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Technical Report ARMET-TR-19050

ROUND ROBIN STUDY TO EVALUATE CONSISTENCY OF 4340 STEEL SPECIMENS MANUFACTURED BY DIFFERENT LASER POWDER BED FUSION MACHINES

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May 2022

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT
COMMAND ARMAMENTS CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-01-0188

1. REPORT DATE (DD-MM-YYYY)
May 2022

2. REPORT TYPE
Final

3. DATES COVERED (*From - To)*

4. TITLE AND SUBTITLE

Round Robin Study to Evaluate Consistency of 4340 Steel Specimens Manufactured by Different Laser Powder Bed Fusion Machines

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

Elias Jelis, Matthew Clemente, Michael Hespos, Shana Groeschler, Eli Golden, and Ryan Carpenter

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army DEVCOM AC, METC
Armaments Engineering Analysis & Manufacturing Directorate
Materials & Producibility Division
(FCDD-ACM-AP)
Picatinny Arsenal, NJ 07806-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army DEVCOM AC, ESIC
Knowledge & Process Management Office (FCDD-ACE-K)
Picatinny Arsenal, NJ 07806-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Technical Report ARMET-TR-19050

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army is evaluating metal additive manufacturing as a next generation technology to enhance capabilities. To exploit the full benefits of this technology, challenges have to be overcome in terms of the manufacturing maturity for part qualification and certification. The U.S. Army Combat Capabilities Development Command Armaments Center [formerly known as the Armament Research, Development and Engineering Center (ARDEC)] located at Picatinny Arsenal, NJ, conducted a round robin build demonstration of Laser-Powder Bed Fusion (L-PBF) using 4340 steel. Six participants took part in the round robin, with equipment including the EOSINT M270, EOSINT M280, 3D Systems ProX 300, and SLM 280. Round robin builds consisted of tensile specimens in the horizontal (XY) and vertical (Z) orientations in the four corners and center location of the build platform, metallurgical cubes at each location, and a K_{IC} fracture toughness specimen in the center. The built specimens were heat treated and machined to appropriate specifications. The mechanical property test results were analyzed as a function of build plate location and orientation across a series of L-PBF machines. Statistical analysis was then used to detect data relationships and general trends.

15. SUBJECT TERMS

Additive manufacturing 4340 Laser-powder bed fusion Round robin Tensile testing Steel

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE
U	U	U

17. LIMITATION OF ABSTRACT
SAR

18. NUMBER OF PAGES
99

19a. NAME OF RESPONSIBLE PERSON
Matthew Clemente

19b. TELEPHONE NUMBER (Include area code) (973) 724-6534

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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ACKNOWLEDGMENTS

The U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ, would like to thank the participants of this study. In no specific order, these are Quad City Manufacturing Laboratory, Rock Island Arsenal, IL, Imperial Machine & Tool Co., Columbia, NJ, Pennsylvania State Applied Research Laboratory, University Park, PA, U.S. Army Research Laboratory, Adelphi, MD, and the National Institute of Standards and Testing, Gaithersburg, MD. Additional thanks to Stacey Clark from the U.S. Army DEVCOM Combat, Control, Communications, Computers, Cyber, Intelligence, Surveillance, and Reconnaissance (C5ISR), Aberdeen Proving Ground, MD, for guidance, as well as the U.S. Army Manufacturing Technology (MANTECH) office, Aberdeen Proving Ground, MD, for program support.

INTRODUCTION

The U.S. Army has a strong interest in developing its additive manufacturing (AM) capabilities. This AM has the potential to build functional weapon components with complex geometries that are not achievable with traditional manufacturing processes. Current AM activities include part redesign to reduce overall part count and decrease weight while maintaining structural integrity through topology optimization as well as direct part replacement. Topology optimization is a method used to place material in an optimal manner as determined mathematically based on load conditions, boundary constraints, and other design criteria. These processes will improve efficiency and reduce the logistics burden. Direct metal laser sintering (DMLS), a method of AM, is a laser-powder bed fusion (L-PBF) process in which a high power laser (200 to 1500 W) fuses metal powder layer by layer until the final part is built. The fused region is defined via a digital model produced through computer-aided design (CAD) software, but it can also be defined through scan data and other reverse engineering techniques. The thin powder layer thickness used for L-PBF, 20 to 50 µm, in contrast to the 50 to 75 µm seen in electron beam melting (EBM or E-PBF), and fine powder size, 10 to 60 µm, as opposed to the 45 to 106 µm in EBM, allow this process to manufacture parts with finer details and less rough surface finishes (i.e., features as thin as 0.016 in. and finishes of Ra ~8.75 µm). The U.S. Army has a variety of weapon components made from 4340 steel, making L-PBF fabrication of 4340 steel parts of particular interest to the Army (ref. 1).

The 4340 grade steel is a nickel-chromium-molybdenum low-alloy steel used in a variety of military and industrial applications. The 4340 can achieve high strength or high toughness depending on the tempering temperature. It also exhibits good fatigue resistance. The chemistry of 4340 is favorable for AM because it does not contain elements which easily acquire oxygen and form oxide inclusions. The 4340 steel AM components can be produced with mechanical properties similar to wrought by controlling the tramp elements in the powder feedstock and by optimizing the L-PBF process parameters (ref. 2). Extensive studies were conducted to develop the process parameters for L-PBF of 4340 (refs. 1 and 3). These studies involved a design of experiments that led to a down-select of parameters based on mechanical test results.

As an extension of this process parameter investigation of 4340 steel, a round robin study was conducted to evaluate the mechanical property variability that can occur on similar and dissimilar L-PBF machines. Collaborative studies, such as this one, are regularly used to help mature the technology of the AM process by identifying sources of variability and establishing standards for defining the key process parameters and qualifying a manufacturing plan. Studies of this nature also help in reducing the cost burden of obtaining larger data sets by spreading the cost of manufacturing among the participants. All machines included in this round robin study used virgin feed stock. The process parameters for this study were developed on EOS M270. On similar machines, no changes to the recommended process parameters were necessary. On dissimilar machines, some process parameters were adapted to start the build and to increase the likelihood of successful completion. The variability of the specimens built in this study was quantified by examining a variety of bulk properties, including tensile strength, density, hardness, fracture toughness, and microstructure. Statistical analysis was then used to detect data relationships and general trends.

BACKGROUND

Several round robin studies have been conducted to advance the AM process maturity by helping to characterize the AM technology, both develop standards for AM materials and process specifications, and define best practices for conducting AM round robin studies. The National Institute of Standards and Technology (NIST) has played a significant role in developing AM round robin protocols (ref. 4). Aside from participating in several round robin efforts (ref. 5), researchers at NIST conducted their own in-house studies to gain insights that can be applied to AM round robin studies overall (ref. 4). The NIST found that while individual machines produced relatively consistent results, the variability between machines was significant. The NIST also emphasized the importance of collecting the salient characteristics of each machine and process parameters to evaluate the sources of inconsistency. In addition, the NIST recommended that machine performance testing and standardized calibration be included in the round robin study. Other AM round robin studies include a study of Inconel 625 specimens manufactured by L-PBF (ref. 5), which also found inconsistency in mechanical properties between laboratories. Among NIST's conclusions was that because of differences between machines, the manufacturing plan needs to be either universal for any machine or specific for each machine. The NIST also encouraged participation from many laboratories to obtain consistent results for statistical analysis.

In the interest of saving time and money, nearly all of the round robin studies discussed in the previous paragraph focused on mechanical properties of specimens built in the XY plane, flat on the build plate. However, this round robin measured the anisotropy resulting from the XY plane and in the Z plane, perpendicular to the build plate. This study was performed using the smallest specimen deemed acceptable, 0.160-in. diameter, while targeting a build time of under 48 hr. This approach was taken to reduce the cost in the feed stock distributed to participating laboratories as well as reduce the time burden on the equipment in use.

Development of Process Parameters

Prior work done in the development of 4340 steel for L-PBF was leveraged in this round robin study. Work originally began by determining powder characteristics suitable for L-PBF. Tests were conducted with a variety 4340 powders of different particle size distributions. Next, a systematic array of process parameters was used to produce a series of test specimens, which were then heat treated. The 4340 steel at nominally 50 Rockwell Scale C (HRC) was chosen because this material's ductility is known to be sensitive to process variations. For example, 4340 at 50 HRC is employed in the American Society for Testing and Materials (ASTM) F519 (ref. 6) test to determine if a coating process imparts too much hydrogen into parts making them susceptible to embrittlement. Process parameters (ref. 2) were selected based on metallography cubes with minimal porosity and no cracking. Then, tensile specimens were built and tested to validate the parameters. The results, shown in table 1, were comparable to wrought in the XY and Z orientations after heat treatment. Next, four verification builds were conducted to evaluate the repeatability of the L-PBF process. The material properties of the verification builds, as seen in table 2, were also comparable to wrought and confirmed the repeatability of the process (ref. 1).

Table 1
L-PBF and wrought 4340 steel strength from evaluation builds

	Yield strength (ksi)	Tensile strength (ksi)	Elongation (%)
Typical wrought properties	220	270	11
Heat treated (Z)	224-227	272-274	12-14
Heat treated (XY)	227-229	275-277	12-14

Table 2
L-PBF 4340 steel, quenched, and tempered, XY and Z orientations for the four verification builds

Sample description	Yield strength (ksi)	Tensile strength (ksi)	Elongation (%)	Standard deviation of percent elongation (%)	Relative standard deviation of percent elongation (%)
Typical wrought	220	270	11	N/A	N/A
Overall Z average	222	281	10.2	1.4	14.1
Overall X-Y average	223	283	11.6	1.0	8.6

Procuring a Lot of Qualified Powder

Feedstock became a concern when deciding on the round robin test plate layout. Original concepts involved lengthy builds with larger geometries. The test plate layout ultimately selected minimized the amount of specimens necessary to study the effects of multiple machines and specimen location. A new lot of 4340 powder was purchased. However, the tensile test results from builds with the new lot of powder had approximately double the standard deviation than from builds produced previously with the original lot. At the time, this variability was deemed unacceptable. The intent of qualifying the powder was to make the feedstock a control and not a variable so the differences between machines could be more easily measured.

Machine maintenance and performance were investigated and ruled out as likely factors of the anomaly. As a variety of possibilities were eliminated, the powder was reexamined. It was discovered that the inconsistent mechanical properties were caused at least in part by the phosphorus content in the feedstock. This second lot of powder was at the high end of the specification limit (0.02%). Based on experience with wrought 4340, the 0.02% phosphorus in the powder was within the American Iron and Steel Institute (AISI) 4340 chemistry limits but would cause embrittlement by segregating at the grain boundaries during austenization. In addition, 0.017% phosphorus powder consolidated via L-PBF increases the likelihood of cracking when building large parts. Therefore, the SAE AMS 6414 (ref. 7) chemistry specification was used to procure the next lot of powder. SAE AMS 6414 is a vacuum arc, remelted wrought product. Instead of vacuum melting, the feedstock charge in the atomization furnace was controlled so that the tramp element concentrations would conform to AMS 6414. Maintaining that level of cleanliness assures improved toughness, especially at cold temperatures. Z-oriented tensile specimens were built and tested to qualify this cleaner powder and these tensile specimens produced acceptable results. This qualification procedure ensured that the powder feedstock was of sufficient quality to not adversely affect mechanical properties. This allowed the round robin study to focus on the effects of different machines as well as specimen location and orientation.

Effect of Different Machines

Differences between machines, such as build methodology and internal component design, can be a source of variations in the mechanical properties. The selection of machines for this study was based on certain criteria, which will be discussed later in the experimental section. The machines that were selected included different recoater systems, laser beam power, laser diameter, and scan strategy. Table 3 shows the fundamental differences among this group of machines. The effects of selected differences are discussed in the following subsection.

Table 3
Fundamental machine differences among participants

	Recoater system	Recoater material	Recoating direction	Was beam diameter adjusted	Maximum laser power	Scan strategy	Scan-rot.	Chamber gas	Gas flow	Build plate preheating
EOSINT M270	Blade	Ceramic	Right to left	Yes	200 W	Stripe	67	N_2	2.05 V	80 °C
EOSINT M280	Blade	Ceramic	Right to left	Yes	400 W	Stripe	67	N_2	2.05 V	80 °C
SLM 280	Blade	Rubber	Back to front (bi-directional)	No	400 W	Stripe	67	Ar	12 mbar and 60% pump speed	80 °C
ProX 300	Roller	Steel with a coating	Left to right (compression right to left)	No	500 W	Hexagonal	45	N_2	15 L/min	50 °C

Recoating Processes

A major difference between the machines is the recoating process. This includes recoater blade geometry and stiffness (soft and hard), speed, dosing, and post-packing. Dissimilarities in the recoater blade affect the interactions (i.e., frictional forces) with the powder layer. The powder packing may be significantly different depending on the recoating system. The recoating parameters (i.e., travel speed) may need to be optimized for sufficient particle packing of each powder layer. Since machines from different original equipment manufacturers (OEM) have different powder feed parameters, they would need to determine the amount of powder required to coat each layer so that they have enough powder to complete the job. The machines used in this round robin had three unique styles of recoating.

The EOS M270 and M280 have a hard recoater system. These machines use a ceramic blade that starts on the operator's left side. Once the melting of a layer is complete, the build platform and the powder dispensing platform drop 1 mm. Operators can set how low the dispensing platform goes, but the default is 1 mm. The recoater arm then moves from the operator's left to the right of the build chamber; the speed can be adjusted, but the default is 500 mm/s. Both platforms then rise to the appropriate heights, and the arm recoats the build area by moving to the operator's left. This speed can also be adjusted, but the default is 80 mm/s. It takes approximately 11 sec between layers.

The SLM 280 has a bi-directional soft recoating system that utilizes a distribution unit. After sieving, powder is sent to the distribution unit. This unit portions the amount of powder needed for each layer. The recoater then dispenses this powder in front of or behind the soft recoater blade depending on whether it is at the back or front of the build. It takes approximately 8 sec between layers.

The ProX 300 has a roller compression style recoating system. This system spreads, smooths, and compacts the powder. These are all adjustable by the operator and vary depending on the powder characteristics. While the layer starts, the scraper on the layering module carries powder from the feeding piston. Once the layer is finished melting, the module then spreads the powder across the layer. A roller then smooths and compacts the powder. It takes approximately 10 sec between layers. There is a roller cleaner that allows the roller to clean itself when the proper sequence is executed.

These differences in recoating methods show that the top region of the part will retain more heat in the SLM 280 machine due to the reduction in the amount of cooling time between layers. The increase in heat retention will result in differences in the local part microstructure and hardness. According to previous studies (ref. 1), areas of a L-PBF 4340 cylinder with a shorter cooling time had a 2 to 3-HRC lower hardness versus regions of longer cooling time.

Scan Strategies

The scan strategy used for this round robin was a stripe approach. This approach has the laser scan in tight parallel lines. Each line is the opposite direction of the one before it. This will produce a stripe geometry that runs perpendicular to the scan directions. This cannot be done on the ProX 300. Instead, the ProX 300 builds each cross section as a pattern of hexagon islands. A hexagonal island scan strategy alters the direction of thermal stress within each hexagon, and, as a result, it can reduce thermal stress in the part. However, an island scan strategy (i.e., checkerboard, hexagonal) takes a longer time to build in comparison to the same component built using a stripe scan strategy. So, while some machines may take longer to complete a build, in part due to the scan strategy, this may result in lower residual stresses and less susceptibility to cracking.

Condensate Removal Methods

Inert gas flow removes condensate from the build chamber. Gas flow parameters are not transferable between machines from different OEMs due to gas flow supply and return locations. Optimizing the gas flow parameters for each OEM is important because inadequate condensate removal from the build area will result in product defects (ref. 8). If the gas flow is inadequate, then condensate particles land on the part and disturb the melt pool or interact with the laser beam (ref. 8). If the gas flow is too high, then it could disturb the powder layer and produce a nonuniform layer. Also, machines of the same model can have different machine architecture. For example, older M270 machine models have a smaller filter box inlet hose versus the dual mode EOSINT M270.

The EOS M270 has a recirculating filter box attached to the build chamber with tubing. This evacuates condensate out the top right corner of the build chamber. Additionally, there is a ring of airflow that comes out from around the lens in order to keep condensate from landing on it.

The EOS M280 has an improved gas flow system from the M270. The M280 has a diffuser nozzle in the upper-middle rear of the build chamber. This nozzle blows 40% of the gas flow from the rear wall. The remaining 60% of gas flow is blown from the rear of the build area just above it. This creates an air knife across the build area. All gas flow is exhausted through a nozzle at the front of the build area.

The SLM 280 creates an air knife above the build area that blows from right to left. This allows for a rapid removal of condensate across the build area. It is recommended that parts are melted from left to right to improve process performance because of this air flow. However, in this study, the test plate was to be sintered from right to left along the build plate.

The ProX 300 has a fume cleaner device located above the area between the feeding and sintering pistons. This device has a suction tube on the left of the sintering piston. The blower is between the airlock door and the collecting tank. There is also a lens cleaner and trap. This creates a gas flow on the underside of the lens trap.

Laser Beam Parameters

The laser beam diameter was not uniform for this study either. Different laser beam diameters produce variation in local melt pool size and geometry, affecting bulk properties. Other laser parameters (i.e., laser power, laser scan speed, and vector overlap) need to be properly adjusted to produce fully dense parts.

