Semi-Empirical Model of Deposit Size and Porosity in 420 Stainless Steel and 4140 Steel Using Laser Engineered Net Shaping

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ABSTRACT

Laser Engineered Net Shaping (LENSTM) samples were fabricated from two technologically important steel alloys, 420 and 4140, in order to study how processing parameters such as powder feed rate and laser traverse velocity affected porosity and deposit dimensions. For both steels, it was found that many possible combinations of laser traverse velocity and powder feed rate will result in negligible porosity provided that the ratio of powder feed rate to laser traverse velocity does not exceed a maximum level. Based on measurements of deposit size and shape in the various experiments, a semi-empirical model is presented that predicts the trend in deposit sizes for various processing parameters.

Keywords: Laser Engineered Net Shaping, Steel Alloys, Porosity, Deposit Size

1 LIST OF SYMBOLS

m	Powder mass	ϕ_L	Minor axis of ellipse describing exposure time as a function of the distance from the center.
t	Time	V_L	Laser voltage
m^*	Critical powder mass	I_L	Laser current
l	Laser travel distance	P_{out}	Power output
θ	Deposited powder contact angle	P_{in}	Power input
d	Deposit depth	η_L	Operating efficiency of laser
w	Deposit width	η_{abs}	Laser absorption efficiency of the material
w_{max}	Maximum deposit width	$\bar{c}_p$	Average heat capacity
X	Characteristic linear mass density	a, b, C, K	Empirical constants
$\bar{t}$	Average exposure time	T_{mp}	Melt pool temperature
$\bar{t}_{exp}$	Average exposure time	t_{max}	Maximum exposure time
$\bar{i}$	Average laser intensity	F	Heat loss factor
I_{max}	Maximum laser intensity		

2 INTRODUCTION

Laser Engineered Net Shaping (LENSTM) is a rapid manufacturing process that uses a laser to create a molten pool on a substrate to which powders are added via feed nozzles. A part can then be built or repaired by traversing the table in the x-y and z directions (Figure 1), with build rate and quality dependent on material properties and process parameters used [1-8]. The rapid cooling rates experienced within the melt pool (from 10^2 Ks⁻¹ to 10^3 Ks⁻¹) and the resulting refinement of the dendritic microstructure lead to increased mechanical properties in LENS builds [9]. Finite element models have been developed to study the thermal behavior, microstructure, residual stresses, and size

of the molten pool of the build ups, during the fabrication [8,10-11], but these cannot account for porosity that develops under certain processing conditions.

The optimization of parts fabricated by LENS is widely conducted on a trial and error basis with the goal of achieving full density (i.e. no porosity) in a minimum of time. There are many parameters that influence the speed and quality of the build as well as energy consumption. Among these are laser input power, laser output power, laser intensity distribution, laser travel velocity and powder feed rate [12-14]. In addition the material being used also has an influence where important material properties are laser absorption efficiency, powder porosity, density, heat capacity, thermal conductivity, and liquidus and solidus temperatures. Most studies undertaken to examine this process focus on finite element and computational fluid dynamic modeling of the melt pool and the build parameters and give only general information about the effect of process parameters on the build rate and quality and porosity, temperature distribution, deposition thickness, pool size, microstructure, and hardness of the final deposit. [1,9,15-21].

While the microstructural refinement inherent to the LENS process can lead to improved mechanical properties, defects such as porosity can significantly degrade strength and thereby create low quality specimens. However, few experimental studies have been conducted to study the dependence of build quality on the process parameters. Though Kobryn et al. [22] and Kummailil et al. [1] have experimentally reviewed the influence of some of these parameters for Ti-6Al-4V and some studies have been undertaken to optimize stainless steel builds [23-25], there is currently little understanding of the relationships between processing parameters and the shape of the deposited metal and whether that metal will exhibit porosity. The porosity has been found to be mainly of two types [26]; 1) gas porosity resulting from the incomplete melting of a powder that initially contained gas porosity and 2) lack of fusion porosity resulting from gaps that form between unmelted or incompletely melted powder particles. While using powders free of gas porosity can eliminate gas porosity in the final specimen, complete melting of the powder is necessary to prevent lack of fusion porosity.

The objective of this study is to investigate how build parameters such as powder flow rate and laser traverse velocity influence porosity of two technologically important alloys, 420 stainless steel and 4140 steel, by the LENS process. Additionally, a semi-empirical model is presented based on empirical data and physical considerations which can be applied to choose process parameters.

