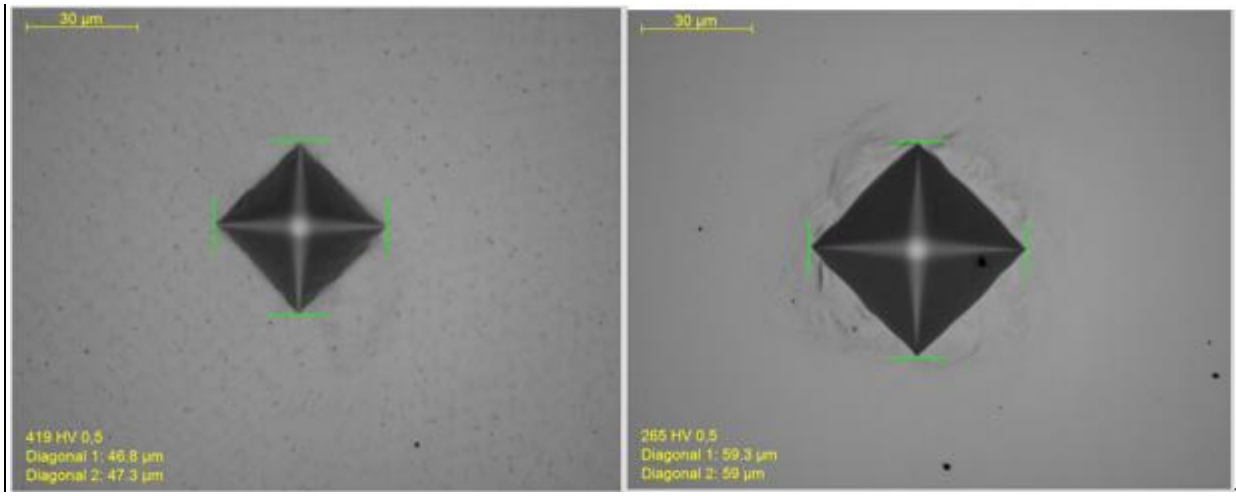

Figure 7: Longitudinal deposition indents. On the left is a Vickers indent into the Stellite 21 deposition and on the right is an indent into the A514 steel. Note the difference in hardness of each material.

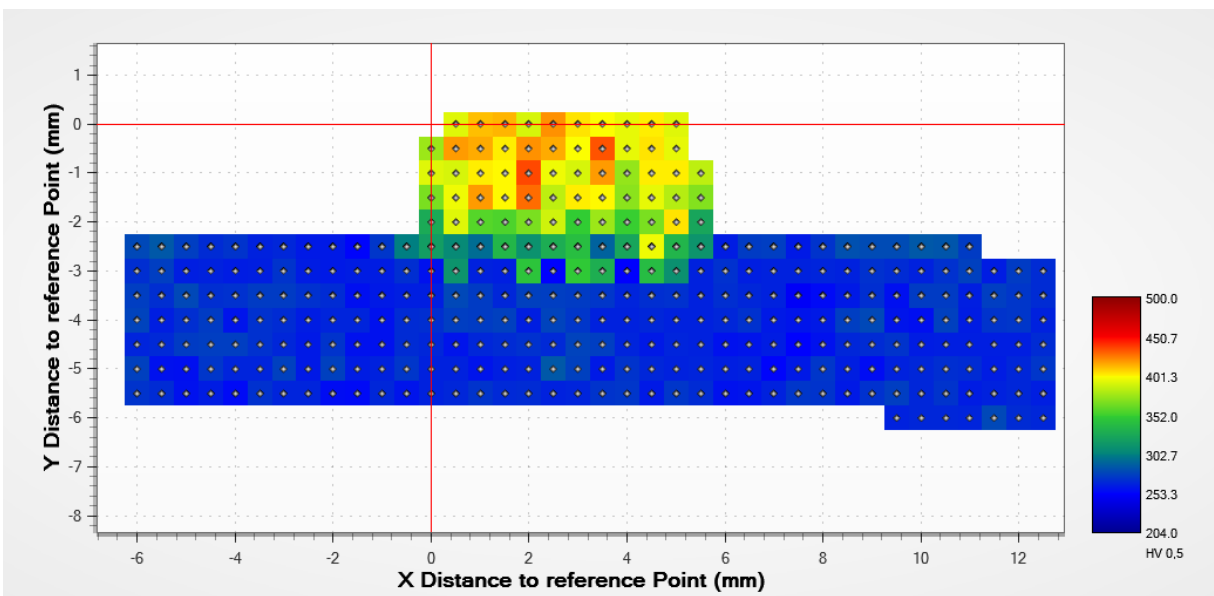

Figure 8: Longitudinal deposition hardness mapping of the deposition, interface, and substrate.