Layer thickness affects the energy density going into the melting process. Energy density is represented with the following equation:

$$E = \frac{P}{t \times v \times d} \tag{1}$$

E is the volumetric applied energy density in Joules per mm^3, P is laser power in Watts, t is layer thickness in mm, d is hatch distance in mm, and v is laser scan speed in mm/s (ref. 2). While this equation does not capture the entire process, it is used as a baseline for comparison of parameters. In this study, all but one participant built their test plates with 0.020-mm layers. Build 3, however, had 0.030-mm layers. This increase in layer thickness not only reduces energy density, but it also decreases the energy applied to the underlying solidified metal. During the L-PBF process, the laser will not only melt the current layer but two to three layers preceding it. The volumetric energy density is a good approximation for the amount of energy input into the powder bed, but it does not account for concentration of laser beam energy. Also, the required laser energy to produce a part to full density is not known as a particular function of build plate temperature related to layer thickness.

The manufacturing plan described in the experimental section following had to be versatile enough to accommodate these machine differences and yet be specific enough to limit variations. Some adaptations to the process parameters were necessary.

EXPERIMENTAL PROCESS

The objective of the 4340 round robin study was to control, as much as possible, the processing variables and to fabricate specimens in different laboratories on various L-PBF machines in order to investigate the effect on mechanical properties. All powder came from a single vendor in a single production run. Data was collected from nine builds with four different models of L-PBF machines from six laboratories. All builds were fabricated using the developed test configuration.

Participant Selection

An initial questionnaire was sent out to candidates to identify participants for the study. This questionnaire is referenced in appendix A. Five qualified facilities agreed to participate alongside the principal investigators. The questionnaire sought to identify the variability in software, hardware, and whether the participant’s facilities could meet the needs of the study. Modification of machine process parameters was a critical requirement for this study. Parameters included, but were not limited to: laser power, layer thickness, beam diameter, and laser scan speed. The ability to modify process parameters was necessary because 4340 is not a qualified material offered by machine manufacturers. Participants included academia, government, and private industry.

Manufacturing Plan Description

Build and Machine Data

A manufacturing plan describing the procedures, processes, and materials for building with 4340 steel powder was distributed to the participants, shown in appendix B. The plan included information such as background on the study and how the plan would be carried out. The goal was for the participants to follow the manufacturing plan as closely as possible in order to minimize variability. Some variability was unavoidable since the process parameters needed to be adapted to different platforms.

Each participant was sent 55 kg of virgin 4340 powder. Glass vials were provided to acquire powder samples, as instructed by the manufacturing guide, before and after the build. The required build files and a data schema to be filled out with machine and build details were sent digitally.

The data schema requested the participants to record a series of data about their machine and build conditions. The hours on the laser and filters were of particular interest in investigation of potential sources for property variation. The schema also captured machine make and model, build plate material, and any issues that occurred during the build such as failed attempts, recoveries, power outages, and any other anomalies. The issues and anomalies will be discussed at length in later sections.

Test Plate

Participants were required to complete one build of the test plate. Each test plate consisted of five clusters: the four corners and the center. The XY and Z orientations were evaluated with tensile specimens at all five locations. The K_{IC} specimens were only in the center (location 3) and not the four corners. Each specimen was built with a two-digit label: the first digit represents the build number (0 through 8), and the second digit represents location (A through Z, then 1 through 9). Three specimens were tested for each condition. In total, the test plate consists of five metallurgical cubes, five rectangular blocks (to be machined into 15 XY-oriented specimens), 15 Z-oriented cylindrical specimens, and a fracture toughness block (to be machined into three K_{IC} specimens). Builds were completed on plates at least 1.5 in. thick. The XY-oriented specimens were labeled from furthest from the build plate to closest. That is, the tensile specimen “D” was on top of the horizontal block. A top and angled view can be seen in figure 1.

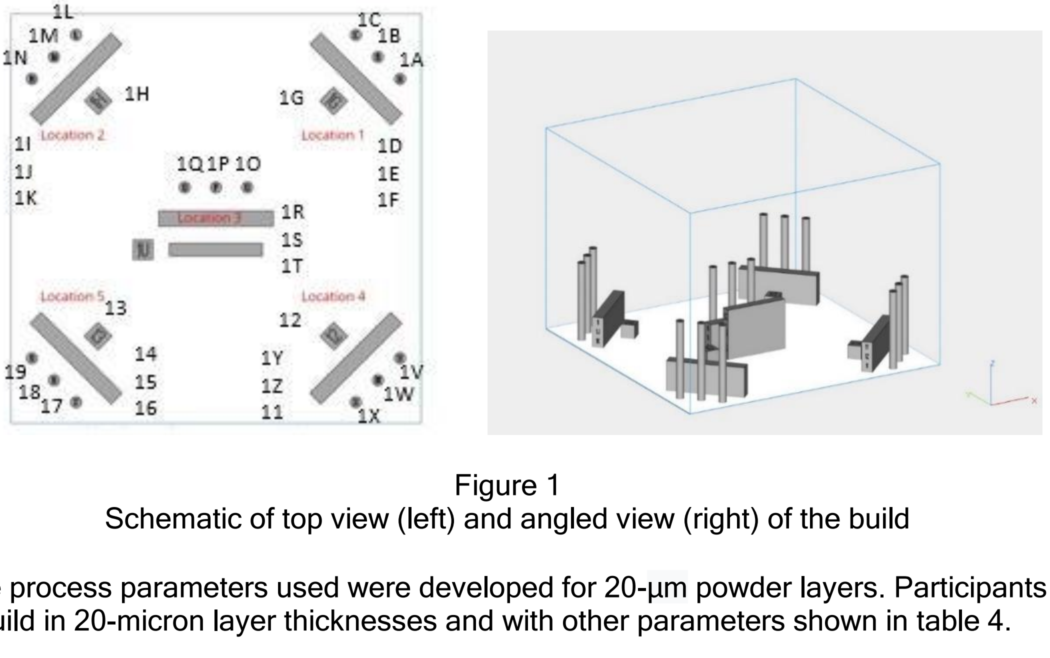


Figure 1
Schematic of top view (left) and angled view (right) of the build

The process parameters used were developed for 20-μm powder layers. Participants were asked to build in 20-micron layer thicknesses and with other parameters shown in table 4.

Table 4
Laser parameters for the 20-µm layer thickness experiment

Laser power	Scan speed	Hatch distance	Layer thickness	Beam setting
185 W	700 mm/s	0.1 mm	0.020 mm	2.0

Post-processing

After completion of the build, the parts were stressed relieved at 1,100 °F for 2 hr while on the build plate, ramping up to temperature with the build plate in the furnace.

Any partially built specimens, that is specimens that did not build to their full height, were labeled for tracking, and the complete and incomplete specimens were measured in the XY plane. The results of these measurements can be seen in appendix C. Participants were not instructed to calibrate their machines for the material provided. This was done in order to save cost and time for the participants. As a result, dimensional variability was expected. Most participants held within 0.010 in. of nominal dimensions. Build 2, however, was the greatest outlier. Build 2 was off from nominal by up to 0.024 in. of a dimension because of the differences in material-dependent scaling. Material-dependent scaling is used to fine tune the process for dimensional accuracy. The parameters provided did not have pre or post-contours, and the increased surface roughness could have been a contributing factor in size variations.

All specimens were removed from the build plate by wire electrical discharge machining (EDM). After EDM removal from the build plate, all specimens were heat treated in a single heat treat batch. An exception is build 0, which is detailed in the following paragraph. The 4340 steel post-build heat treatment was as follows: stress relieving at 593 °C for 1 hr, normalizing at 900 °C for 1 hr (furnace cool to 650 °C), and then air cooling to ambient. Specimens were austenitized at 816 °C, quenched in oil, and double tempered at 190 °C for 2 hr each in accordance with AMS 2759 (ref. 9). The nominal hardness after heat treat was 50 HRC.

The round robin organizer completed four builds that are included in the data sets. The first build, build 0, was a separate heat treat batch. Build 0 was done to verify the parameters and powder. During this build, erratic recoating was observed, and this led to larger amounts of spatter than normal. The tensile results of this build were more inconsistent than previous results. The bearings used for the recoating mechanism had failed and were replaced after build 0. Build 1 had a recoater jam at 53.62 mm. This jam caused the build to be unrecoverable, leading to the incomplete build of all Z-oriented specimens. The organizer's third build, build 7, also experienced recoating issues and five specimens were removed during this build. The organizer's final build, build 8, had to have all three Z-oriented tensile specimens in the bottom right, location 4, removed. All notes on these builds can be seen in appendix D. Builds 1, 7, and 8 were heat treated with the other participant's build specimens.

Powder Characterization

Participants also sent back the powder samples they had collected. Participants were instructed to collect a sample (~100 g) of the virgin powder and a powder sample from the center of the build area after completion of the build.

Prior to being sent to the participants, the powder was analyzed using electron dispersive spectroscopy—a semi-quantitative chemical analysis—to ensure it met the required specification and to confirm the vendor's certification. Powder samples returned by participants underwent a series of characterization tests. Internal particle porosity was qualified rather than quantified, due to lack of standards for quantitative analysis. To assess internal particle porosity, powder was mounted and polished with Struers Tegramin-30 auto-polisher to expose particle cross sections of a sampling. Powder morphology was analyzed using scanning electron microscopy (JOEL JSM-6510LV) and particle size distribution was measured using laser diffraction process with a Horiba LA-950V2 machine. Combustion analysis was performed with the Horiba EMGA-620W to determine oxygen content.

Material Characterization

The five metallurgical cubes from each participant's build were analyzed by the Archimedes' density method in accordance with ASTM B311 (ref. 10). The longitudinal cross section of the cubes was mounted, ground, and polished to reveal the layers of the build process. Defects were analyzed and will be discussed in the results and discussion section. Ten Vickers microhardness measurements at a 1-kg load were also performed on each polished specimen using Struers DuraScan-70 equipment.

Mechanical Properties

After final heat treatment, the horizontal tensile specimens were cut from their respective blocks using EDM, turned on a CNC lathe to a 0.16-in. reduced section, and tested in accordance with ASTM E8 (ref. 11). The horizontal specimen axes were 0.235, 0.575, and 0.915 in. from the surface of the build plate. The reduced section of the net shape Z tensile rods was also machined to a 0.16-in. reduced section. The test was performed at room temperature on a MTS test frame with V-serrated wedges in hydraulic grips and a 50,000-lb load cell.

Fracture toughness (K_{1C}) specimens were milled on the top and bottom surfaces, notched using EDM, and then tested in accordance with ASTM E399 (ref. 12), single-edge bend method. The tests were performed on an MTS test frame with a 5,000-lb load cell using 2,500-lb load range. The test frame and controller was interfaced to an Adwin-Gold FTA computer system. Strain was measured with crack opening displacement gage. The specimens and test fixtures were conditioned to -65 °F for over an hour prior to testing at cold temperature.

Fractography was performed with optical binocular (Nikon SMZ 1500) and scanning electron microscopes (JOEL JSM-6510LV) on specimens with unexpected or irregular failure modes or performance.

RESULTS AND DISCUSSION

Powder Characterization

The virgin powder had low internal powder porosity with a predominately spherical morphology as seen in figure 2. After consolidating by L-PBF, optical emission spectroscopy (Thermo Scientific ARL 4460) along with carbon/sulfur combustion (LECO CS-200) chemical analyses confirmed the powder certification (app. E) provided by the powder manufacturer and the AMS 6414 (ref. 7) chemistry requirement as seen in table 5. The particle size distribution was consistent within the lot as seen by the powder samples collected from the six participants before and after the build. A measurable, but insignificant, increase in oxygen content was observed in the used powder.

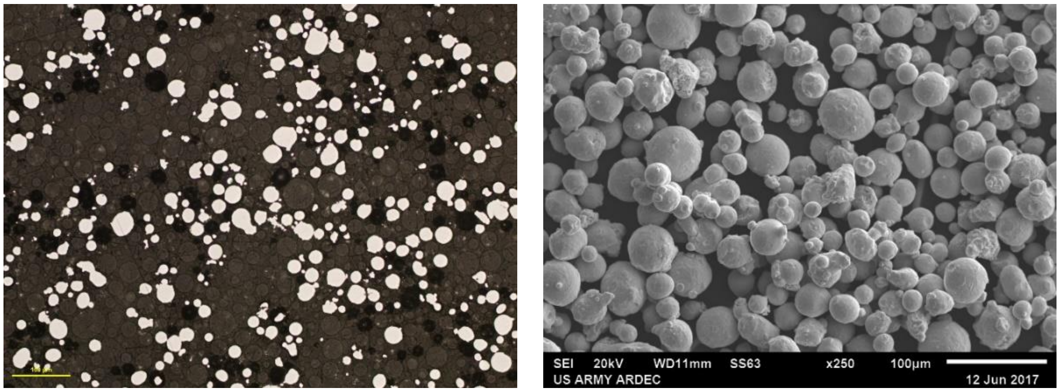


Figure 2
Powder spherical morphology as seen in an optical micrograph of a cross section (left) and in a 250x magnification scanning electron micrograph image (right)

Table 5
AMS 6414 specification, powder manufacturer's certification, and chemistry of consolidated part

Element	AMS 6414 specification (Wt %)	Part (Wt %)	Certification (Wt %)
C	0.38 - 0.43	.4	0.4
Mn	0.65 - 0.90	0.63	0.67
P	0.01 maximum	0.010	0.006
S	0.01 maximum	0.004	0.003
Si	0.15 - 0.35	0.27	0.21
Ni	1.65 - 2.0	1.75	1.91
Cr	0.70 - 0.90	0.80	0.78
Mo	0.20 - 0.30	0.26	0.25
Cu	0.35 maximum	0.01	0.01

Bulk Properties

Hardness

The average microhardness for all specimens in this study, after heat treatment, was consistently 546 HV_{1kg}, which converts to 52 HRC. The results were consistent except for build 2's, which had somewhat of a higher standard deviation than the other builds due to OEM hardware differences. Hardness values were as expected for the heat treatment condition outlined in the experimental section.

Density

The density of all the metallurgical cube samples, measured using Archimedes' method, was near 99% theoretical density or better assuming the density of 4340 steel is 7.85 g/cm^3. The Archimedes' density averaged 99.2%, this is considered fully dense in materials science. Results were consistent for all builds.

Microstructure

The microstructure of the samples, as built, can be seen in figure 3. The microstructure is non-homogenous because there is evidence of the thermal signature along with grain growth in the Z direction. After heat treatment, the microstructure is tempered martensite as seen in figure 4. The scale bars on the left and right are 50 µm and 10 µm, respectively. However, large defects on the scale of 100 to 200 µm were observed in samples from several builds indicating lack of fusion as shown in figures 5 and 6. These lack of fusion defects stemmed from a sub-optimal process. Defects of this size negatively impact mechanical properties as evidenced in the tensile plots in the following figures. Build 3 used a thicker layer (30 µm) than specified in the manufacturing guide, and this likely contributed to the large defects shown in figure 6. The 30-µm layers might have resulted in inadequate melt pool overlap and increased condensate generation. In addition, small round pores were observed in some samples, which indicates trapped gas as shown in figure 7.