Figure 1 Schematic of the LENSTM process

3 EXPERIMENTAL

Laser engineered net shaping (LENSTM) was used to produce 1 cm³ deposits of laser sintered 420 stainless steel and 4140 steel powders (-80/+325) on substrates of 420 stainless steel and 1045 steel respectively. Prior to deposition, the substrates were glass bead blasted and cleaned with acetone. The 420 stainless steel specimens were produced by Fused Innovation (Neenah, WI, USA), using an Optomec Inc. Model MR-7 system at a fixed laser current of 18 Amps. The 4140 specimens were produced by Benét Laboratories (Watervliet, NY, USA) using an Optomec Inc. Model 850-R system at a constant laser power of 400 W. Processing parameters including laser traverse velocity and powder feed rate were varied systematically as shown in Table 1.

Table 1: Sample preparation parameters and measured properties

Sample	Laser traverse velocity dl/dt (mm/s)	Powder Feed Rate dm/dt (g/min)	Linear Mass Density dm/dl (g/mm)	Porosity (Area%)	Deposit Width (μm)	Deposit Depth (μm)
SS420-01	6.4	22	0.058	6.00	252	
SS420-02	8.5	22	0.043	4.40	480	216
SS420-03	10.6	22	0.035	4.50	749	239
SS420-04	6.4	13	0.034	2.70	781	247
SS420-05	8.5	13	0.025	2.10	568	276
SS420-06	10.6	13	0.020	1.60	787	368
SS420-07	6.4	6	0.016	0.60	521	221
SS420-08	6.4	4	0.010	0.00	301	120
SS420-09	8.5	6	0.012	0.20	508	213
SS420-10	10.6	6	0.009	0.00	492	285
4140-01	6.4	3	0.008	0.40	922	288
4140-02	6.4	5	0.013	0.26	1173	409
4140-03	6.4	7	0.018	0.26	1265	--
4140-04	6.4	12	0.031	4.55	--	--
4140-05	8.5	5	0.010	0.28	905	353
4140-06	8.5	7	0.014	0.28	1068	355
4140-07	8.5	12	0.024	11.97	--	--
4140-08	10.6	5	0.008	0.45	968	383
4140-09	10.6	7	0.011	0.48	1064	395
4140-10	10.6	12	0.019	5.99	1178	--

To provide a benchmark for the effects of processing conditions on the shape of the melt pool formed, a 1018 steel substrate (glass bead blasted and cleaned) was treated at laser currents of 34, 36, 38 and 40 Amps and laser traverse speeds of 6.35, 7.41 and 8.47 mm/s.

The LENS processed specimens were sectioned, polished and observed at 50X and 100X magnifications using a Nikon Eclipse TS100 optical microscope. The Area percentage of porosity

was determined using a routine created on Clemex Vision Professional Edition image analysis software. The deposit width and depth were measured after etching with Vilella's Reagent (45 ml Glycerol + 14 ml HNO₃ + 30 ml HCl).

4 RESULTS AND DISCUSSION

4.1 Porosity

Porosity and deposited size have been determined for both 420 and 4140 steel powders at various laser velocities and powder feed rates as shown in Table 1. Although spherically shaped pores were found indicating some gas porosity, the vast majority of the observed porosity was large and irregularly shaped indicating lack of fusion caused by incomplete melting. No trend for porosity shape change was observed. Figure 2A shows that in 420 stainless steel specimens produced using a given laser traverse velocity there are 2 types of powder feed rate-dependent porosity behavior. For a given laser traverse velocity, there seems to be a maximum powder feed rate that allows for the production of fully dense specimens and above this powder feed rate it seems that porosity increases with increasing powder feed rate. Additionally, it seems that the maximum powder feed rate increases with increasing laser traverse velocity. From this it can be concluded that for fully dense parts there is a maximum amount of powder which can be deposited per unit length of laser travel.

Figure 2: Variation of total porosity with (a) powder feed rate and (b) linear mass density for various laser velocities in 420 stainless steel

In order to combine both powder feed rate and laser traverse velocity into a single parameter that can be used to determine which combinations of powder feed rate and laser traverse velocity result in fully dense specimens, the linear mass density (dm/dl) is used, which is the ratio of powder flow rate (dm/dt) divided by the laser traverse velocity (dl/dt) and represents the a maximum amount of powder which can be deposited per unit length of laser travel. Figure 2(b) shows that there is no porosity below an optimal linear mass density (dm^*/dl), while above this optimal value, the porosity increases linearly with increasing linear mass density. From the experimental results, it will be seen that dm^*/dl can be considered a fixed value and the optimal powder flow rate, dm^*/dt , can be determined for an arbitrary velocity, dl/dt , according to Equation (1).

$$dm^*/dt = (dm^*/dl) dl/dt \quad (1)$$

For the case of 420 stainless steel on a 420 stainless steel substrate, the average of 0.0115 g/mm was taken as the critical linear mass density of the system as shown in Table 2.