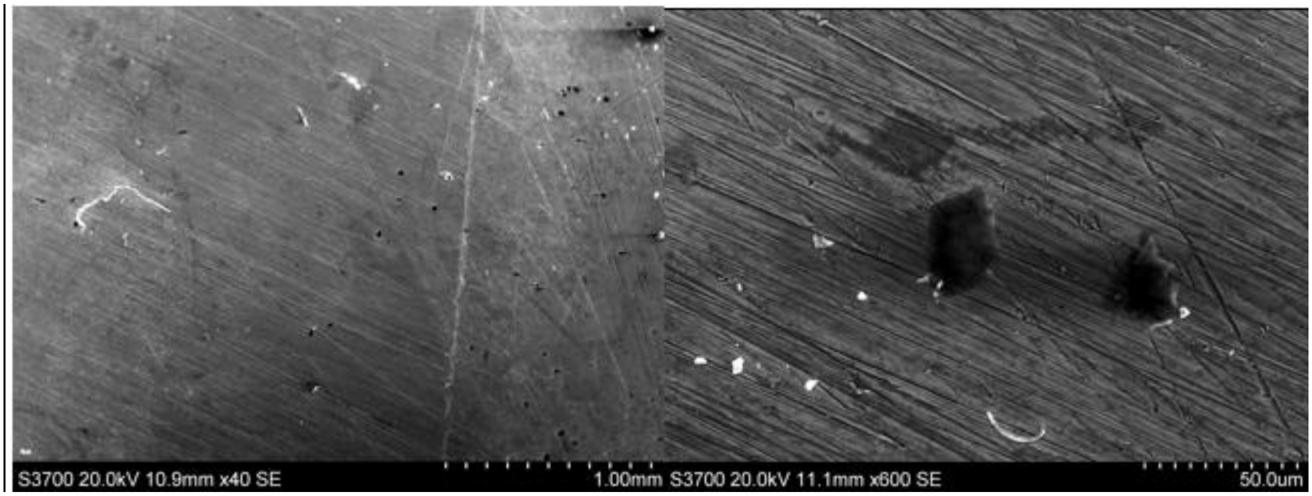

Figure 9: Longitudinal/Transverse deposition SEM imaging of pores and cross sectional surface. The image on the left shows right side of the deposition. The pores located on the right side of the left image are near the surface of the deposition. The image on the right is a close up of two of the pores.