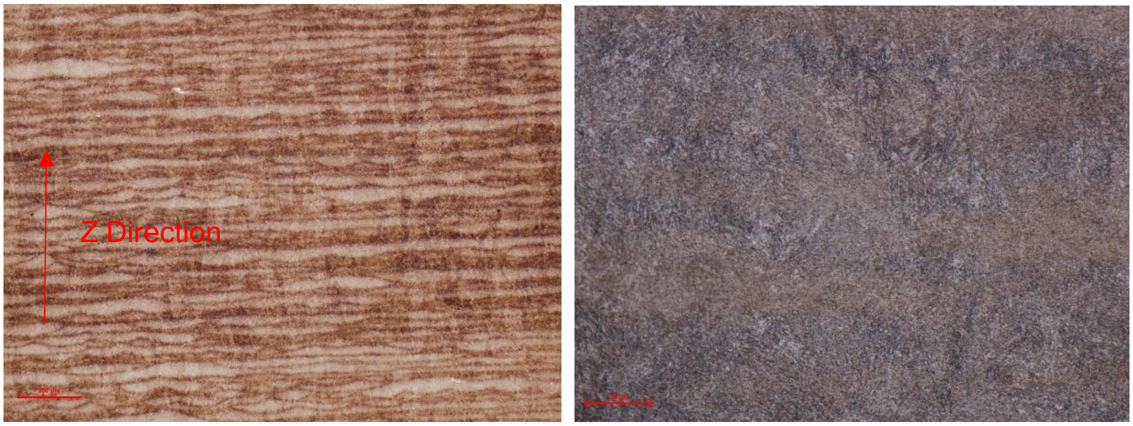


Figure 3
Representative micrographs of the as-built specimens at 200-µm scale (left)
and 50-µm scale (right)

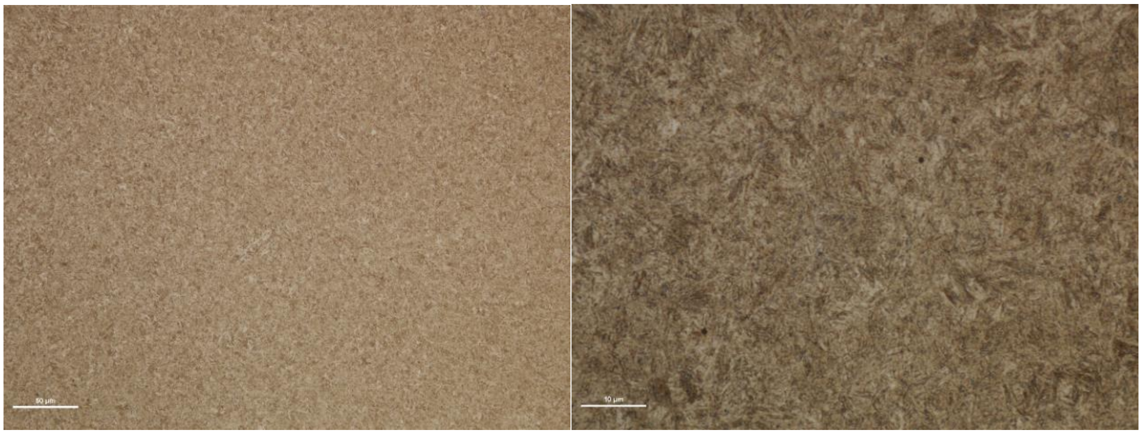


Figure 4
Representative micrographs of the etched martensitic after heat treatment
at 50-µm scale (left) and 10-µm scale (right)

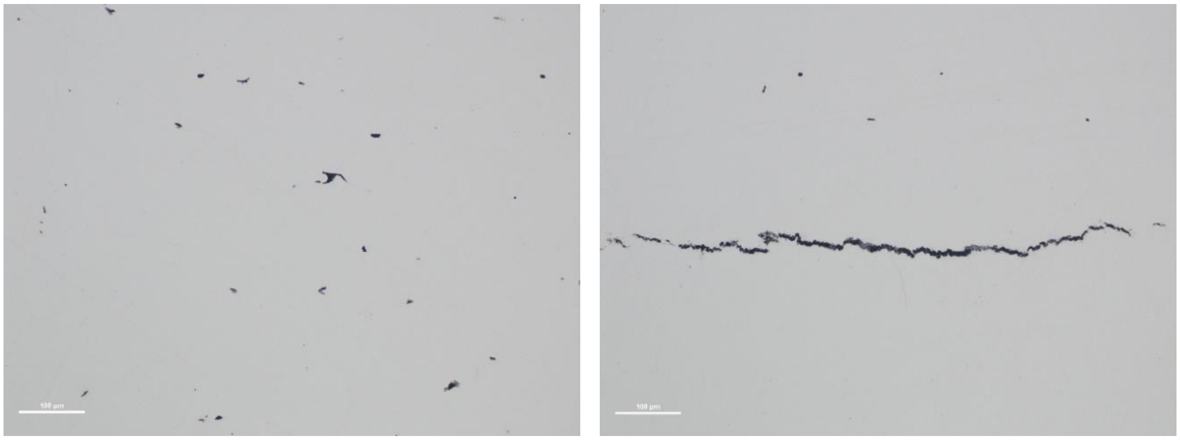


Figure 5
Build 2 unetched microstructure showing lack of fusion defects (left) and interlaminar cracking (right) at 100-µm scale

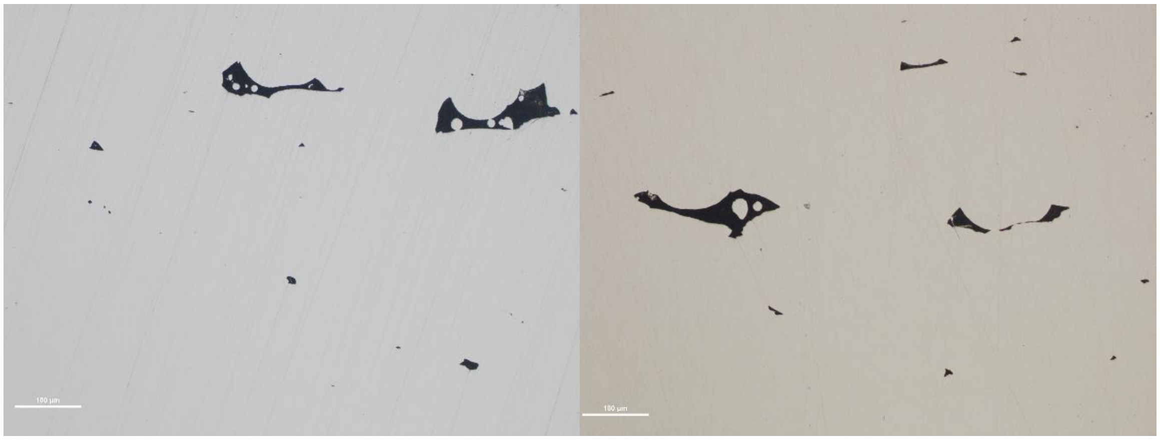


Figure 6
Build 3 unetched microstructure showing lack of fusion defects at 100-µm scale

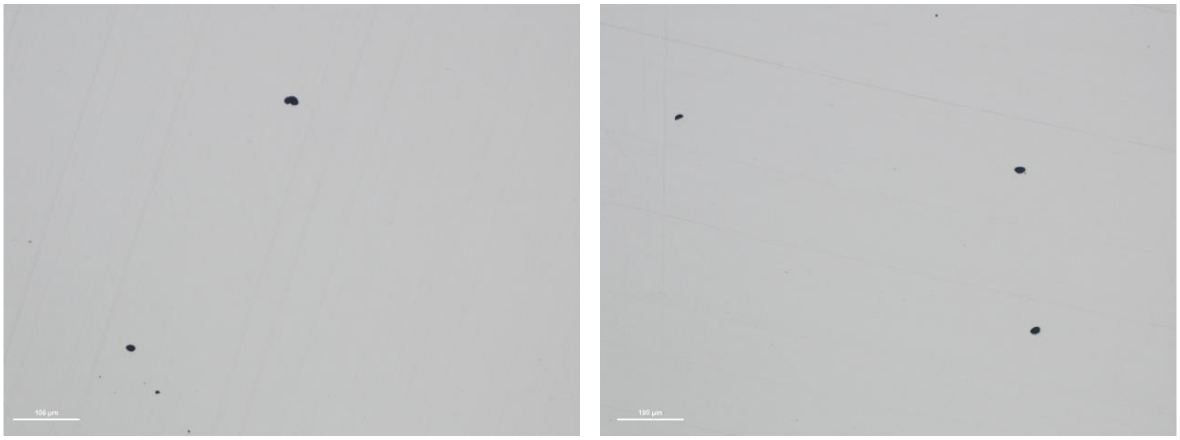


Figure 7
Build 5 unetched microstructure showing round trapped gas pores at 100-µm scale

Tensile Test Results

Overall Results and Observations

129 of 270 tensile specimens complied with minimum properties expected for wrought 4340 heat treated as per AMS 2759F: 205 KSI yield, 235 KSI tensile, and 6% elongation. Less than 1% of XY specimens failed the 6% minimum elongation. 38% (52 of 135) of Z specimens failed to build to a height that could be machined into tensile specimens. Out of the completed Z-oriented specimens, over 70% failed to meet the 6% minimum elongation. When including the Z specimens that failed to build to height, the failure rate becomes ~85%. The Z-tensile specimens were built round, as opposed to a square or rectangular cross section, to save on build time and post build machining cost. Building the Z-tensile specimens as rods is more difficult than monolithic blocks because round columns are less rigid and more likely to bend than rectangular blocks. The aspect ratio for the Z specimens is 10:1, and commonly accepted design criteria for L-PBF states aspect ratios should not exceed 7:1. A high aspect ratio may lead to vibrations when passed over by the recoater blade, which could generate defects in the specimen or part. Uneven powder packing caused by vibrations would affect heat flow across particles during the formation of the melt pool.

Note that participants with the same model of machine had different levels of success in specimen completion percentage. In one build, the Z-tensile specimens built to the full height, but in another build with the same parameters, none of the Z specimens built to full height, see figure 8. If the Z-tensile specimens were built and machined from a block similar to the XY-oriented samples, then more Z-tensile specimens may have been completed. The Z-tensile rods were intended to be challenging and to bring to light the numerous differences between the participants' machines as well as analyze anisotropy.

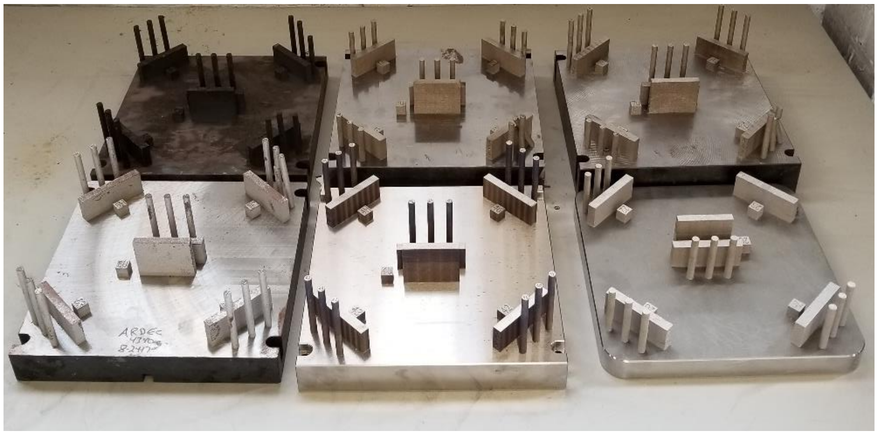


Figure 8
Collection of builds from participants

Appendix D has the notes from the participants' builds. Build 2 was done on a ProX 300, using the hexagonal, not the stripe strategy as specified in the manufacturing plan. This build resulted in significant cracks throughout some of the parts. Build 3 was done using an incorrect layer thickness (30 µm instead of 20 µm), and this resulted in build failure. This was an operator error and not a machine limitation. Build 4 completed but needed additional powder added to the dispenser at 48 mm, resulting in a stoppage. Build 5 had recoater jamming issues as well at approximately 56 mm, which led to removing two tensile specimens. More recoater problems occurred at approximately 70 mm and led to more tensile specimens being removed from the remaining build. Build 6 completed without any recoater jamming, but there were times when the recoater was clipping some of the tensile specimens.

When evaluating the broken tensile specimen fracture surfaces, large defects were observed with a scanning electron microscope (SEM), see figures 9 through 11. The defects cover more area in the XY plane than in the Z plane, a disk being a simple representation of their shape. One possible explanation for the presence of the defects is that spatter, airborne particles the laser ejects from the powder bed, falls back into the heat-affected zone or lands on another region of the part, and the laser partially melts it afterwards. These particles are weakly bonded to the part. As a result, the recoater blade hits the protruding particles, which creates a discontinuity. This can create disturbances in the powder bed and adversely affect recoating.

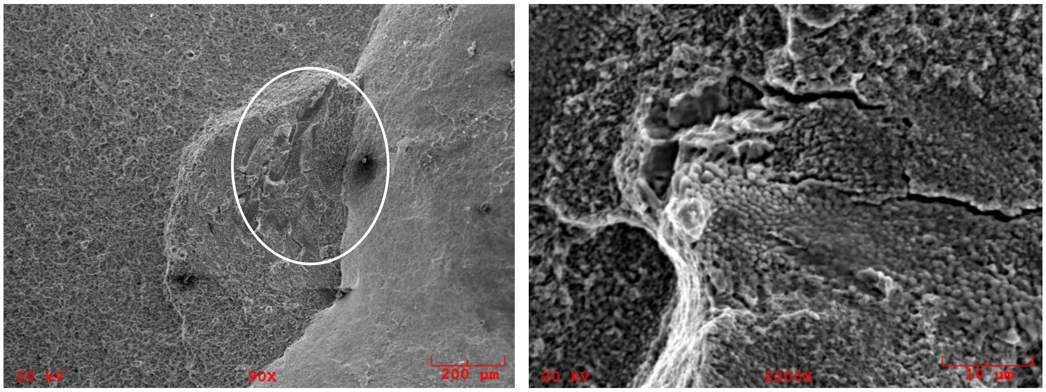


Figure 9
Specimen #8L-SEM micrograph of fracture surface at 90x magnification (left) and at 2,200x magnification (right)

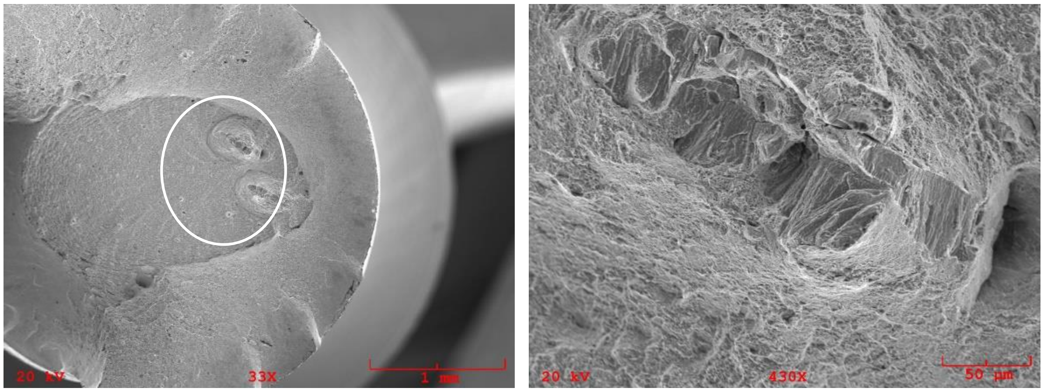


Figure 10
Specimen #81- SEM micrograph of fracture surface at 33x magnification (left) and at 430x magnification (right)

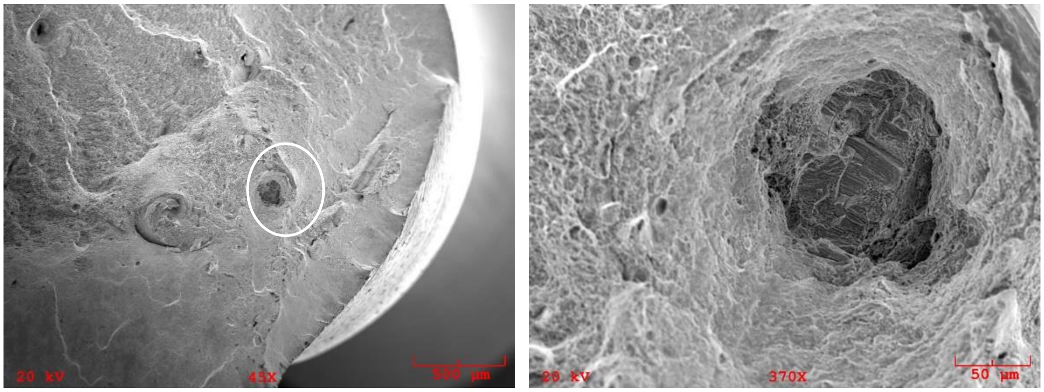


Figure 11
Specimen #7K-SEM micrograph of fracture surface at 45x magnification (left) and at 370x magnification (right)

The spatter might also affect the heat flow on the following layers' melt pool due to altered morphology and specific heat. A higher concentration of localized heat can lead to local chemical segregation near the defect region. There is evidence of segregation because there is significantly higher nickel and chromium concentrations near the defect sites versus the remaining bulk material, as seen using energy dispersive X-ray spectroscopy [EDS (figs. 12 through 15 and tables 6 and 7)]. Furthermore, if the gas flow does not adequately remove the spatter and condensate, then those particles can occlude or scatter the laser beam resulting in discontinuous melt pools. If critical defects are initiated at one layer, it will negatively impact the Z-tensile specimen more than the XY-tensile specimen because the defect is oriented perpendicular to the tensile axis, having its widest cross section in that plane.