Table 2: Determined optimal linear mass density

Laser traverse velocity dl/dt (mm/s)	Optimal mass feed rate dm^*/dt (g/min)	Critical linear mass density dm^*/dl (g/mm)
6.4	4.52	0.0118
8.5	5.15	0.0101
10.6	8.04	0.0126
Average		0.0115

It should be noted that the optimal linear mass density is constant only for a given combination of powder material, substrate material, and laser power. Therefore it would be expected to vary with the laser power selected, the powder composition and the substrate composition. However, the optimal linear mass density can be determined with a minimal number of experiments by measuring porosity for different linear mass densities (i.e. powder flow rate / laser traverse velocity) and determining the maximum linear mass density at which the porosity is zero. This is shown in Figure 3 from the experiments using 4140 stainless steel on a 1045 steel substrate, where the optimal linear mass density is approximately 0.018 g/mm.

Figure 3: Variation of total porosity with linear mass density in 4140 steel

4.2 Melt Pool Size

In order to attempt a means of predicting the shape and size of the deposit that results from the LENS process, it is important to study the characteristics of the melt pool for various processing conditions. A substrate of 1018 was laser treated without depositing powder to determine the relationship between melt pool size and input laser power. Figure 4 shows a typical cross-section of the substrate. It is clear that the melted region has an approximate shape of a circular section and it can be assumed that as the laser traversed the sample the melt pool took the shape of a spherical cap. Both the processing parameters and melt pool measurements are given in Table 3 and allow for the determination of how laser traverse velocity affects width and depth of the spherical cap under constant laser power. Although there is considerable scatter in the data due to the difficulty in exactly determining the edge of the melt pool, the melt pool width and depth appear to decrease with an increase in the ratio of laser current/laser traverse velocity as shown in Figures 5(a) and 5(b). This behavior is associated with the amount of power absorbed and then dissipated by the substrate; where higher laser power would generally be expected to result in larger melt pools and higher laser traverse velocity would generally be expected to result in lower exposure times and therefore produce smaller melt pools. However, increasing the laser speed allows less time for the energy already in the melt pool to be dissipated into the substrate. Therefore the interaction between the laser power and the velocity can generate relatively uniform melt pools for various combinations of power and velocity. The aspect ratio (i.e. the width over the depth of the melt pool) was found to be nearly constant at about 0.427, as is shown above in Table 3.

Table 3: Processing conditions and melt pool dimensions for laser-treated 1018 steel substrate

Sample	Laser Current I_L (A)	Laser/Table Speed dl/dt (mm/s)	$I_L/(dl/dt)$ (A/(mm/s))	Melt pool Width w_{mp} (μm)	Melt pool Depth d_{mp} (μm)	Aspect Ratio d_{mp}/w_{mp}
1018-1	34	6.35	5.354	932	376	0.403
1018-2	36	6.35	5.669	923	414	0.449
1018-3	38	6.35	5.984	922	404	0.438
1018-4	40	6.35	6.299	988	459	0.464
1018-5	34	7.41	4.588	918	356	0.388
1018-6	36	7.41	4.858	892	371	0.416
1018-7	38	7.41	5.128	1016	424	0.417
1018-8	40	7.41	5.398	963	437	0.454
1018-9	34	8.47	4.014	863	373	0.432
1018-10	36	8.47	4.250	878	371	0.423
1018-11	38	8.47	4.486	943	398	0.422
1018-12	40	8.47	4.723	959	400	0.417
Average						0.427
Standard Deviation						0.022

Figure 4: Optical Micrograph of Solidified Melt Pool at 100X

4.3 Deposit Size and Shape

From the information presented above, 1) it is possible to determine the optimal powder flow rate for a given laser traverse velocity in order to produce fully dense specimens and 2) it was found that the aspect ratio of the melt pool in the substrate is constant regardless of laser traverse velocity. Therefore, if the shape of the final deposit can be related to shape of the melt pool and powder flow rates and laser velocities are used that produce fully dense specimens, then it should be possible to predict the shape of the material deposited for these processing conditions.