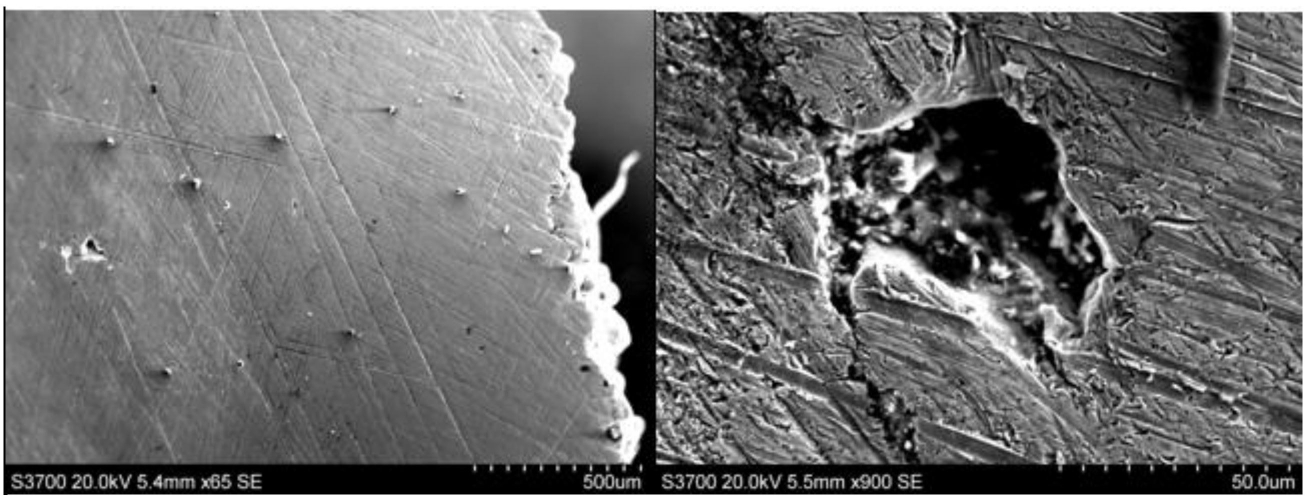

Figure 10: Image on the left is of the Stellite 21 Longitudinal deposition upper right edge SEM imaging of pores and cross sectional surface. The image on the right is of a pore in the core material of the Stellite 21 deposition.

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

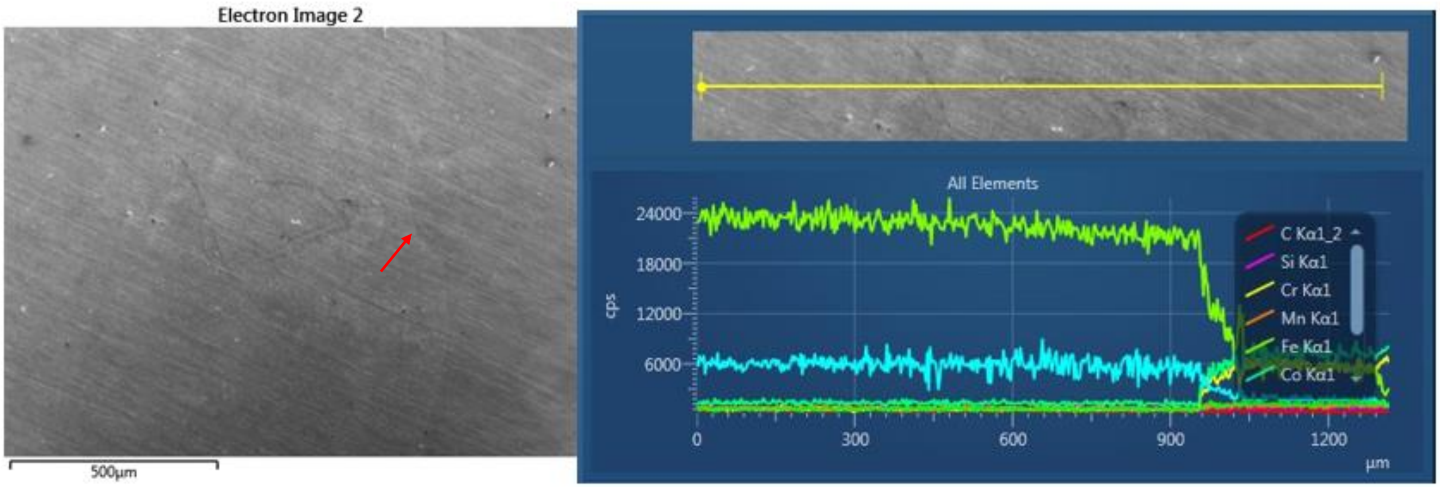

Figure 11: EDS line scans of the Longitudinal/Transverse deposition A514 (on the left)/Stellite 21 (right) chemical analysis.