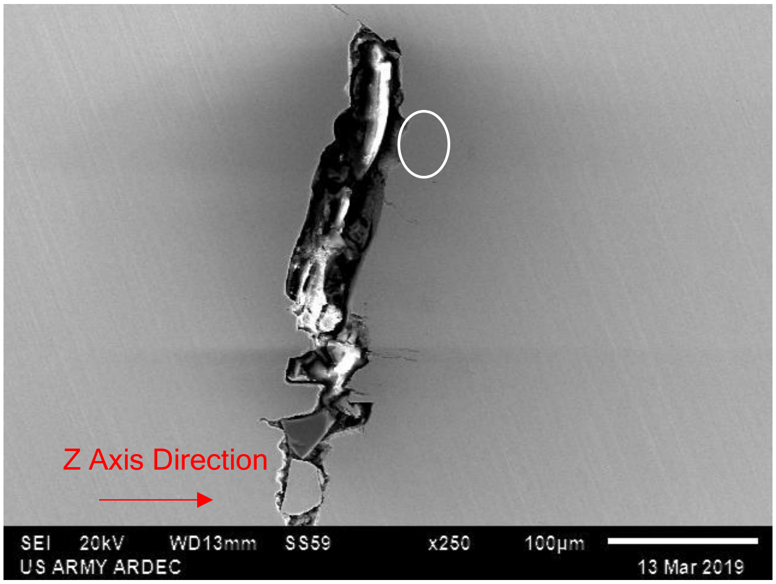


Figure 12
Specimen #88-SEM micrograph of a defect from a polished longitudinal cross section of the pulled tensile round at 250x

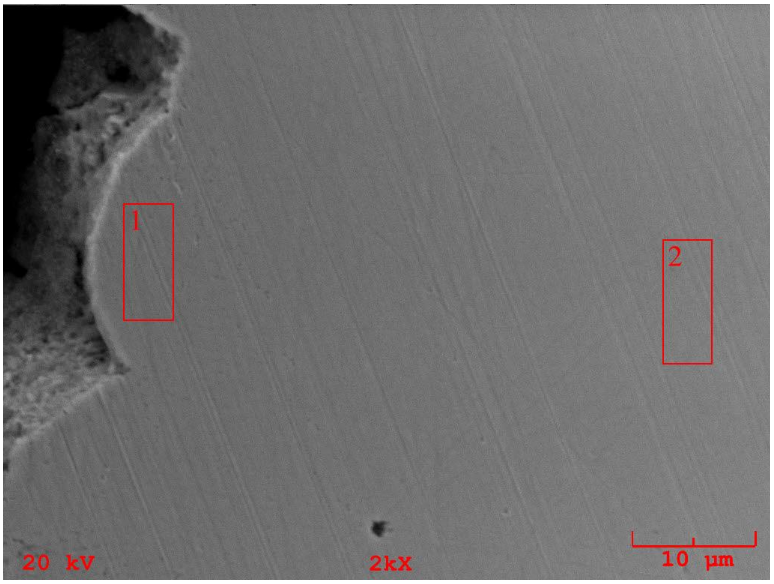
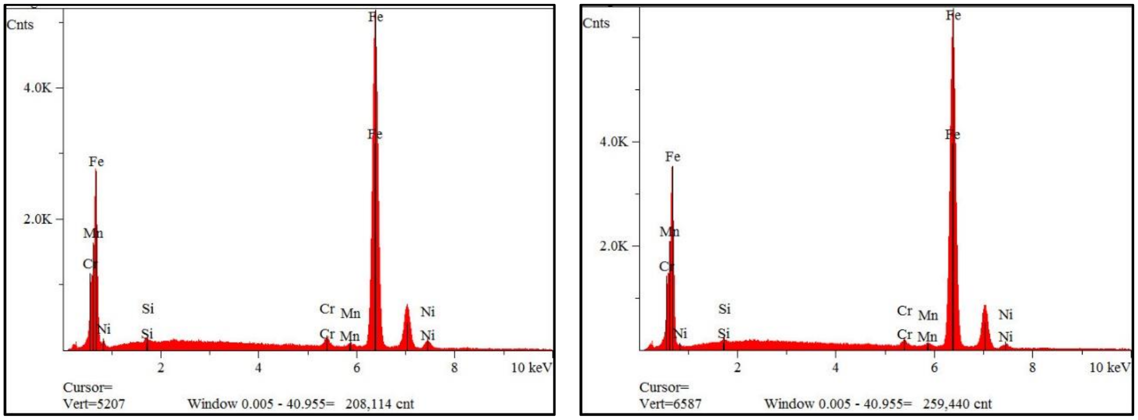


Figure 13
Specimen #88- 2,000x SEM micrograph of the defect in figure 12



(a)
Region 1

(b)
Region 2

Figure 14
EDS spectrum from figure 13

Table 6
EDS results from figure 14

Element	EDS results from spectrum fig. 14a	EDS results from spectrum fig. 14b
Fe	94.59	96.38
Mn	0.43	0.45
Si	0.48	0.43
Ni	3.58	2.09
Cr	0.92	0.65

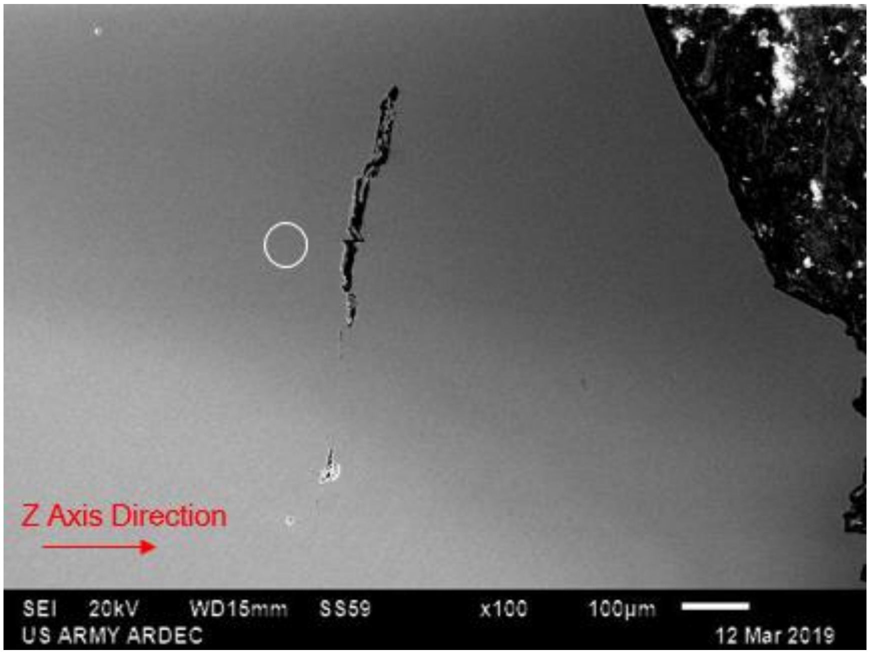


Figure 15
Specimen #58-SEM micrograph of a defect from a polished longitudinal cross section of tensile specimen at 100x

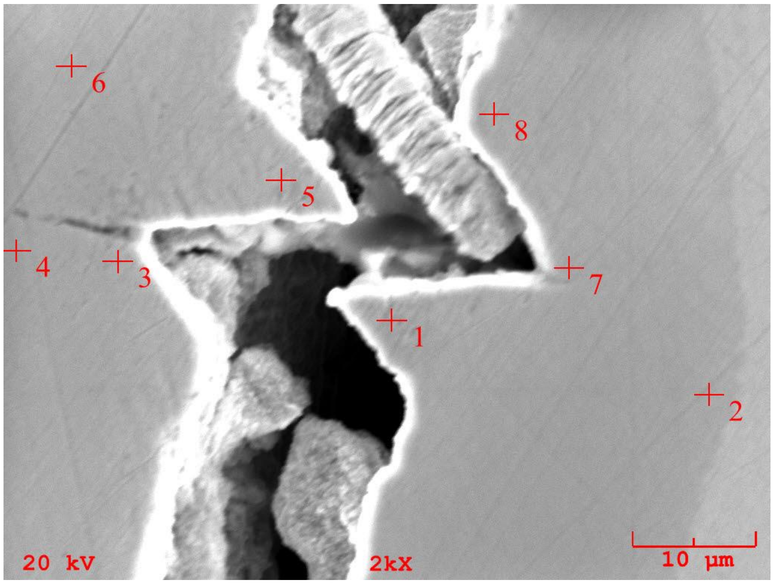


Figure 16
Specimen #58-2,000x of the defect from figure 15

Table 7
EDS results from figure 16

Element	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8
Fe	94.51	95.72	93.93	95.99	95.06	96.60	95.89	95.50
Mn	0.52	0.48	0.49	0.52	0.51	0.35	0.60	0.36
Si	0.60	0.37	0.53	0.45	0.50	0.37	0.58	0.42
Ni	3.54	2.73	4.18	2.36	3.16	2.05	2.19	2.88
Cr	0.83	0.70	0.87	0.69	0.78	0.63	0.73	0.85

Specific Tensile Test Results

Table 8 summarizes the average tensile test results in the XY and Z orientations for completed specimens only. Note that all three ductility measurements (percent elongation, strain at break, and reduction in area) in the Z orientation are about half of the XY orientation. The strength is more consistent than ductility, but, again, the Z-oriented specimens are lower strength. The standard deviation shown in table 8 is calculated from the average tensile properties for each specimen's location on the build plate. That is, the value shown is the standard deviation of the averages for all locations.

Table 8
Average tensile test results for all nine round robin builds

Average tensile properties for all nine XY round robin builds					
	Yield stress (ksi)	Peak stress (ksi)	% elongation	% strain at break	% reduction in area
Grand average	227.1	280.9	9.21	8.76	30.86
Standard deviation	1.06	0.49	0.73	0.52	4.00
Average tensile properties for all nine Z round robin builds					
	Yield stress (ksi)	Peak stress (ksi)	% elongation	% strain at break	% reduction in area
Grand average	225.1	267.0	4.07	4.52	10.25
Standard deviation	2.52	5.11	0.79	0.88	3.97

Table shows the yield strength and percent elongation with standard deviation as a function of specimen location on the build plate. The standard deviation shows more variability in specimens built in the Z orientation. The large standard deviations occurred when few specimens were built above a 2-in. height, and many of those that did had latent defects.

Table 9
Average tensile test results for all nine round robin builds based on location

Cluster location on build plate (XY)		Yield stress (ksi)	Yield stress standard deviation	% elongation	Elongation standard deviation
1- Top right	D average	227.36	5.53	10.00	1.41
	E average	228.18	2.93	9.73	1.82
	F average	226.87	4.44	9.58	2.11
2 - Top left	I average	227.18	3.46	9.39	2.13
	J average	226.85	3.61	9.61	1.05
	K average	229.10	4.53	8.34	1.90
3 - Center	R average	226.21	2.89	8.44	1.97
	S average	226.60	2.42	9.12	2.45
	T average	226.18	2.79	8.75	1.53
4 - Bottom right	Y average	224.86	3.38	10.21	1.35
	Z average	227.96	3.84	8.83	1.45
	1 average	227.98	2.56	10.60	0.93
5 - Bottom left	4 average	226.28	3.10	8.19	1.46
	5 average	228.14	3.36	8.63	2.00
	6 average	226.55	3.51	8.79	2.08
	Grand average	227.09	3.49	9.21	1.71
	Standard deviation	1.06	0.83	0.73	0.43
Cluster location on build plate (Z)		Yield stress (ksi)	Yield stress standard deviation	% elongation	Elongation standard deviation
1 - Top right	A average	219.87	15.88	5.95	4.62
	B average	222.97	2.94	3.93	2.54
	C average	227.70	1.46	4.60	2.82
2 - Top left	L average	226.62	6.87	2.69	1.77
	M average	226.93	6.55	4.04	2.78
	N average	223.33	4.59	3.39	2.87
3 - Center	O average	226.25	2.83	4.16	3.60
	P average	225.98	4.32	3.62	1.40
	Q average	227.06	2.88	4.12	1.97
4 - Bottom right	V average	228.46	2.39	3.72	2.57
	W average	220.36	13.00	4.92	2.89
	X average	226.19	2.84	4.95	3.99
5 - Bottom left	7 average	224.82	2.67	4.10	3.33
	8 average	224.64	5.30	3.42	1.84
	9 average	224.80	3.56	3.48	3.06
	Grand average	225.06	5.21	4.07	2.80
	Standard deviation	2.52	4.08	0.79	0.86

The yield and tensile strength remained consistent throughout this study, but the XY-orientation strength was more consistent than the Z-orientation strength. The heat treatment including normalize, austenitize, quench, and tempering contributed to the consistent strength and mitigated the effect of layered microstructure. However, ductility measurements (percent elongation, strain at break, and reduction in area) are more sensitive and can discriminate among the different locations on the build plate. The ductility measurements can also discriminate among the different participants and different machines. As noted in the background, 4340 steel at nominally 50 HRC was chosen for this study because of its sensitivity to process variations.

For many Z-oriented tensile specimens, the builds that did not complete or had significant visible defects were not machined and not tested for tensile properties. Only the specimens that built approximately 2 in. or taller without visual defects were machined, tensile tested, and counted in the statistics shown in tables 8 and 9. The failed builds can appear better than builds that made it to full height despite some interruption that caused poor ductility. For example, when reviewing the statistics in tables 8 and 9, the center of build plate looks brittle, but the center might have been the only area to complete the build, whereas the corner areas did not reach the nominal 2-in. build height. To correct this shortcoming, the failed build areas are included in the color plots shown in the Statistical Analysis section.

Given either the XY or Z orientation, the individual tensile properties were averaged for each test plate location and then sorted by ductility measurements. Certain corners ranked worse across the four different machines. The ductility was lower on the left side of the build plate in both the XY and Z orientations across the four different machines. For example, in the XY orientation, the lower left corner (4, 5, 6) had the lowest ductility measurements and the upper left corner (K in particular) had the second lowest ductility measurements. In the Z orientation, the upper left corner (L, M, N) had the lowest ductility measurements and the lower left corner (8 in particular) had the second lowest ductility measurements. Overall, the XY orientation was more consistent and ductile than the Z orientation. In the Z orientation, the worst areas were consistently the worst; that is, the left side of build plate was always the most brittle. Machine design or gas flow characteristics may have similar weakness across all four machines. Previous work on the EOS M270 equipment found the upper left corner to produce the furthest from nominal tensile properties (ref. 1).

Average tensile test results broken down by build are shown in table 10. Recall that there were 15 XY and 15 Z-tensile specimens in five clusters on the build plate, and that ductility measurements are useful in discriminating among the builds. Unexpectedly, build 0, which was originally believed to be unacceptable, had the highest ductility and largest number of specimens complying with minimum mechanical properties. This shows the importance of machine maintenance condition on material properties.

Table 10
Average tensile properties of each build

		Yield stress (ksi)	Peak stress (ksi)	Calculated % elongation	Strain at break (%)	Reduction in area (%)
Build 0 - XY	Average	231.14	284.12	11.61	10.25	40.31
	Standard deviation	3.1	1.69	1.76	1.18	9.24
	% relative standard deviation	1.3%	0.6%	15.2%	11.5%	22.9%
Build 0 - Z	Average	226.2	282.04	6.87	6.98	20.26
	Standard deviation	3.5	2.03	1.93	1.81	10.53
	% relative standard deviation	1.5%	0.7%	28.1%	25.9%	52.0%

Table 10
(continued)

		Yield stress (ksi)	Peak stress (ksi)	Calculated % elongation	Strain at break (%)	Reduction in area (%)
Build 1 - XY	Average	228.21	281.16	8.5	8.22	27.14
	Standard deviation	3.15	1.33	1.32	0.83	6.78
	% relative standard deviation	1.4%	0.5%	15.5%	10.1%	25.0%
Build 1 - Z		Recoater jammed, recover failed.				
Build 2 - XY	Average	230.45	281.06	7.68	8.2	27.02
	Standard deviation	4.54	1.01	1.21	1.07	9.08
	% relative standard deviation	2.0%	0.4%	15.8%	13.0%	33.6%
Build 2 - Z		Process not optimized for machine.				
Build 3 - XY	Average	227.25	280.31	7.47	7.2	18.65
	Standard deviation	2.43	2.32	1.74	1.33	10.13
	% relative standard deviation	1.1%	0.8%	23.3%	18.5%	54.3%
Build 3 - Z	Average	215.22	223.03	0.72	1.19	1.83
	Standard deviation	10.73	26.97	0.52	0.42	1.16
	% relative standard deviation	5.0%	12.1%	72.2%	35.3%	63.4%
Build 4 - XY	Average	225.98	280.2	9	8.96	32.61
	Standard deviation	2.58	1.05	1.46	1	7.06
	% relative standard deviation	1.1%	0.4%	16.2%	11.2%	21.6%
Build 4 - Z	Average	227.23	278.93	5.71	6.2	14.17
	Standard deviation	3.3	2.08	2.35	1.57	10.08
	% relative standard deviation	1.5%	0.7%	41.2%	25.3%	71.1%
Build 5 - XY	Average	225.72	280.22	8.87	8.56	29.35
	Standard deviation	2.26	1.2	0.99	0.71	4.18
	% relative standard deviation	1.0%	0.4%	11.2%	8.3%	14.2%

Table 10
(continued)

		Yield stress (ksi)	Peak stress (ksi)	Calculated % elongation	Strain at break (%)	Reduction in area (%)
Build 5 - Z	Average	228.24	275.8	3.59	3.74	5.36
	Standard deviation	2.28	3.85	1.09	0.83	2.35
	% relative standard deviation	1.0%	1.4%	30.4%	22.2%	43.8%
Build 6 - XY	Average	226.18	281.91	9.97	9.14	33.91
	Standard deviation	2.23	1.03	1.96	1.32	11.64
	% relative standard deviation	1.0%	0.4%	19.7%	14.4%	34.3%
Build 6 - Z	Average	227.35	279.29	3.49	4.88	11.19
	Standard deviation	2.45	5.15	2.47	2.84	9.06
	% relative standard deviation	1.1%	1.8%	70.8%	58.2%	81.0%
Build 7 - XY	Average	225.78	280.16	8.99	8.57	28.54
	Standard deviation	3.52	2.06	0.63	0.6	3.73
	% relative standard deviation	1.6%	0.7%	7.0%	7.0%	13.1%
Build 7 - Z	Average	225.93	275.87	2.95	2.97	4.47
	Standard deviation	5.01	2.43	1.54	2.19	4.47
	% relative standard deviation	2.2%	0.9%	52.2%	73.7%	100.0%
Build 8 - XY	Average	224.82	278.61	9.16	8.73	33.17
	Standard deviation	3.6	1.95	1.06	0.8	5.69
	% relative standard deviation	1.6%	0.7%	11.6%	9.2%	17.2%
Build 8 - Z	Average	224.98	271.72	3.44	3.68	5.91
	Standard deviation	1.83	2.58	0.53	0.65	2.07
	% relative standard deviation	0.8%	0.9%	15.4%	17.7%	35.0%

A summarization of K_{1c} fracture toughness results versus temperature for L-PBF and wrought 4340 is shown in figure 17. For a given temperature, the specimens came from the same vertical location in the K_{1c} block. The specimens were oriented in the rolled plate L-S orientation of ASTM E399 (ref. 12) or X-Z orientation of ISO 12135 (ref. 7). There was good agreement between tensile and toughness results. For example, wrought K_{1c} specimens were somewhat tougher, and this correlates with the tensile ductility measurements discussed earlier. That is, the L-PBF ductility measurements are somewhat more brittle than typical wrought 4340 at similar hardness. As expected, there is a general trend toward more brittle properties with colder temperatures. A few warmer temperature results were invalid, as Pmax/Pq = 1.2 (peak load divided by candidate load), and cannot exceed 1.1. That being the case, those few invalid results are presented with valid results in figure 17.

