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**PARAMETER DEVELOPMENT FOR LASER POWDER BED FUSION
OF 4340 STEEL AT 60-MICRON LAYERS**

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14. ABSTRACT Process parameters were developed by the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ, for laser powder bed fusion (L-PBF) of 4340 steel on an EOS M290 three-dimensional (3D) printer at 60-micron layer thickness to decrease build time (approximately 33%) as compared to previously developed 4340 steel parameters at 40-micron layer thickness. Optimal process parameters (hatch distance and laser scan speed) were selected based on the highest specimen density produced from an experiment where these parameters were varied. A verification build was then built with the optimized parameter set. It consisted of X, Y, and Z-oriented tensile coupons in five locations (four corners and the center of the build plate). The tensile specimens were then machined, heat treated, and characterized. Two tensile blocks were removed from the front of the build plate due to spatter particles that settled on the tensile blocks which could have caused the recoater blade to jam. All but one specimen in the front of the build platform met wrought 4340 steel minimum requirements.											
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INTRODUCTION

Laser powder bed fusion (L-PBF) is a metals additive manufacturing (AM) process which uses a laser to selectively fuse together layers of metal powder. The parts built in this manner, layer by layer, can be produced fully dense to net shape and include highly complex features that would be difficult or impossible to make using traditional subtractive manufacturing techniques. The AM process complements other manufacturing processes by allowing rapid tooling and prototyping (ref. 1).

Process parameters for L-PBF of 4340 steel were developed at the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ, because this specific metal is found in many U.S. Army commodities (refs. 2 and 3). 4340 steel is a low-alloy steel with high strength and adequate toughness.

The objective of this effort is to decrease the build time of L-PBF 4340 steel to reduce the cost for large components. Originally, 4340 steel parameters were developed for builds with a 40-micron layer thickness on the EOS M290 three-dimensional (3D) printer in which required tensile properties were met consistently. The build times were too high to meet the program cost requirements. Therefore, 60-micron layer thickness parameters were developed and were shown to decrease the build time by approximately 33%. However, the minimum tensile requirements were not met consistently.

BACKGROUND

Optimized process parameters for L-PBF of 4340 steel for the EOS M290 3D printer were developed by first building metallurgical cubes of 4340 steel by varying process parameters. These parameters were hatch distance and laser scan speed across 15 different iterations (parameter combinations). The densities of these cubes, as a function of the parameters, were then analyzed to determine the parameter set which produced the highest density according to image analysis utilizing optical microscopy. Next, a verification build was completed to generate samples using the highest density parameter set. Tensile properties were evaluated as a function of build plate location.

EXPERIMENTAL

Fifteen metallurgical cubes were built at different hatch distances and laser scan speeds with a 60-micron layer thickness. The cubes were then removed from the build plate, mounted, and polished. Porosity of the X-Z plane was measured in the unetched condition at 100X magnification using optical microscopy. The X-Z plane was selected to evaluate the effects of build layers on porosity.

The build layout of the verification build is depicted in figure 1. The layout included a cluster of tensile specimens and metallurgical cubes built at five locations (center and four corners). Each cluster included three horizontal (X-Y) and three Z-oriented tensile specimens. Refer to the gnomon in figure 1 (right) for orientation.

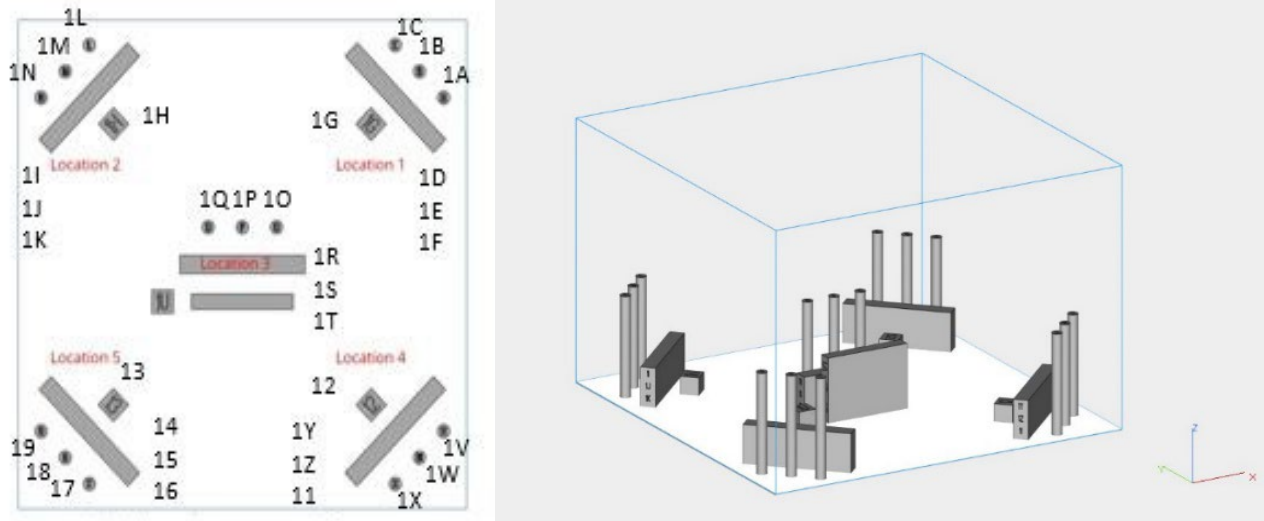


Figure 1
Schematic of top view (left) and angled view (right) of the verification build

The post-build heat treatment was as follows: the parts were stress relieved at 593 °C (1,099 °F) for 1 hr. Next, they were normalized at 900 °C (1,652 °F) for 1 hr, furnace cooled to 650 °C (1,202 °F), and then air cooled to ambient. Finally, the specimens were austenitized at 816 °C (1,501 °F), quenched in oil, and double tempered at 190 °C (374 °F) for 2 hr each in accordance with (IAW) AMS2759 (ref. 3). The nominal hardness after heat treating was 50 Rockwell hardness (HRC).