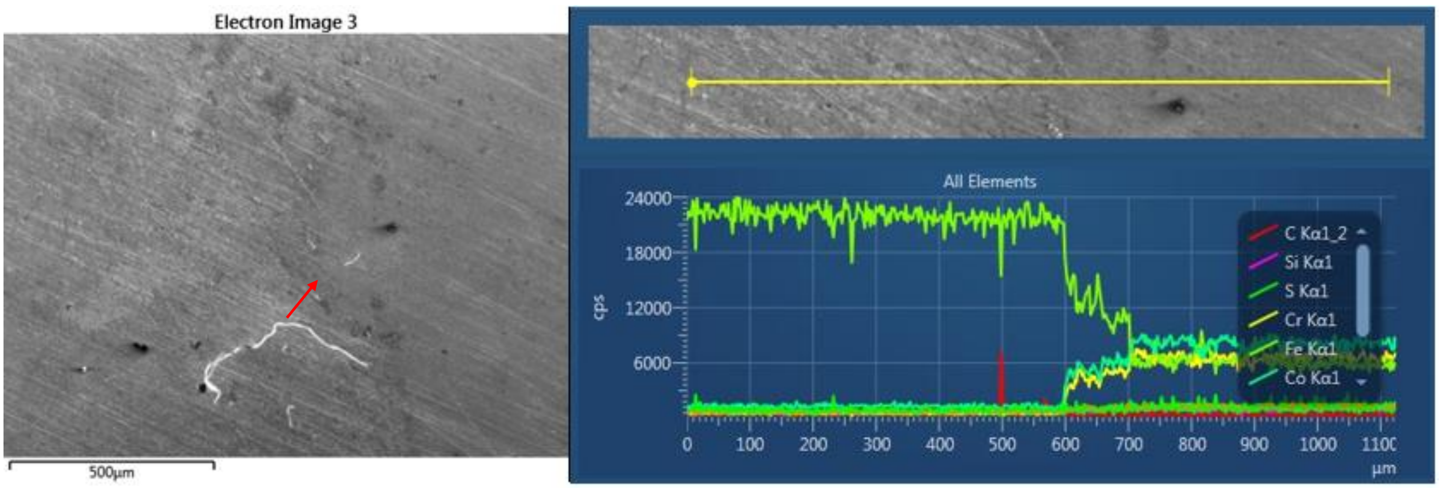

Figure 12: EDS line scans of the Longitudinal/Transverse deposition A514 (on the left)/Stellite 21 (right) chemical analysis.

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

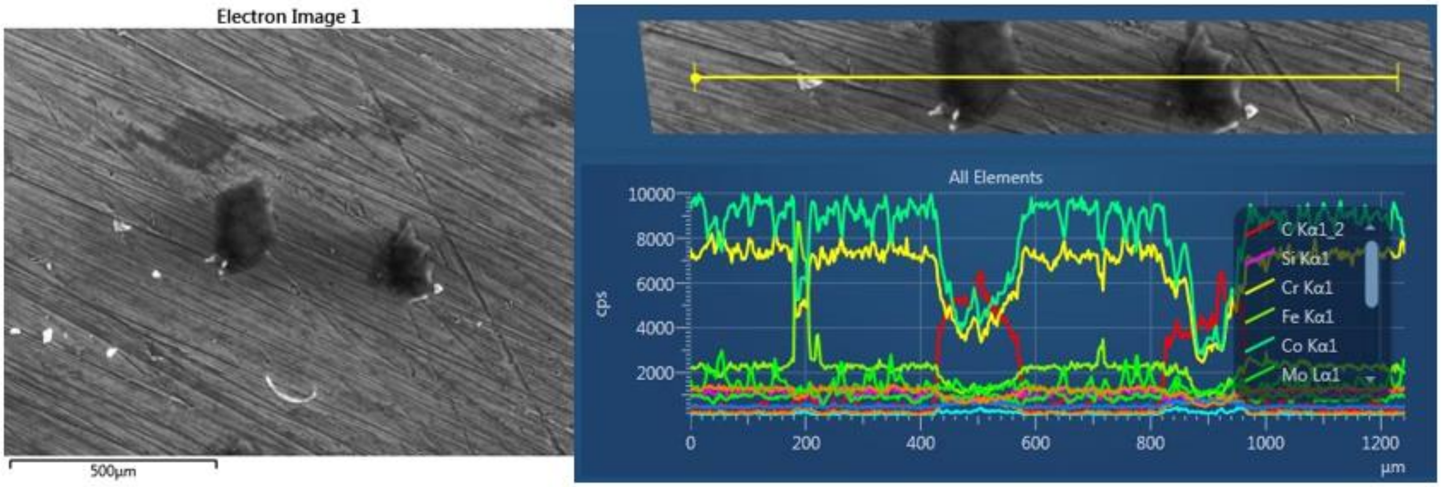

Figure 13: EDS line scans of the Longitudinal/Transverse deposition Stellite 21 (right) chemical analysis near surface pores.