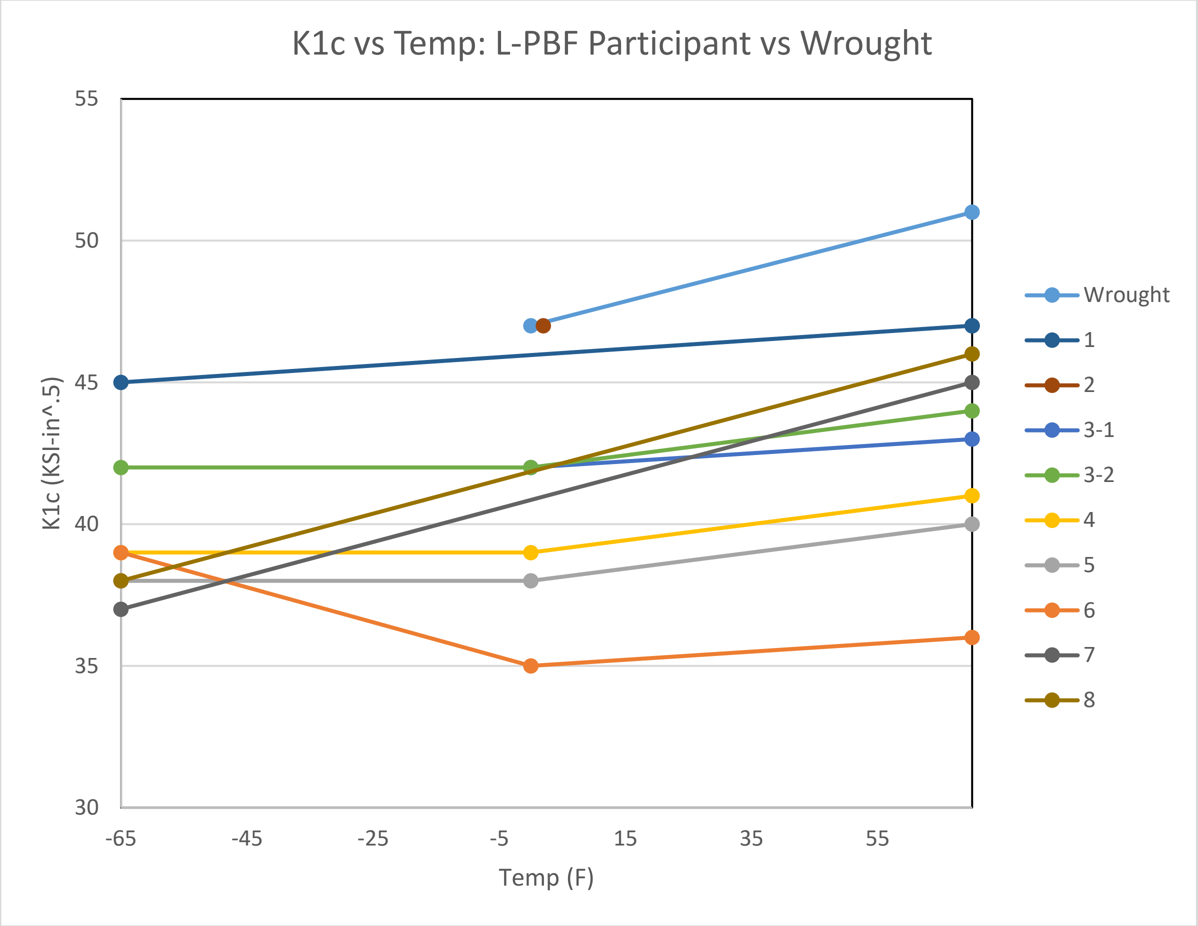


Figure 17
Graph of K_{1c} fracture toughness versus temperature for L-PBF and wrought

There were several anamolies with the K_{1c} data. First, there are two sets of K_{1c} data from participant 3 (3-1 and 3-2) because the first layer was double exposed multiple times and some of the parts did not build correctly, which meant the center cluster was built a second time. In addition, there was only one data point from participant 2 because the K_{1c} block had extensive cracking. As a result, acceptable specimens were not able to be machined from the other regions of the K_{1c} block.

Statistical Analysis of Tensile Data

A statistical analysis was conducted to quantify the influence of specimen orientation, build plate location, and L-PBF machine type to the tensile properties of the specimens built. The graphs and charts in this section are intended to provide a visual perspective of the results. It must be noted that there are other factors that influence a specimen's tensile properties such as machine maintenance, feed stock, and operator. These elements were not intentionally varied for this study.

Figure 18 shows the number of tensile specimens that built to at least a 2-in. height and complied with minimum tensile strength requirements (205-ksi yield, 235-ksi tensile, and 6% elongation). None of the participants successfully built all 30 tensile specimens and passed the minimum tensile strength requirements.

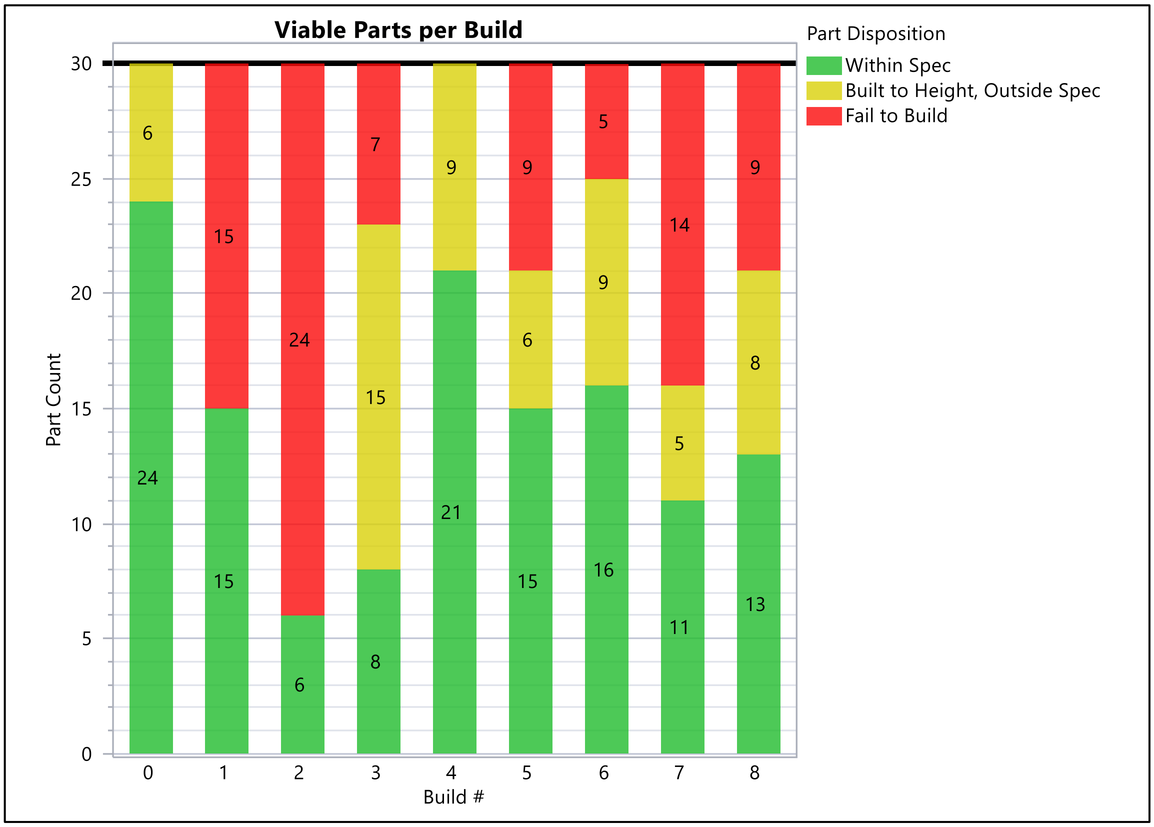


Figure 18
Number of specimens within specification by build number

Most tensile specimens built successfully in the XY orientation, but 40% of the specimens in the Z orientation failed to build, including two participants that were not successful in building any Z specimens, see figure 19. These two figures also show increased likelihood of build success in the middle of the build plate. The association between build plate location and the successful building of a specimen is emphasized in figure 20. Figure 20, comparing proportion of build failure by build plate location, shows that the location with the smallest proportion of build failures was the center (~12%) and the location with the highest proportion of build failures was at location 4, at the bottom right (~39%). Therefore, building viable tensile specimens in the bottom right corner is more difficult.

Figure 19
Heat map of build failure, XY orientation (left) and Z orientation (right)

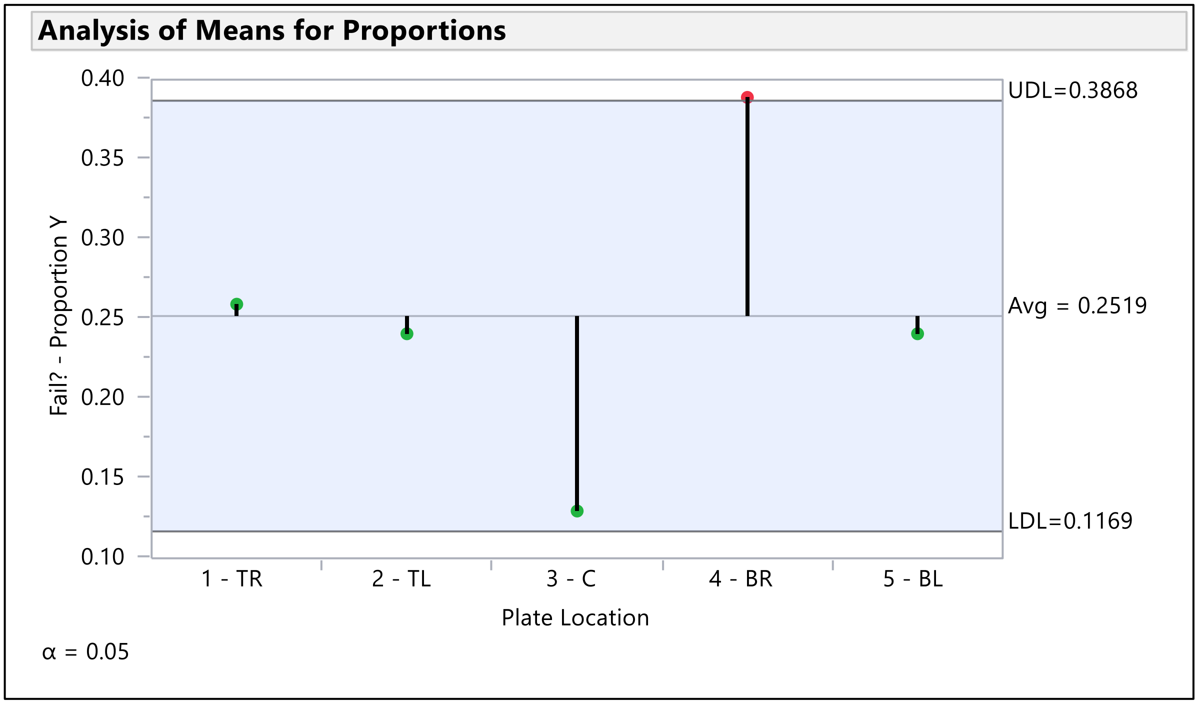


Figure 20
Build failure proportions by plate location

The heat maps indicating yield strength in figure 21 show that every specimen built in the XY orientation reached the 205-ksi minimum yield strength, while two specimens built in the Z orientation did not reach the minimum yield strength. In addition, the range of tensile strength values is narrower in the XY orientation than in the Z orientation. Clearly, yield strength is not a discriminating factor, nearly all specimens passed 205 ksi minimum.

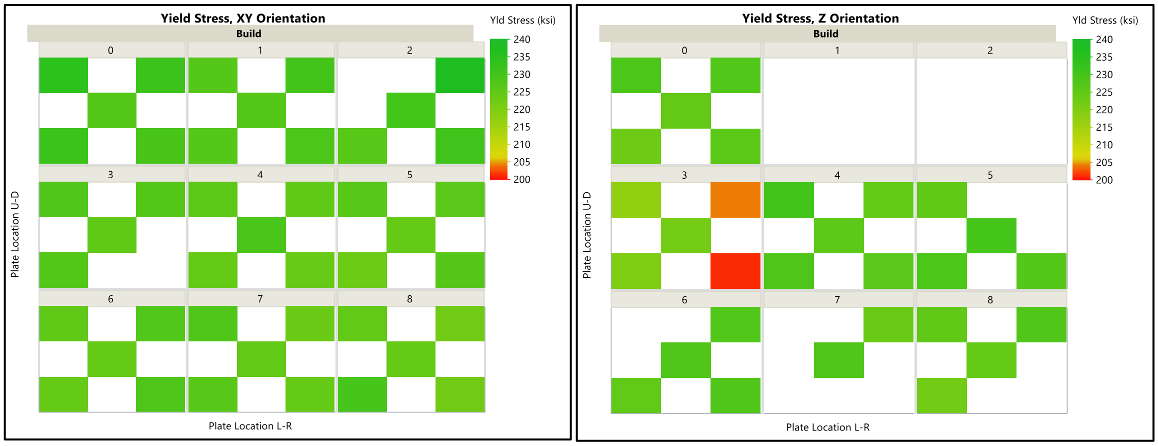


Figure 21
Heat map of yield stress, XY orientation (left) and Z orientation (right)

The heat maps indicating percent elongation in figure 22 show the influence of orientation. 97% of the XY specimens passed the 6% minimum elongation, as shown by the green squares. In contrast, the majority (77%) of specimens built in the Z orientation failed to meet 6% minimum elongation. This contrast between results in the XY orientation and Z orientation can be seen clearly in the bar graph in figure 23. While the bars representing samples in the XY orientation are primarily to the right of the blue line representing the material specification, the majority of the bars representing samples in the Z orientation are to the left of the blue line.

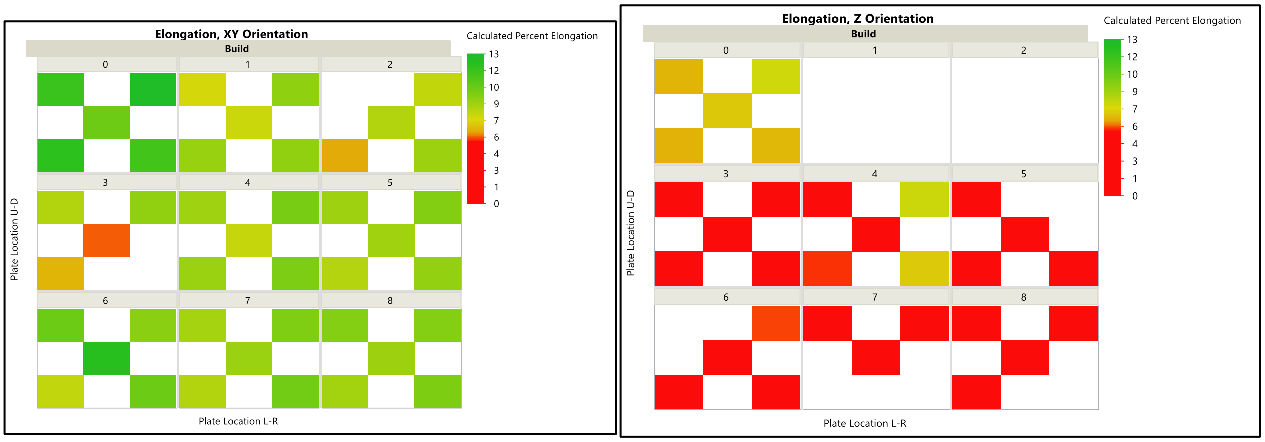
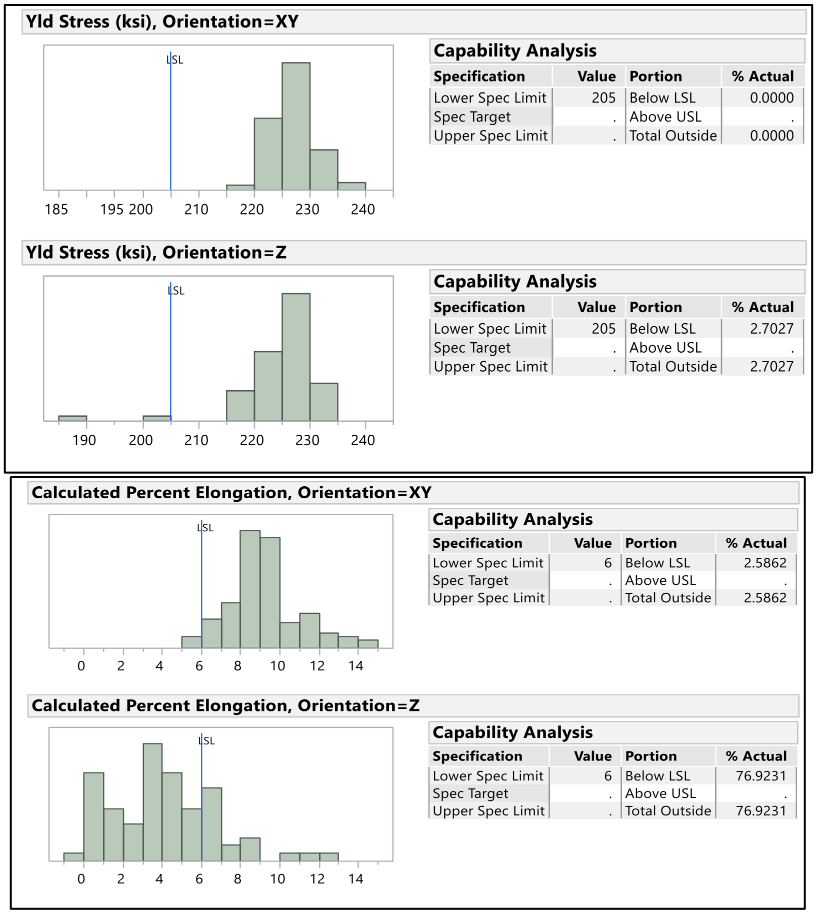