To begin, one must determine the shape of an idealized deposit. In this work, the shape of an ideal deposit (i.e. one that has not undergone significant remelting during deposition of subsequent deposited layers) is assumed to be a circular section that has the same width as the melt pool. Furthermore, it is assumed that the height of the deposited powder is roughly equal to the depth of the melt pool. The melt pool is formed by the melting of the substrate and is deepest in the center, where laser intensity is greatest. The melt pool becomes shallower as distance from the center increases until at a distance of $w/2$ the substrate is not melted. Because of superheat in the melt pool, the

deposited powder will melt and join the melt pool. The liquid above the melt pool should take on a characteristic “drop” shape, which is modelled as a spherical cap of height $d/2$ and shape dictated by the equilibrium between surface tensions of the solid, liquid and gas. The general shape of the ideal deposit is shown in Figure 6(a), while Figure 6(b) shows that these structures do form in actual specimens. Because the contact angle, θ , as shown in figure 2(a) is determined by surface tensions of solid, liquid and gas phases, it is assumed not to vary much with deposit sizes that are practical with LENS; meaning that the ratio of deposit depth to deposit width, d/w , can be described by Equation (2) which is derived from the geometry of circular sections and is assumed to be constant as was the case in the melt pool experiments described above.

$$\frac{d}{w} = \frac{1 - \cos \theta}{\sin \theta} = \text{constant} \quad (2)$$

Figures 7(a) and 8(a) show that the aspect ratios of the deposited material are approximately constant for a given laser intensity, powder material, substrate material combination. Values of d/w were found to be 0.4040 and 0.3573 for the 420 and 4140 steels, respectively.

Though studies of microstructural cross-sections indicate that such idealized structures do form as shown in Figure 6(b), scallop-shaped deposits are more prevalent in the final microstructure as is clear from many of the other deposits in Figure 6(b). This is the result of remelting of the ideally shaped deposit during subsequent depositions. In Figure 2(b) material above the ideal deposit was deposited from left to right and appears to be a continuous single deposit across the entire sample. Because of the remelting, it is often difficult to find deposits in the sample where width and depth measurements can be made.

Figure 6: (a) Ideal deposit shape showing contact angle, θ . (b) Experimental micrograph of 420 stainless steel showing representative ideal deposit at center

The assumption from Equation (1) (namely that there is a fixed amount of material per unit length that can be deposited regardless of velocity) requires that Equation (2) must be approximate only and that in reality deposit depth should decrease slightly with increasing deposit width. However, because there is difficulty in measuring deposit depth due to remelting, this change of deposit depth with increasing width is ignored in this work.

The deposit width, w , would be expected to vary with the size of the melt pool and the amount of material being deposited onto that melt pool. It would also be expected that for a fixed melt pool size, the width of the deposit could only continue increasing for as long as powder would become stuck. Above a certain powder feed rate for the given melt pool size, some of the powder would simply fail to stick. The general trend would then be expected to increase towards a maximum deposit size. Although increasing the deposit size by exceeding the optimum powder feed rate would likely result in increasing porosity. Equation (3) is proposed to describe the expected trend of deposit width.

$$w \propto w_{\text{melt pool}} = w_{\text{max}} \left(1 - F \ln \left(\frac{X}{dm/dl} \right) \right) \quad (3)$$

The maximum deposit width, w_{max} , must be on the order of the diameter of the laser in that this is the region of the material under the most intense exposure to the laser. However it must be adjusted for the time that the substrate is exposed to the laser. The maximum exposure time, t_{max} , and the maximum intensity of the laser, I_{max} , are both at the center of the laser and decrease with distance from the center. For this reason average exposure time, $\bar{t}$, and average intensity, $\bar{I}$, are important factors to be considered for the maximum deposit width. Because the shape of the laser is assumed circular, the exposure time as a function of the distance from the center takes the shape of half an ellipse with a major axis of $\phi_L/(dl/dt)$ and a minor axis of ϕ_L , the ratio of the average exposure time to maximum exposure time is described in Equation(4).

$$\bar{t}/t_{\text{max}} = \frac{\bar{\phi}_L (dl/dt)}{\phi_L (dl/dt)} = \frac{1/2 \pi (\phi_L/2) \phi_L}{\phi_L} = \pi/4 \quad (4)$$

The laser intensity spatial distribution is assumed to be Gaussian and therefore Equation (5) describes the ratio of average intensity to maximum intensity.

$$\bar{I}/I_{\text{max}} = 1/2 \quad (1)$$

The width of the melt pool also depends on the energy input per unit length of laser travel and the energy stored in the melt pool per unit length of laser travel. Equation (6) describes this ratio in terms of the Laser Voltage, V_L , Laser Current, I_L , operating efficiency of the laser ($P_{\text{out}}/P_{\text{in}}$), η_L , absorption efficiency of the material, η_{abs} , average heat capacity, $\bar{c}_p$, and average change in melt pool temperature, $\Delta \bar{T}_{\text{mp}}$. The factor C must be determined experimentally.