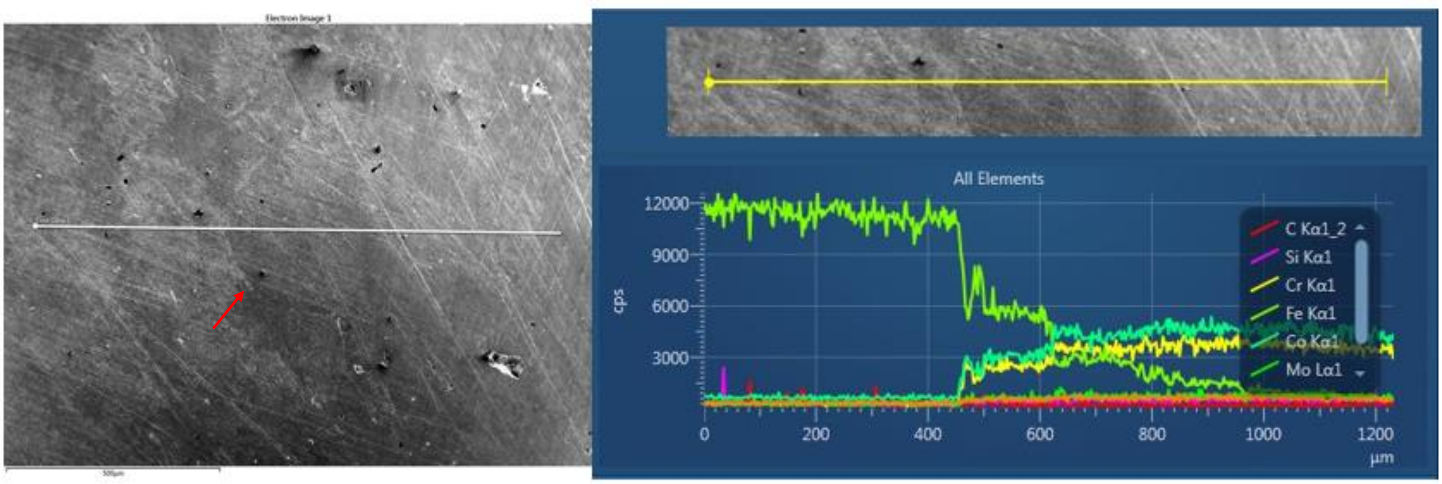

Figure 14: EDS line scans of the Longitudinal deposition A514 (on the left)/Stellite 21 (right) chemical analysis.