Figure 22
Heat map of percent elongation, XY orientation (left) and Z orientation (right)



Yld Stress (ksi), Orientation=XY

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	205	Below LSL	0.0000
Spec Target	.	Above USL	.
Upper Spec Limit	.	Total Outside	0.0000

Yld Stress (ksi), Orientation=Z

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	205	Below LSL	2.7027
Spec Target	.	Above USL	.
Upper Spec Limit	.	Total Outside	2.7027

Calculated Percent Elongation, Orientation=XY

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	6	Below LSL	2.5862
Spec Target	.	Above USL	.
Upper Spec Limit	.	Total Outside	2.5862

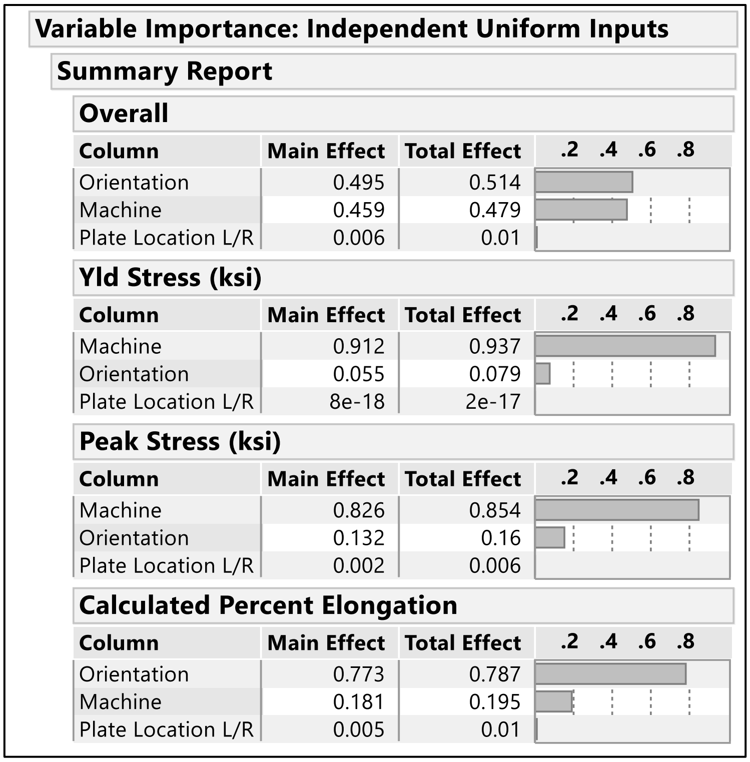
Calculated Percent Elongation, Orientation=Z

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	6	Below LSL	76.9231
Spec Target	.	Above USL	.
Upper Spec Limit	.	Total Outside	76.9231

Figure 23
Ductility measurements versus specification

A summary report of the influence of orientation, machine type, and plate location on tensile properties in figure 24 shows that the machine type has a greater effect on strength, while specimen orientation has a greater influence on elongation. The summary report also shows that location on the build plate does influence tensile properties, but its effects are dwarfed by effects of orientation and machine. Future studies could investigate the effect other factors such as feed stock, operator performance, and time between layers, which were not intentionally varied in this study.



Variable Importance: Independent Uniform Inputs

Summary Report

Overall

Column	Main Effect	Total Effect
Orientation	0.495	0.514
Machine	0.459	0.479
Plate Location L/R	0.006	0.01

Yld Stress (ksi)

Column	Main Effect	Total Effect
Machine	0.912	0.937
Orientation	0.055	0.079
Plate Location L/R	8e-18	2e-17

Peak Stress (ksi)

Column	Main Effect	Total Effect
Machine	0.826	0.854
Orientation	0.132	0.16
Plate Location L/R	0.002	0.006

Calculated Percent Elongation

Column	Main Effect	Total Effect
Orientation	0.773	0.787
Machine	0.181	0.195
Plate Location L/R	0.005	0.01

Figure 24
Variable importance indices by property

CONCLUSIONS

This study attempted to translate parameters on similar and dissimilar laser-power bed fusion (L-PBF) machines and assess the effects on bulk material properties. The machines involved in this study had differences in the recoater system, air flow, laser beam power, and scan strategy. The results of this study show that greater control must be held across a multitude of process parameters to achieve consistent results. Translating parameters across different machines requires development and testing.

The influence of orientation, machine type, and plate location on tensile properties shows that the machine type has a greater effect on strength, while specimen orientation has a greater influence on elongation. Also, location on the build plate does influence tensile properties, but its effects are dwarfed by effects of orientation and machine. Future studies could investigate the effects of other factors such as feed stock, operator performance, and time between layers, which were not intentionally varied in this study.

This study highlights the anisotropic results of the layer-by-layer process of L-PBF. The consistency across the XY specimens does show promise for a more widespread adoption of the process depending on the operational condition of the component being built. 99% of XY-oriented specimens complied with wrought 4340 material properties, while 85% of Z specimens failed to meet the specification. This large anisotropy demonstrates the need for XY and Z data to fully understand the performance of L-PBF material.

Recommendations

To properly conduct a round robin study across a variety of machines, process parameter optimization is necessary for each machine prior to the study. The optimization must produce fully dense parts with near wrought mechanical properties in both XY and Z orientations. Once this is done, then the effects of process variables (i.e., variable powder layer thickness, thermal stress, and variation in gas flow) can be evaluated.

The questionnaire used for this study was not sufficient in choosing participants. It did down-select the availability of machines to be considered, and it should have been followed up with qualification testing. This would place a heavier demand on those participating, and it may have shown indications of issues with Z-oriented properties. This would have resulted in a better selection of participants. While this would have narrowed the overall scope of the study, it may have led to a more in-depth analysis of machines with more common attributes. A qualification run would have also familiarized the participants with the data schema resulting in a more cohesive set of schemas for the full test plate.

It is also recommended that operators be certified for future studies. The qualifications of operators and their familiarity with both the hardware and software at their facilities should be a consideration when selecting participants. This round robin study would have benefitted from the organizer having a greater understanding of what the exact processes and deviations from the manufacturing plan were during the setup and execution of the builds.

This study would have also benefited from a more robust data schema and manufacturing plan. While all participants provided responses to the data schema, there were inconsistencies among the responses. Deviations from the manufacturing plan were noted by the participants. Some failed to adequately fill out the data schema and later cleared up some of the discrepancies. Future round robin studies should continue to focus on similar machines to properly evaluate variations before moving to dissimilar machines.

Future Work

Defect causation and classification are required to better understand and minimize process flaws. In-process monitoring techniques such as melt pool monitoring, high-resolution optical imaging of powder bed, controlling machine parameters, and other data are needed to effectively characterize the build and better understand the formation of flaws.

Additionally, modeling and simulation of the L-PBF process is an important tool to understand thermal stresses in the part and provide solutions to minimize those stresses (altering scan strategies, increasing support material, modifying the process parameters). It will also be valuable in describing phenomena observed from in-process monitoring. Understanding and eliminating critical process defects along with a strong manufacturing plan are essential in establishing standards required to build reliable parts.

REFERENCES

1. Jelis, E., Hespos, M. R., and Ravindra, N. M., “Process Evaluation of AISI 4340 Steel Manufactured by Laser Powder Bed Fusion,” Journal of Materials Engineering and Performance, Vol. 27, pp. 63-71, January 2018.

2. Jelis, E., “Development of Low Alloy Steel by Direct Metal Laser Sintering,” Dissertation, New Jersey Institute of Technology, Newark, NJ, 2017.

3. Jelis, E., Clemente, M., Kerwien, S., Ravindra, N. M., and Hespos, M. R., “Metallurgical and Mechanical Evaluation of 4340 Steel Produced by Direct Metal Laser Sintering,” JOM: The Journal of the Minerals, Metals, & Materials Society, Vol. 67, No. 5, pp. 582-589, May 2015.

4. Moylan, S., Brown, C., and Slotwinski, J., “Recommended Protocol for Round-Robin Studies in Additive Manufacturing,” Journal of Testing and Evaluation, Vol. 44, No. 2, March 2016.

5. Brown, C., Jacob, G., Stoudt, M., Moylan, S., Slotwinski, J., and Donmez, A., “Interlaboratory Study for Nickel Alloy 625 Made by Laser Powder Bed Fusion to Quantify Mechanical Property Variability,” Vol. 25, No. 8, pp. 3390-3397, June 2016.

6. ASTM F519 – 18, “Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments,” ASTM International, Conshohocken, PA, 2018.

7. SAE International, “Steel, Bars, Forgings, and Tubing 0.80Cr – 1.8Ni – 0.25Mo (0.38 – 0.43C) (SAE 4340) Vacuum Consumable Electrode Remelted,” AMS 6414M, SAE International, Warrendale, PA, December 2016.

8. Ferrar, B., Mullen, L., Jones, E., Stamp, R., Sutcliffe, C. J., “Gas flow effects on selective laser melting (SLM) manufacturing performance,” Journal of Materials Processing Technology, Vol. 212, No. 2, pp. 355-364, February 2012.

9. SAE International, “Heat Treatment of Low-Alloy Steel Parts Minimum Tensile Strength 220 ksi (1517 MPa) and Higher,” AMS 2759F, SAE International, Warrendale, PA, 2018.

10. ASTM B311 – 17, “Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity,” ASTM International, Conshohocken, PA, 2017.

11. ASTM E8/E8M, “Standard Test Methods for Tension Testing of Metallic Materials,” ASTM International, Conshohocken, PA, 2015.

12. ASTM E399 – 12e3, “Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc of Metallic Materials,” ASTM International, Conshohocken, PA, 2012.

APPENDIX A
PARTICIPANT QUESTIONAIRE

ARDEC[1] 4340 Round Robin Questionnaire
Machine Type

1. Software
    a. Support Software Version (i.e. Magics):
    b. Equipment Software Version / Parameter Editor (i.e. PSW):
2. AM Equipment Type:
3. Laser Type/Power:
4. Recoating System (Blade/Roller Type):
5. Heat treatment / stress relief capabilities (Y/N):
6. Build Platform
    a. Plate dimensions/material type:
    b. Plate surface roughness:
    c. Preheating temperature:
    d. Build plate needed for round robin?
7. Build Chamber
    a. Atmosphere type:
    b. Min O2 levels:
    c. Max build height:
8. Date of Last Calibration:
9. Ability to Change Process Parameters (Y/N)
    a. Layer thickness:
    b. Scan speed:
    c. Power:
    d. Beam offset:
    e. Laser jump speed:
    f. Stripe width/overlap:
    g. Contour thickness/corridor:
    h. Skin thickness:
    i. Edge factor/threshold:
    j. Recoating charge/boost/speed:
    k. Other (If not in above list, please list below)
10. Address and POC to ship powder to:

11. Cooperation Agreements or other Documentation Needed for Participation?
12. We intend to publish information from the study. Is there any information which should not be shared?
13. Estimated turnaround time from receipt of powder to build completion?

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[1] At the time of the study, the U.S. Army Armaments Research Development and Engineering Center (ARDEC) was the name of the organization currently known as the U.S. Army Combat Capabilities Development Command Armaments Center.

APPENDIX B
MANUFACTURING PLAN

Manufacturing Plan for 4340 Laser Powder Bed Fusion

This manufacturing plan describes the procedures, process, and materials that were developed at ARDEC[2] to print in 4340 steel utilizing a Laser Powder Bed Fusion and for the participants to follow as closely as possible. The purpose is to tightly control processing variables and to document the fabrication of test samples for material property data comparison.

0. Scope and Purpose of Study

   ARDEC will conduct a round robin assessment of various Laser-Powder Bed Fusion machines for 4340 in order to improve the ARDEC manufacturing framework. This is an extension on previous verification builds based on the variability in gathered data and discussions with other institutions on best practices. The focus will be the laser powder bed fusion, otherwise known as the direct metal laser sintering process.

   ARDEC will distribute virgin 4340 powder. Other consumables (such as build plates) will be sent to the participants as needed. Powder will be sampled prior to printing, sample vials will be sent for sampling prior to printing and post printing. Each participant will follow the manufacturing plan as close as possible with the ARDEC provided build files. If the job file, Magics, or slice files are not compatible, ARDEC will assist in constructing the job file with the participant. *This document serves as a guide only, if aspects of the manufacturing plan cannot be followed, they should be identified and addressed with ARDEC and alternate parameters and build details can be determined.*

   Each participant will send the built samples, still on the build plate, to ARDEC. ARDEC will heat treat, remove from the build plates, machine samples, and perform mechanical testing. ARDEC will analyze the data and summarize. All data will be shared with the participant. The data may be published, if the participants wish, the specific results will not be publically attributed. All participants may keep any unused powder and other parts for their own use.

   Each participant should set aside small powder samples for analysis at ARDEC. The samples should include the virgin material and the powder sieved after the build has been completed.

1. Part description, images, associated files.
   a. STL file: Sent via email
   b. JOB file/slice file/Magics file: Sent via email
   c. Process Parameters for Powder Bed Fusion: Sent via email, to be filled out by operator
2. Powder Description
   a. Powder will be supplied to the participants by ARDEC. The powder will arrive with samples vials for storage of the powder before and after the build for analysis of the powder.
   b. Virgin powder will be used for this study.
   c. Powder Storage and Handling: Best Practices
   d. Powder Spec Sheets will be provided
3. Build Preparation
   a. Build platforms can be provided upon request. If using your own, please use the following guidelines:
      i. Material: 1010-1025 steel

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[2] See footnote 1 in appendix A.

    - ii. Thickness: Between 1.5-2 in. thick (if suitable for your machine)
    - iii. Condition: Ground flat to a machined finish
    - iv. Cleanliness: Clean as much of the prior powder as possible and using best practices for ensuring as little contamination as possible.
    - v. Platform level to manufacturer’s guideline within 50 micron using dial indicator.
    - vi. Preheat: Platform should be heated to a temperature of 80 degrees Celsius nominal (50-100C) or according to the manufacturer’s guidelines if it cannot be adjusted.
- b. Recoater System: If using EOS machine, a ceramic blade free of nicks and scratches should be used. If using another machine, please use the system that is within the manufacturer’s specified useful lifetime and/or original specification. It should also be cleaned according to best practices of the manufacturer’s guidelines.
- c. Sufficient quantity of virgin powder for build completion to be loaded into the equipment from shipped containers.
- d. One layer of powder should cover the build plate prior to build start.
- e. Maintenance and Cleaning: Maintained and clean to best of ability for interior, optics, hoppers, recoaters, etc.
- f. Process Parameter:
    - i. ARDEC will be providing via email, JOB files with process parameters preset. For those using EOS machines, please adhere to the settings as much as possible. Please report any changes and/or deviations from the settings and disclose the parameter set. The base parameter set was built using the following parameters:
        1. Base parameter set: the EOS 4340 parameters sent out will be from an EOS M270 with 200 Watt laser.
        2. Layer Thickness : 20 µm layer
        3. Adjust Tab
            - a. The parts will be grouped and the exposure settings will be the same across. Do not change the position and/or rotation of the groups or specimens.