Upon completion of heat treatment, the tensile specimens were prepared with a 0.16-in. (4.06-mm) reduced section IAW ASTM E8 (ref. 4). Horizontal specimens were cut with centers at 0.235 in. (5.97 mm), 0.575 in. (14.61 mm), and 0.915 in. (23.24 mm) from the surface of the build plate. The tensile testing was performed at room temperature on an MTS test frame with V-serrated wedges in hydraulic grips and a 50,000-lb load cell. The mechanical properties were compared to wrought 4340 steel heat treated to 50 HRC to determine whether the process parameters were acceptable.

RESULTS

Parameter Development

The hatch distance and laser scan speed were varied. The resulting metallurgical cube specimen densities exceeded 99.9% according to image analysis for many parameter sets. Parameter A3 had the lowest porosity (fig. 2 and table 1). Therefore, the A3 parameter set was selected for the verification build.



Figure 2
Image analysis of sample A3

Table 1
Parameter sets along with their corresponding image analysis results for the 60-micron layer thickness development build

Parameters	Laser power (Watts)	Laser scan speed (mm/sec)	Hatch distance (mm)	Density image analysis (%)
A1	300	500	0.08	99.36
A2	300	650	0.08	99.96
A3	300	800	0.08	99.97
A4	300	950	0.08	99.96
A5	300	1,100	0.08	99.94
A6	300	500	0.1	98.98
A7	300	650	0.1	99.92
A8	300	800	0.1	99.96
A9	300	950	0.1	99.96
A10	300	1,100	0.1	99.93
A11	300	500	0.12	99.40
A12	300	650	0.12	99.93
A13	300	800	0.12	99.91
A14	300	950	0.12	99.86
A15	300	1,100	0.12	99.45

Mechanical Properties

Process parameters for the verification build are included in table 2. All tensile specimens exceeded minimum wrought requirements except for one of the samples in the front left corner (sample 17). The ductility of the specimen was lower than the minimum requirement, as shown in table 3. The gas flows from the back to the front of the build chamber. The large defect (>100 microns) on the fracture surface of the sample with the lowest ductility is shiny, which is indicative of spatter particle which bonded to the interior of the part with the laser during the build (fig. 3). The two front X-Y tensile blocks were removed because the recoater blade hit spatter particles that settled on the surface of the build, which created an uneven powder bed layer that would eventually form defects. These defects could have resulted in the ceramic blade jamming on the spatter irregularities. (However, for the previously investigated 40-micron layer verification build, all components were able to be built without issue and all components met minimum mechanical properties.) Also, the Z-oriented tensiles in the back right corner (1A, 1B, and 1C as per fig. 1) were not included because they were not heat treated properly.

Table 2
Process parameters for verification build

Laser power	300 Watts
Laser scan speed	800 mm/sec
Hatch distance	0.08 mm
Layer thickness	0.06 mm
Stripe width	4 mm
Stripe overlap	0.08 mm
Laser beam diameter	0.08 mm
Build platform temperature	160 °C
Gas pressure	1.00 mbar
Inert gas used	Argon
Gas nozzle	Grid
Hatch rotation	47 deg

Table 3
Tensile results for the verification build with parameter set A3 from the parameter development build

	Yield strength (ksi)	Tensile strength (ksi)	Elongation (%)	Strain at break (%)	Reduction in area (%)
Average	220.09	273.34	11.24	10.18	39.34
Standard deviation	2.15	1.06	1.78	1.50	9.03
Relative standard deviation (%)	0.98	0.39	15.85	14.69	22.94
Minimum	215.95	270.85	4.23	4.28	6.15
Maximum	223	275.4	12.34	11.25	47.44
Requirement	215 min	270 min	6 min	6 min	10 min

Note: The numbers highlighted in red indicate failure to reach minimum tensile requirements.



Figure 3
Fracture surface of the tensile specimen with the lowest ductility (sample 17)

CONCLUSIONS

Process parameters were developed by the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ, for laser powder bed fusion (L-PBF) of 4340 steel on an EOS M290 three-dimensional (3D) printer at 60-micron layer thickness to decrease build time (approximately 33%) as compared to previously developed 4340 steel parameters at 40-micron layer thickness. Optimal process parameters (hatch distance and laser scan speed) were selected based on the highest specimen density produced from an experiment where these parameters were varied. A verification build was then built with the optimized parameter set. It consisted of X, Y, and Z-oriented tensile specimens in five locations (four corners and the center of the build plate). The specimens were then machined, heat treated, and characterized. Two tensile blocks were removed from the front of the build plate due to spatter particles that settled on the blocks which could have caused the recoater blade to jam. All but one specimen in the front of the build platform met wrought 4340 steel minimum requirements.

The laser parameters were modified to create fully dense parts for 4340 steel printed with 60-micron layers. However, the limiting factor is the spatter removal from the build platform. One possible explanation is that the gas flow through the grid nozzle may not be adequate to remove the spatter from the parts in the back, and so the spatter then falls on the parts in the front. Additionally, the suction from the extraction nozzle in the front may not be strong enough to remove the spatter generated by the parts in the front during lasing. The suction of the extraction nozzle cannot be modified, and the gas flow is at maximum. Therefore, it is not possible to modify machine parameters to remove more spatter. The ineffective spatter removal can lead to failed builds and the lowering of mechanical properties as shown from the verification build.

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STEEL AT 60 MICRON LAYERS

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