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

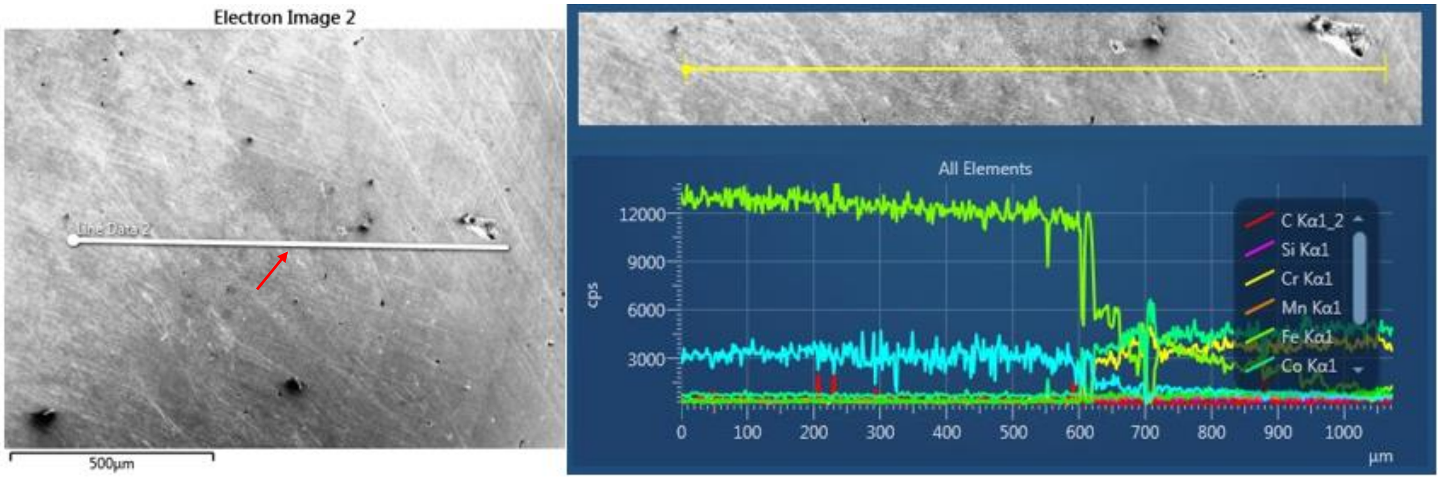

Figure 15: EDS line scans of the Longitudinal deposition A514 (on the left)/Stellite 21 (right) chemical analysis.

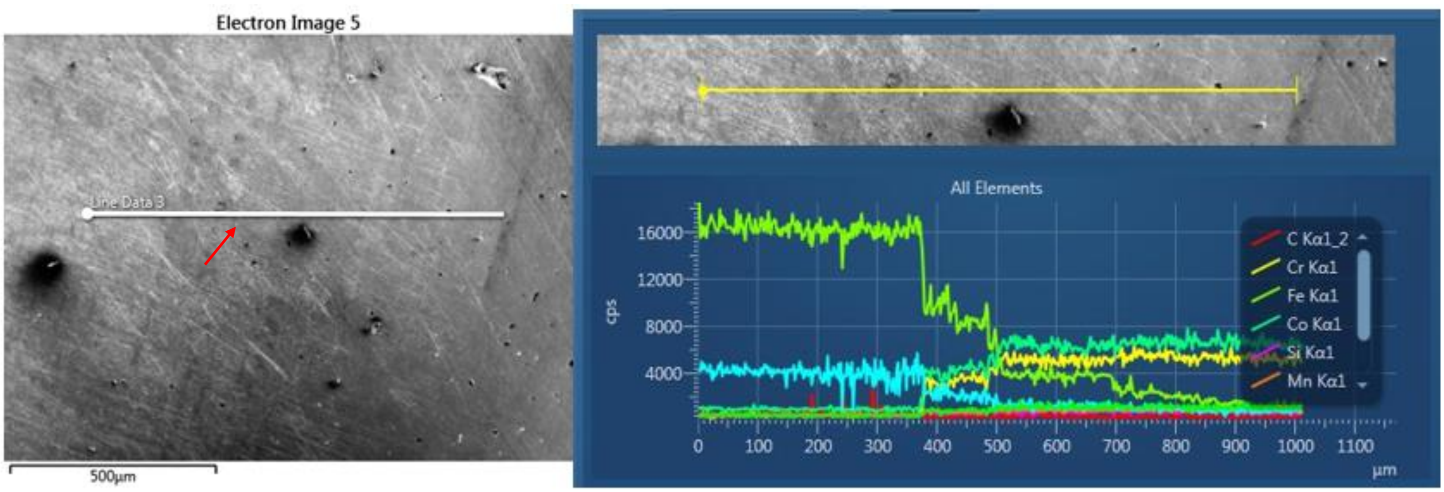

Figure 16: EDS line scans of the Longitudinal deposition A514 (on the left)/Stellite 21 (right) chemical analysis.

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 settings used for part 1, phase 1, of the DED DOE.

Deposition/Sample Number	Trans/Long, Pattern 1	Longitudinal, Pattern 2
Recipe Number	16	17
Powder Material	Stellite 21	Stellite 21
Substrate	A514	A514
Deposition Dimensions	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.
Pass Separation	1.5 mm	1.5 mm
Pattern	Trans/Long. Alternate. Default	Longitudinal Stacked
Head Speed	800 mm/min	800 mm/min
Laser Power Setting	1100 W	1100 W
Layer Step-Up Height	1 mm	1 mm
Grain Sieving	<45 micrometer	<45 micrometer
Ambient Process Temperature	70 °F	70 °F
Ambient Process Humidity	NA	NA
Notes	Baked 1.5hrs @550F	Baked 1.5hrs @550F

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