4. Exposure Parameters

   a. 4340 Precontours

      i. Tab1

	Speed (mm/s)	Power (W)	Beam Offset (mm)	Thickness (mm)	Corridor (mm)	Contour	Post Contour
Standard	490	57	0.08	0.04	0.04	Yes	No
OnPart	490	57					
Downskin	490	38					

      ii. Tab2

	Speed (mm/s)	Power (W)	Beam Offset (mm)	Thickness (mm)	Corridor (mm)	Contour	Post Contour
Standard	490	57	0.04	0.04	0.04	Yes	No
OnPart	490	57					
Downskin	490	38					

      iii. Edges

	Edge Factor	Threshold	Min. Radius Factor	Beam Offset (mm)	Speed (mm/s)	Power (W)	Edges	Post Edges
Parameter	2	3	0	0	700	60	No	No

b. 4340 Core

i. Stripes

	Distance (mm)	Speed (mm/s)	Power (W)	Beam offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

ii. UpDown

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X/Y	Overlap with inskin (mm)	Sky writing	Minimum length (mm)
Upskin	0.1	400	195	0	No	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes				

iii. Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

c. 4340 Postcontours

i. Table 1

	Speed (mm/s)	Power (W)	Beam offset (mm)	Thickness (mm)	Corridor (mm)	Contour	Post contour
Standard	490	57	0.02	0.04	0.04	Yes	Yes
On Part	490	57					
Downskin	490	38					

ii. Table 2

	Speed (mm/s)	Power (W)	Beam offset (mm)	Thickness (mm)	Corridor (mm)	Contour	Post contour
Standard	490	57	0	0.06	0.04	Yes	Yes
On Part	490	57					
Downskin	490	38					

iii. Edges

	Edge factor	Threshold	Minimum radius factor	Beam offset (mm)	Speed (mm/s)	Power (W)	Edges	Post edges
Parameter	2	3	0	0	700	60	Yes	Yes

            - iv. 4340 Exposure Skin/Core
                1. Skin Thickness (x/y): 200mm
                2. Skin Thickness (z): 200mm
                3. Base Radius: 0 mm
                4. Core Open to Platform: No
                5. Skin/Core: Yes
    2. Building
        a. Start Height: .02mm
        b. Final Height: 70.56mm
        c. Layer Thickness: 20 micron
    3. DMLS
        a. DMLS will be checked
        b. Preexposure will be set to .12 mm
    4. Recoating
        a. Minimum Charge amount: 125%
        b. Maximum Charge amount: 130%
        c. Dosing boost amount: 400%
        d. Recoater Speed 1: 500mm/s
        e. Recoater Speed 2: 80 mm/s
        f. Lower Dispenser Platform: 1.00 mm
        g. Contact free outward travel: Yes
    5. Scanner Settings
        a. Automatic Calibration: Yes
    6. Build Chamber Environment
        a. Purge Gas: Nitrogen
        b. Flow rate: On EOS (5 meters)
        c. Flow meter Voltage: On EOS (2.05 V)
        d. Filtration: Enabled
        e. Oxygen Level: <1.3% (13,000 ppm) Maximum

5. In Process
    a. If exceed oxygen level (1.3% - 13000 ppm) then build will be stopped
    b. Pause/Build Interrupt: Disclose reason and continue.
6. Post Build
    a. Remove build plate once cool and remove excess powder.
    b. Store small sample of the used powder in the vial. Take a well-blended sample.
    c. May keep any unused powder for own use or can return powder if desired.
    d. Send plate and sample powder to ARDEC.
7. Schema
    a. Manufacturing Data should be recorded using the following format: Powder Bed Fusion Template

APPENDIX C
SPECIMEN MEASUREMENT SUMMARY

	Nominal	1	2	3	4	5	6	7	STDDEV
A	0.27	0.269	0.283	0.275	0.2667	0.2727	0.2682	0.2688	0.005
B	0.27	0.2704	0.2812	0.275	0.2682	0.2751	0.27	0.2709	0.004
C	0.27	0.2703	0.2757	0.276	0.2677	0.2735	0.2681	0.269	0.003
DEF-1	2.75	2.755	2.766	2.756	2.741	2.75	2.747	2.749	0.007
DEF-2	0.375	0.381	0.396	0.385	0.374	0.381	0.376	0.377	0.007
G	0.472	0.475	0.49	0.479	0.471	0.478	0.471	0.472	0.006
H	0.472	0.475	0.49	0.477	0.47	0.478	0.473	0.475	0.006
IJK-1	2.75	2.754	2.762	2.759	2.739	2.75	2.748	2.752	0.007
IJK-2	0.375	0.379	0.399	0.381	0.374	0.382	0.376	0.379	0.008
L	0.27	0.2695	0.274	0.276	0.2684	0.2738	0.269	0.2699	0.003
M	0.27	0.2707	0.28125	0.275	0.2678	0.2751	0.2702	0.2702	0.004
N	0.27	0.2699	0.282	0.276	0.2677	0.2772	0.2698	0.2707	0.005
O	0.27	0.2695	0.2813	0.275	0.2677	0.273	0.2672	0.2698	0.005
P	0.27	0.2696	0.2808	0.274	0.2644	0.2737	0.267	0.2699	0.005
Q	0.27	0.2695	0.282	0.274	0.2663	0.2747	0.27	0.2693	0.005
RST-1	2.75	2.754	2.75	**N/A**	2.741	2.753	2.744	2.754	0.005
RST-2	0.375	0.378	0.392	**N/A**	0.372	0.381	0.375	0.38	0.006
U	0.472	0.475	0.486	0.479	0.468	0.48	0.473	0.475	0.005
V	0.27	**BENT**	0.274	0.277	0.2671	0.2734	0.2677	**N/A**	0.004
W	0.27	0.27	0.2808	0.276	0.2672	0.2746	0.268	0.2705	0.005
X	0.27	0.2709	0.2837	0.277	0.2676	0.2753	0.269	0.2708	0.005
YZ1-1	2.75	2.756	2.766	**N/A**	2.741	2.749	2.743	2.753	0.008
YZ1-2	0.375	0.381	0.394	**N/A**	0.373	0.381	0.375	0.378	0.007
2	0.472	0.475	0.4915	0.482	0.468	0.478	0.47	0.476	0.007
3	0.472	0.475	0.4915	0.48	0.469	0.479	0.475	0.474	0.007
456-1	2.75	2.755	2.766	2.759	2.741	2.749	2.747	2.756	0.008
456-2	0.375	0.38	0.3965	0.382	0.373	0.381	0.379	0.38	0.007
7	0.27	0.2704	0.2868	0.274	0.2674	0.2734	0.2696	0.2727	0.006
8	0.27	0.2702	0.2826	0.275	0.2682	0.273	0.2703	0.2716	0.004
9	0.27	0.2705	0.287	0.274	0.2679	0.2738	0.2691	0.2706	0.006
K1-1	2.24	2.242	2.251	2.247	2.234	2.242	2.234	2.243	0.006
K1-2	0.315	0.318	0.333	0.325	0.315	0.3215	0.314	0.319	0.006

APPENDIX D
DATA SCHEMA

Build Facility			
Organization:	US Army ARMY		
Facility:	Picatinny Arsenal		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	EOSINT M270		
Support Software Version:	Magics 20		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	69.6F/42%/45.5F		
Filtration System Type	H13/F9 (Large coarse over fine)		
Current Hours on Installed Filters	117.2		
Equipment Software/Parameter Editor:	PSW 3.7.60		
Recoater System	Ceramic Blade	Other:	
Build Stakeholders			
Operator Name:	Elias Jelis		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	Low carbon steel		
Build Plate Manufacturer:			
Build Plate Chemistry Certificate			
Build Plate Dimensions: (x,y.z) (L*W*H) ?	9.85"x 9.85"x1.83"	Build Plate Label:	29
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:			
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71
Dosing Boost Amount	400 %	Preheat Temperature (deg C):	80

Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Build 0:

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:	6/16/17	STL File:	**Provided**
Build Run Time:	~48hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	EOSINT M270
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.7.60
Last Machine Calibration Date:	2/4/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**2/4/2017**
Laser Type	**Yb 200W-1060nm**
Fiber Diameter, µm:	100
Beam Setting	2.0
Current Laser Hours	7411.6
Optical Scanning Device	Galvomotors
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	F-theta
Chamber Atmosphere	Nitrogen
Process Control Software Origin:	Magics 19.0
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
Feed: 150/150 initial; At .38mm 120/120; At .80mm 150/150; At .84 mm,
125/125 Slight Vibration during recoater travel.
Plate was chipped on top left corner
Did not fully feed bottom left tensile block and outermost left z tensile round (19)
initially More spatter at bottom left corner

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core

Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS

Checked	Y
Pre-exposure	0.12

Build 1

Build Facility			
Organization:	US Army ARMY		
Facility:	Picatinny Arsenal		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	EOSINT M270		
Support Software Version:	Magics 20		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	68.7F/42%/45.9F		
Filtration System Type	H13/F9 (Large coarse over fine)		
Current Hours on Installed Filters	110.03		
Equipment Software/Parameter Editor:	PSW 3.7.60		
Recoater System	Ceramic Blade	Other:	
Build Stakeholders			
Operator Name:	Matthew Clemente		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	Low carbon steel		
Build Plate Manufacturer:			
Build Plate Chemistry Certificate			
Build Plate Dimensions: (x,y.z) (L*W*H) ?	9.85"x 9.85"x1.82"	Build Plate Label:	26
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:			
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71
Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:	9/24/17	STL File:	**Provided**
Build Run Time:	~44hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	EOSINT M270
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.7.60
Last Machine Calibration Date:	8/3/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**8/3/2017**
Laser Type	**Yb 200W-1060nm**
Fiber Diameter, µm:	100
Beam Setting	2.0
Current Laser Hours	7949.9
Optical Scanning Device	Galvomotors
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	F-theta
Chamber Atmosphere	Nitrogen
Process Control Software Origin:	Magics 19.0
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
Spatter at all region except top right and middle Feed : 150/150; At 1.02, it drops to 125/125%
Build stopped at 53.62 at 44 hours build time (recoater jammed and excessive spatter all over chamber). Recovery of the build was attempted, but failed due to part failure.

4340 Core Stripe Exposure							
	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure										
	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer	
Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core	
Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS	
Checked	Y
Pre-exposure	0.12

Build 2

Build Facility			
Organization:	*		
Facility:	*		
Building Number:	*		
Machine Manufacturer:	3dsystems		
Machine Model:	prox300		
Support Software Version:	px control 2.1.3.3		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	50% humidity/74 degrees farenheight		
Filtration System Type	external		
Current Hours on Installed Filters			
Equipment Software/Parameter Editor:	Phenix manufacturing		
Recoater System	Roller Compression	Other:	
Build Stakeholders			
Operator Name:	*		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	aisi 430		
Build Plate Manufacturer:	3d systems		
Build Plate Chemistry Certificate			
Build Plate Dimensions: (x,y.z) (L*W*H) ?	250mmx250mmx25mm	Build Plate Label:	
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:			
Process Parameter Settings			
1000 ppm	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	1000 ppm
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	n/a
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	52.5
Dosing Boost Amount	n/a	Preheat Temperature (deg C):	50
Lower Dispenser Platform	n/a	Contact Free Outward Travel	n/a

Process Information				
Sample #:	1	2	3	4

Laser Scan Parameters - Part Exposure	See exposure Tab

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	Provided
Build End Date:	9/23/17	STL File:	Provided
Build Run Time:	42	Build File (i.e Magics etc.):	Provided
Batch Location on Build Plate Top View (See Image Below):	Whole		
Build Top View Image (Include Batch Location on Build Plate):	N/A		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	3d systems
Additive System Model:	prox 300
Additive System Serial No.:	*
Machine Software Version Number:	2.1.3.3
Last Machine Calibration Date:	May-17
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**May-17**
Laser Type:	Yt Fiber - 1070nm
Fiber Diameter, µm:	
Beam Setting	n/a
Current Laser Hours	
Optical Scanning Device	n/a
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	f-theta lens
Chamber Atmosphere	nitrogen
Process Control Software Origin:	OEM
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
Processing Parameters used:
Speed: 700mm/s Power-
185 Watts
Hatch spacing 0.100 mm
Layer thickness -.02mm
Scanning strategy changed to a hexagon island based scan strategy with Angles alternating +/-45
degrees hexagon width 4 mm
Hexagon overlap .05mm 02
max- 1000ppm
Oven 50 degrees C
Sintered layer 1 x3
sinter layer 2 x2 sinter
layer
Due to powder limitations only built up to 52.5 mm tall
At layer 852(17.04mm) build was stopped to move
powder At layer 1008(20.14mm) build was stopped to
move powder

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	n/a	n/a	n/a	
	Hexagon Width (mm)	Hexagon Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	no	no	Yes	no	Angle +/-45

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin										
Downskin										

4340 Core Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core

Skin Thickness (x/y)	
Skin Thickness (z)	
Base radius	
Core Open to Platform	
Skin/Core	

DMLS

Checked	Y
Pre-exposure	

Build 3

Bu+A3:E67ild Facility			
Organization:	*		
Facility:	*		
Building Number:	N/A		
Machine Manufacturer:	SLM Solutions		
Machine Model:	280 HL		
Support Software Version:	Magics 21.11		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	21.6c		
Filtration System Type	Paper filter		
Current Hours on Installed Filters	N/A		
Equipment Software/Parameter Editor:	Build Processor		
Recoater System	Rubber Blade	Other:	
Build Stakeholders			
Operator Name:	*		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	1018 Steel		
Build Plate Manufacturer:	*		
Build Plate Chemistry Certificate	**N/A**		
Build Plate Dimensions: (x,y.z) (L*W*H) ?	278mm x 278mm x 25.4	Build Plate Label:	N/A
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:	50%		
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	30
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71
Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4

Approved for public release; distribution is unlimited

Laser Scan Parameters - Part Exposure	See exposure Tab

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	Provided
Build End Date:	11/16/17	STL File:	Provided
Build Run Time:	27hrs Build# 1 / 11hrs Build#2	Build File (i.e Magics etc.):	Provided
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	N/A		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	N/A

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	SLM Solutions
Additive System Model:	280 HL
Additive System Serial No.:	N/A
Machine Software Version Number:	
Last Machine Calibration Date:	Mar-17
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**Nov-14-17**
Laser Type:	Nd:YAG - 1060nm
Fiber Diameter, µm:	Unknown
Beam Setting	2.0
Current Laser Hours	Unknown
Optical Scanning Device	Unkown
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	Unknown
Chamber Atmosphere	Argon
Process Control Software Origin:	OEM
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
2 builds with noncritical errors which prevented parts for being build.

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core

Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS

Checked	Y
Pre-exposure	0.12

Build 4

Build Facility			
Organization:	*		
Facility:	*		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	M270		
Support Software Version:	PSW3.6 Build 86		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	20.7 C/50%/NA		
Filtration System Type	EOS Recycling Filter Unit		
Current Hours on Installed Filters	385.66		
Equipment Software/Parameter Editor:			
Recoater System		Other:	
Build Stakeholders			
Operator Name:	*		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	2200-4373 Building platform DirectBase S36		
Build Plate Manufacturer:	EOS		
Build Plate Chemistry Certificate			
Build Plate Dimensions: (x,y.z) (L*W*H) ?	250 x 250 x 36 mm	Build Plate Label:	
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:			
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71

Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:		STL File:	**Provided**
Build Run Time:	~48hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	M270
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.6 Build 86
Last Machine Calibration Date:	9/8/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**9/8/2017**
Laser Type:	Yb fiber laser
Fiber Diameter, µm:	
Beam Setting	2.0
Current Laser Hours	3139.0
Optical Scanning Device	
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	
Chamber Atmosphere	Nitrogen
Process Control Software Origin:	
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Not
At 48 mm Build Height; added morre material to the Dispensor after calculating that I was a bit short for the remaining Build.es Here:

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core

Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS

Checked	Y
Pre-exposure	0.12

Build 5

Build Facility			
Organization:	*		
Facility:	*		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	M280		
Support Software Version:	Windows Embedded Standard: Service Pack 1: 64 bit		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	72˚F/39%RH (@ Start)		
Filtration System Type	M280 LAS (F9: 457x457x150 mm)		
Current Hours on Installed Filters	5 hr 19 min (Full PM performed before these builds, 5hr 19 min for the required fine tuning build). Note two builds for this cycle - one aborted at 14hr 11 min, and the final build 52hr 52 min		
Equipment Software/Parameter Editor:	PSW 3.8 Build 72		
Recoater System	Ceramic Blade	Other:	
Build Stakeholders			
Operator Name:	*		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	Steel		
Build Plate Manufacturer:	EOS		
Build Plate Chemistry Certificate	**none**		
Build Plate Dimensions: (x,y.z) (L*W*H) ?	standard	Build Plate Label:	
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:			
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.5
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02

Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71
Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:		STL File:	**Provided**
Build Run Time:	~48hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	M280
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.8 Build 72
Last Machine Calibration Date:	8/31/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**8/31/2017**
Laser Type:	Yb Fiber - 400W
Fiber Diameter, µm:	?
Beam Setting	2.0
Current Laser Hours	5622.33 (at start of first build)
Optical Scanning Device	EOS standard, x-y galvo
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	EOS standard, x-y galvo with f-theta lens
Chamber Atmosphere	nitrogen
Process Control Software Origin:	
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here: I had a fair bit of trouble with the tall cylinders, recoater jam stopped the build at 56.10 mm. I had to remove two parts from the build at

that juncture. That stuff is super hard and very difficult to get past the recoater once it starts to clip it.

Then several more at around 69-70 mm.

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core

Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS

Checked	Y
Pre-exposure	0.12

Build 6

Build Facility			
Organization:	*		
Facility:	*		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	EOS M270 Ext Ti		
Support Software Version:	PSW 3.4		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	73 F; 42% RH		
Filtration System Type	ULT F9 & H13		
Current Hours on Installed Filters	~ half filter life		
Equipment Software/Parameter Editor:	PSW 3.4		
Recoater System	Ceramic Blade	Other:	
Build Stakeholders			
Operator Name:	*		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	Provided by ARDEC		
Build Plate Manufacturer:	Provided by ARDEC		
Build Plate Chemistry Certificate	**Provided by ARDEC**		
Build Plate Dimensions: (x,y.z) (L*W*H) ?	Provided by ARDEC	Build Plate Label:	
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	N/A	
If Recycled, What % Recycled:			
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20

Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71

Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:	8/26/17	STL File:	**Provided**
Build Run Time:	~48hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):	Center		
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	*
Specimen location in part:	**In accordance with ARDEC instructions**
Definition of Initial Location and Orientation for a Part:	**In accordance with ARDEC instructions**

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	M270 Ext Ti
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.4
Last Machine Calibration Date:	6/6/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**6/6/2017**
Laser Type:	IPG 200W
Fiber Diameter, µm:	
Beam Setting	2.0
Current Laser Hours	8460.0
Optical Scanning Device	
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	f-theta
Chamber Atmosphere	Nitrogen
Process Control Software Origin:	
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
From what I can tell the recoater blade caught on sample 6b at 44.5mm, caused deflection, and created a defect. In addition, minor defects are visible on 6L,6M, and 6N at the same height. An additional similar defect is visible at 55mm on 6L. I do not see issues with the other parts. The build completed, and the recoater did not jam and stop the build. This event happened over the weekend when no one was around.

Also, there was some confusion gathering the post-build powder. The powder that was sent was gathered after the sieving operation.

