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Technical Paper

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 (LENS^{TM}) 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.

1. Introduction

Laser engineered net shaping (LENS^{TM}) 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 (Fig. 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 K s^{-1} to 10^3 K s^{-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.

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Nomenclature

m	powder mass
t	time
m^*	critical powder mass
l	laser travel distance
θ	deposited powder contact angle
d	deposit depth
w	deposit width
w_{max}	maximum deposit width
X	characteristic linear mass density
$\bar{t}$	average exposure time
$\bar{t}_{exp}$	average exposure time
$\bar{I}$	average laser intensity
I_{max}	maximum laser intensity
ϕ_L	minor axis of ellipse describing exposure time as a function of the distance from the center
V_L	laser voltage
I_L	laser current
P_{out}	power output
P_{in}	power input
η_L	operating efficiency of laser
η_{abs}	laser absorption efficiency of the material
$\bar{c}_p$	average heat capacity
a, b, C, K	empirical constants
T_{mp}	melt pool temperature
t_{max}	maximum exposure time
F	heat loss factor

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.

2. Experimental

Laser engineered net shaping (LENS^{TM}) was used to produce 1 cm^3 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.

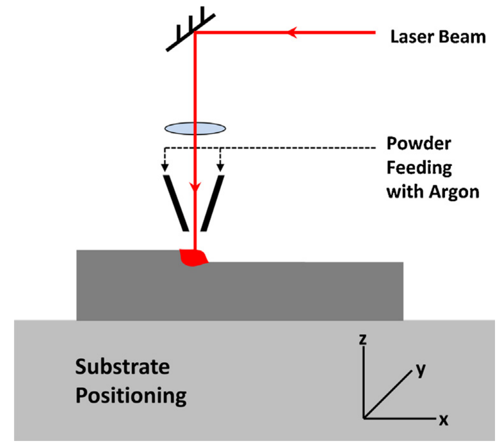

Fig. 1. Schematic of the LENS^{TM} process.

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 A and laser traverse speeds of 6.35, 7.41 and 8.47 mm/s.

The LENS processed specimens were sectioned, polished and observed at 50× and 100× 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 HNO_3 + 30 ml HCl).

3. Results and discussion

3.1. 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

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	–