$$\frac{\text{Energy Input/Length}}{\text{Energy Stored/Length}} = \frac{\eta_{\text{abs}} \eta_L}{(dm^*/dl) \bar{c}_p \Delta \bar{T}_{\text{mp}}} \left(\frac{V_L I_L}{dl/dt} \right) = C \frac{I_L}{dl/dt} \quad (6)$$

Equation (7) is proposed to describe the maximum width of the deposits. It has the properties that when there is no laser power, the deposit width is zero and when the laser is at rest, the deposit width is infinite, but in reality would be limited to the width of the plate.

$$w_{\text{max}} \propto \phi_L (\bar{t}_{\text{exp}}/t_{\text{max}}) (\bar{I}/I_{\text{max}}) \frac{\eta_{\text{abs}} \eta_L}{(dm^*/dl) \bar{c}_p \Delta \bar{T}_{\text{mp}}} \left(\frac{V_L I_L}{dl/dt} \right) = C \phi_L (\pi/4) (1/2) \frac{I_L}{dl/dt} = \frac{K}{dl/dt} \quad (7)$$

The factor F in Equation (3) is necessary to account for the heat transferred from the melt pool to places other than the deposited powder. Since more heat is transferred to the substrate and surroundings when the laser traverse velocity is low, Equation (8) is proposed.

$$F = \frac{1}{a(dl/dt) + b} \quad (8)$$

In summary, the width of the deposited material, w , for a given linear mass density and laser traverse velocity can be determined from Equations (3), (7), and (8) if the empirical factors K, a, and b can be determined from experimental data and X is assumed to be 1 g/mm. The height of the deposit is then can then be calculated from the aspect ratio as described by Equation (2). Using the experimentally determined width and depth of the deposits in the 420 and 4140 steel samples, the empirical values of Table 4 were determined using best fit regressions. Figures 7 (b)-(c) and Figures 8(b)-(c) show a comparison of the predictions of the semi-empirical model with the experimentally determined data.

Table 4: Values of empirical parameters used in the model in equations (2) to (8)

Material	K ($\mu\text{m}/[\text{mm/s}]$)	X (g/mm)	a (s/mm)	b	d/w
SS420	11,100	1	0.3	3.6	0.4040
4140 Steel	20,000	1	0.7619	1.9238	0.3573

Figure 7: Variation of deposit depth in 420 Stainless Steel a) with deposit width b) with deposited linear mass density for laser traverse velocity of 6.4 mm/s c) with deposited linear mass density for laser traverse velocity of 10.6 mm/s. (Data points are experimentally measured values and solid lines are the predicted values using Equations (2)-(8) and the empirical parameters of Table 4.)

Figure 8: Variation of deposit depth in 4140 Steel a) with deposit width b) with deposited linear mass density for laser traverse velocity of 6.4 mm/s c) with deposited linear mass density for laser traverse velocity of 10.6 mm/s. (Data points are experimentally measured values and solid lines are the predicted values using Equations (2)-(8) and the empirical parameters of Table 4.)

5 CONCLUSION

A constant power LENS process was used to synthesize specimens for various laser traverse velocities and powder feed rates using 420 stainless steel powders on a 420 stainless steel substrate and 4140 steel powders 1045 steel substrates. Analysis of the samples show the following:

1. Fully dense specimens can be produced for many possible combinations of laser traverse velocity and powder feed rate.

2. Fully dense specimens will result if the ratio of powder feed rate to laser traverse velocity does not exceed a maximum level.
3. The maximum ratio has been designated the optimal linear mass density and represents the maximum amount of powder that can be deposited per unit length of laser travel at a given laser power setting for a given powder and substrate material combination.
4. For laser traverse velocities and powder feed rates that result in linear mass density values higher than the optimal value, lack of fusion porosity will result.
5. In experiments with powder feed rates of zero (i.e. laser melted substrates) it was found that the aspect ratio of deposited material (i.e. maximum height/maximum width) was constant regardless of laser traverse speed.
6. In experiments with powder feed rates greater than zero it was found that the aspect ratio of deposited material (i.e. maximum height/maximum width) was constant regardless of laser traverse speed and powder feed rate.
7. A semi-empirical model was proposed to predict the maximum width and height of the deposited material for a given laser traverse speed and powder feed rate in a constant laser power LENS process.

The above can be used to minimize the number of experiments necessary to produce fully dense samples as well as optimize fabrication speed by using the maximum powder feed rate that can be used with a given laser traverse speed. Being able to predict the shape and dimensions of the deposited material is also valuable in optimizing fabrication speed, since the spacing between depositions can be optimized.

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