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer	
Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure Skin/Core	
Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS	
Checked	Y
Pre-exposure	0.12

Build 7

Build Facility			
Organization:	US Army		
Facility:	Picatinny Arsenal		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	EOSINT M270		
Support Software Version:	Magics 20		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	72.3F/47%/50.9F		
Filtration System Type	H13/F9 (Large coarse over fine)		
Current Hours on Installed Filters	145.02		
Equipment Software/Parameter Editor:	PSW 3.7.60		
Recoater System	Ceramic Blade	Other:	

Build Stakeholders			
Operator Name:	Elias Jelis		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		

Build Plate Information			
Build Plate Material / Specification:	Low carbon steel		
Build Plate Manufacturer:			
Build Plate Chemistry Certificate			
Build Plate Dimensions: (x,y.z) (L*W*H) ?	9.85"x 9.85"x1.91"	Build Plate Label:	28

Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	1 at 74microns screen size	
If Recycled, What % Recycled:	100.0%		

Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71
Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:	9/29/17	STL File:	**Provided**
Build Run Time:	49.2hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	EOSINT M270
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.7.60
Last Machine Calibration Date:	8/3/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**8/3/2017**
Laser Type	**Yb 200W-1060nm**
Fiber Diameter, µm:	100
Beam Setting	2.0
Current Laser Hours	7984.9
Optical Scanning Device	Galvomotors
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	F-theta
Chamber Atmosphere	Nitrogen
Process Control Software Origin:	Magics 19.0
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
Start dosing 150/150. Lowered to 125/125
at .42mm At 41.96 mm build height:
specimen 77 was removed.

At 43.220mm build height: Recoater Jammed and specimen 79 was
removed. Closed and pumped down single exposure
At 47.580mm build height: specimen 78 was removed
At 59. 680 mm build height: removed bottom right corner (7V,7W,7X)

4340 Core Stripe Exposure							
	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure										
	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer	
Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

4340 Exposure	Skin/Core
Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS	
Checked	Y
Pre-exposure	0.12

Approved for public release; distribution is unlimited

Build 8

Build Facility			
Organization:	US Army ARMY		
Facility:	Picatinny Arsenal		
Building Number:	*		
Machine Manufacturer:	EOS		
Machine Model:	EOSINT M270		
Support Software Version:	Magics 20		
Machine Room Ambient Conditions (Temp/Humidity/Dewpoint)	72.7F/35%/43.3F		
Filtration System Type	H13/F9 (Large coarse over fine)		
Current Hours on Installed Filters	23.4		
Equipment Software/Parameter Editor:	PSW 3.7.60		
Recoater System	Ceramic Blade	Other:	
Build Stakeholders			
Operator Name:	Elias Jelis		
Customer Name:	US Army ARDEC		
Customer Facility:	Picatinny		
Customer Organization:	Powder Prototyping Technology Branch		
Build Plate Information			
Build Plate Material / Specification:	Low carbon steel		
Build Plate Manufacturer:			
Build Plate Chemistry Certificate			
Build Plate Dimensions: (x,y.z) (L*W*H) ?	9.85"x 9.85"x1.42"	Build Plate Label:	25
Additive Material			
Additive Material Type (Metal Class):	Powder	Additive Material Lot #:	Y5846B
Additive Material Specification (Metal Grade):	4340 Steel	Powder Specification Sheet:	N/A
Additive Material Manufacturer or Provider:	Carpenter Powder Products		
Powder Size Range, µm or sieve:	22-53 micron	For Lot #, explain the number of times the powder has been recycled below:	
Powder Origin (Virgin, Recycled):	Virgin	twice after mixing at 74microns screen size	
If Recycled, What % Recycled:	100.0%		
Process Parameter Settings			
Exposure Parameter Filename	**4340_P185_S700_H010_W4_T20**	Chamber Oxygen Level (%)	<1.3%
Recoater Speed 1, mm/sec (±%)	500	Flow Meter Voltage (V)	2.05
Recoater Speed 2, mm/sec (±%)	80	Layer Thickness: (micron)	20
Recoater Min Dosing	Start: 150% @1mm: 125%	Start Height (mm)	0.02
Recoater Max Dosing	Start: 150% @1mm: 125%	Final Height (mm)	71
Dosing Boost Amount	400%	Preheat Temperature (deg C):	80
Lower Dispenser Platform	1mm	Contact Free Outward Travel	Yes

Process Information				
Sample #:	1	2	3	4
Laser Scan Parameters - Part Exposure	See exposure Tab			

Batch Information			
Does this Build Fall Under ITAR?	No	Drawing #:	N/A
Batch Label:	N/A	Drawing File:	**Provided**
Build End Date:	10/27/17	STL File:	**Provided**
Build Run Time:	49.3hrs	Build File (i.e Magics etc.):	**Provided**
Batch Location on Build Plate Top View (See Image Below):			
Build Top View Image (Include Batch Location on Build Plate):	**N/A**		

Part Definition	
Part Drawing/Geometry:	
Specimen location in part:	
Definition of Initial Location and Orientation for a Part:	

Description of Part Locations and Orientations (ISO/ASTM 52921)

Location (X, Y, Z) (in):	N/A			
Reorientation (A, B, C) (deg):	N/A			
Initial Orientation:	N/A			

Build Information

Number of Layers	N/A			
Slice Height	N/A			
Slice File	N/A			

Machine Parameter Settings

Additive System Manufacturer:	EOS
Additive System Model:	EOSINT M270
Additive System Serial No.:	*
Machine Software Version Number:	PSW 3.7.60
Last Machine Calibration Date:	8/3/2017
Last Machine Calibration Document:	**N/A**
Last Machine Maintenance Date:	**8/3/2017**
Laser Type	**Yb 200W-1060nm**
Fiber Diameter, µm:	100
Beam Setting	2.0
Current Laser Hours	8109.8
Optical Scanning Device	Galvomotors
Scanning Optic Characteristics (focal length, optical arrangement (such as f-theta lens)	F-theta
Chamber Atmosphere	Nitrogen
Process Control Software Origin:	Magics 19.0
Streaming Data	**N/A**
Summary Data	**N/A**

Insert Build Notes Here:
Start and Final dosing
150/150. @42.160
removed 8V @42.540
removed 8W, 8X Built
to final height

4340 Core Stripe Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Beam Offset (mm)	X Hatch	Y Hatch	
Parameter	0.1	700	185	0.04	Yes	Yes	
	Stripe Width (mm)	Stripes Overlap (mm)	Skywriting	Offset	Alternating	Rotating	Rotated Angle
	4	0.05	Yes	Yes	Yes	Yes	67

4340 Core UpDown Exposure

	Distance (mm)	Speed (mm/s)	Power (W)	Thickness (mm)	Alternating	X	Y	Overlap w/ Inskin (mm)	Skywriting	Min. Length (mm)
Upskin	0.1	400	180	0	No	Yes	Yes	0.1	Yes	0.3
Downskin	0.04	3000	195	0	Yes					

4340 Core Skip Layer

Skipped Layers	0
Offset Layers	0
Expose First Layer	Yes

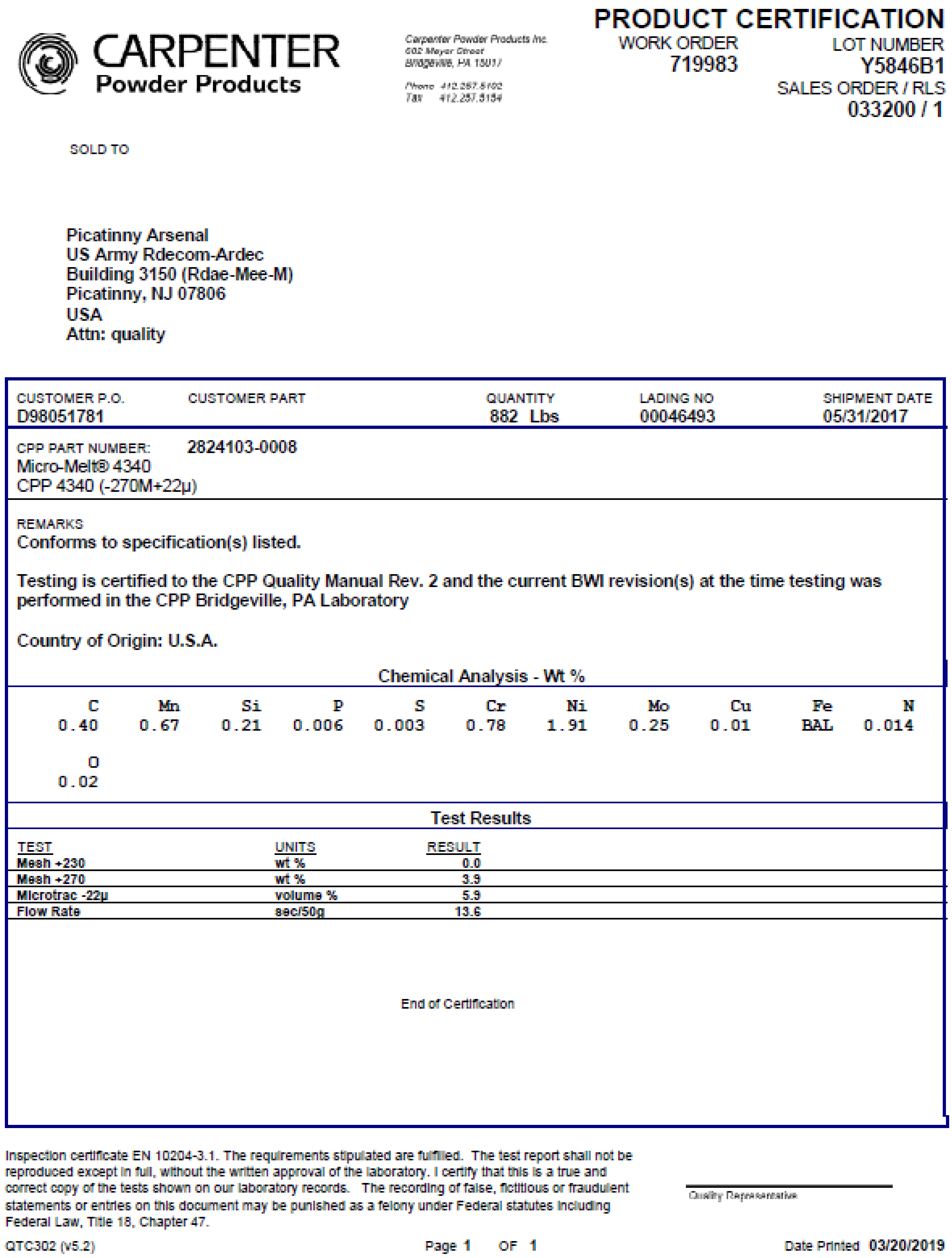
4340 Exposure Skin/Core

Skin Thickness (x/y)	200mm
Skin Thickness (z)	200mm
Base radius	0mm
Core Open to Platform	No
Skin/Core	Yes

DMLS

Checked	Y
Pre-exposure	0.12

APPENDIX E
POWDER CERTIFICATION



CARPENTER
Powder Products

Carpenter Powder Products Inc.
600 Mayer Street
Bridgeville, PA 15017

Phone 412.257.5102
Fax 412.257.5154

PRODUCT CERTIFICATION

WORK ORDER	LOT NUMBER
719983	Y5846B1
	SALES ORDER / RLS
	033200 / 1

SOLD TO

Picatinny Arsenal
US Army Rdecom-Ardec
Building 3150 (Rdae-Mee-M)
Picatinny, NJ 07806
USA
Attn: quality

CUSTOMER P.O.	CUSTOMER PART	QUANTITY	LADING NO	SHIPMENT DATE
D98051781		882 Lbs	00046493	05/31/2017

CPP PART NUMBER: 2824103-0008
Micro-Melt® 4340
CPP 4340 (-270M+22µ)

REMARKS
Conforms to specification(s) listed.

Testing is certified to the CPP Quality Manual Rev. 2 and the current BWI revision(s) at the time testing was performed in the CPP Bridgeville, PA Laboratory

Country of Origin: U.S.A.

Chemical Analysis - Wt %

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe	N
0.40	0.67	0.21	0.006	0.003	0.78	1.91	0.25	0.01	BAL	0.014
O										
0.02										

Test Results

TEST	UNITS	RESULT
Mesh +230	wt %	0.0
Mesh +270	wt %	3.9
Microtrac -22µ	volume %	5.9
Flow Rate	sec/50g	13.6

End of Certification

Inspection certificate EN 10204-3.1. The requirements stipulated are fulfilled. The test report shall not be reproduced except in full, without the written approval of the laboratory. I certify that this is a true and correct copy of the tests shown on our laboratory records. The recording of false, fictitious or fraudulent statements or entries on this document may be punished as a felony under Federal statutes including Federal Law, Title 18, Chapter 47.

Quality Representative

QTC302 (v5.2) Page 1 OF 1 Date Printed 03/20/2019

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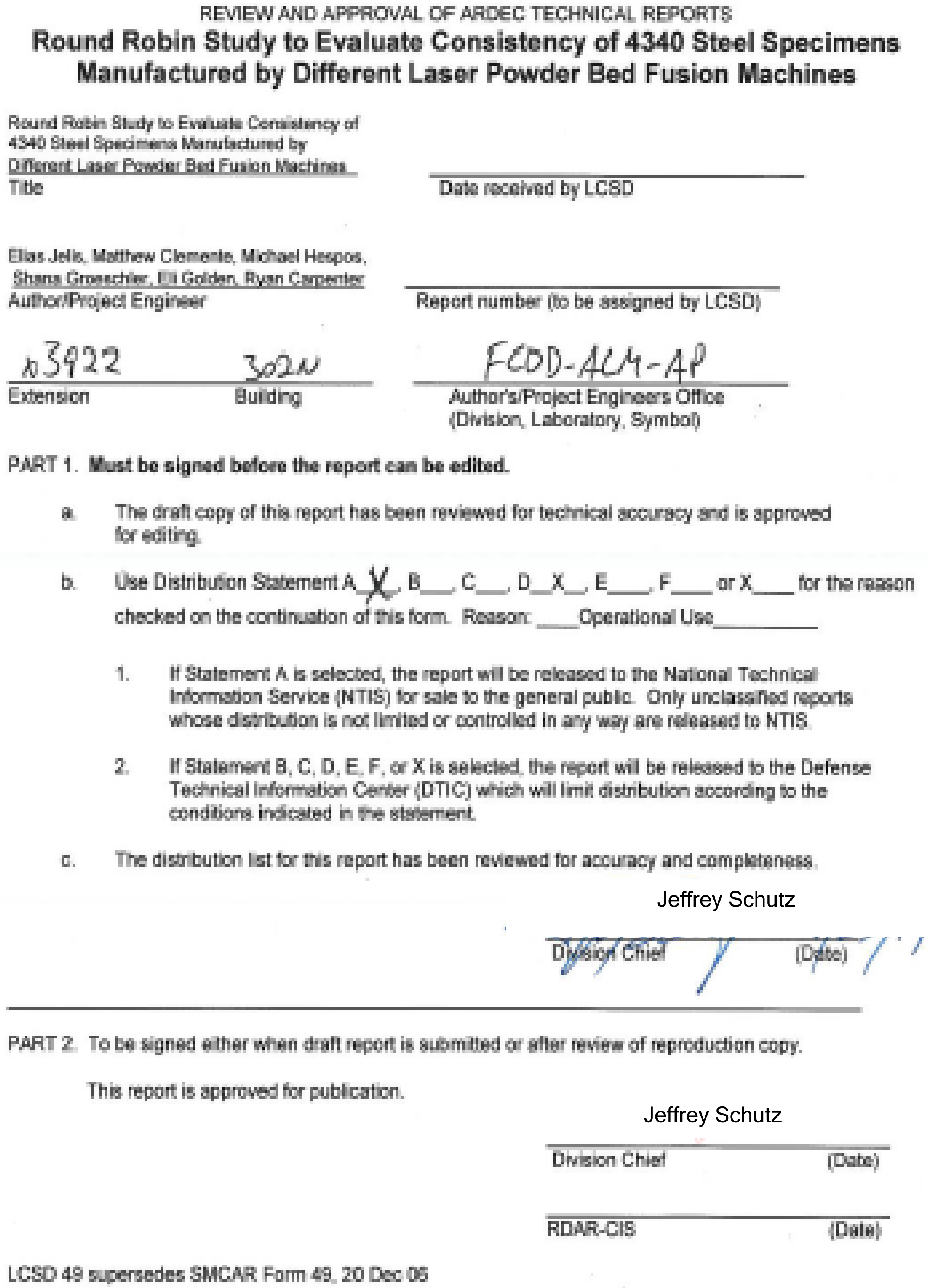

REVIEW AND APPROVAL OF ARDEC TECHNICAL REPORTS

Round Robin Study to Evaluate Consistency of 4340 Steel Specimens Manufactured by Different Laser Powder Bed Fusion Machines

Round Robin Study to Evaluate Consistency of
4340 Steel Specimens Manufactured by
Different Laser Powder Bed Fusion Machines
Title

Date received by LCSD

Elias Jelis, Matthew Clemente, Michael Hespos,
Shana Groeschler, Eli Golden, Ryan Carpenter
Author/Project Engineer

Report number (to be assigned by LCSD)

x3922 Extension
302N Building

FCDD-ACM-AP
Author's/Project Engineers Office
(Division, Laboratory, Symbol)

PART 1. **Must be signed before the report can be edited.**

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Jeffrey Schutz
Division Chief (Date)

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Jeffrey Schutz
Division Chief (Date)

RDAR-CIS (Date)

LCSD 49 supersedes SMCAR Form 49, 20 Dec 06