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Laser powder bed fusion of nickel alloy 625: Experimental investigations of effects of process parameters on melt pool size and shape with spatter analysis☆

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ABSTRACT

Laser powder bed fusion (L-PBF) as an metal additive manufacturing process that can produce fully dense 3D structures with complex geometry using difficult-to-process metal powders such as nickel-based alloy 625 which is one of the choice of metal materials for fabricating components in jet engines and gas turbines due to its high strength at elevated temperatures. L-PBF process parameters and scan strategy affect the resultant built quality and structural integrity. This study presents experimental investigations of the effects of process parameters and scan strategy on the relative density, melt pool size and shape. Fabricated test coupons were analyzed with two objectives in mind: i) to determine how close each coupon was to fully dense and ii) to determine melt pool dimensions (width and depth) and shape for each coupon. The identification and definition of a dynamic melt pool has been performed, a condition which indicates that melt pool geometry is constantly changing as the laser scans and moves along a single track. In order to gain in-depth understanding of the laser fusion processing of powder material, an in-situ thermal camera video recording is performed and analyzed for meltpool size, spattering particles, and heating and cooling rates during processing of powder material nickel alloy 625. The results reveal in-depth process information that can be used for further validation of modeling studies and adopted for the industrial practice.

1. Introduction

Metal additive manufacturing technology is attractive with unique applications in various industries for replacement or customized parts with complex geometries and structures [11,12,27]. As a metal additive manufacturing process, laser powder bed fusion (L-PBF) or traditionally known as selective laser melting process is favorable in obtaining fully dense structures without a need for post processing [9,21]. Many research studies have been reported on its applications, process improvement and parameter optimization [35,36,38,43] and numerical modeling to predict the temperature field, melting and evaporation ([13,14,29,30,37,40]) and microstructure analysis and prediction [2,41,42]. However, L-PBF process requires relatively high energy density levels and lower scan velocities to successfully melt and fuse the powder metal material when compared to laser sintering processes [15,25]. Due to high energy intensities applied with the high power laser beam, there may be meltpool instabilities, issues related to material spattering and balling, rapid material evaporation and keyhole effects [34,38]. Resultant built part quality, structural integrity and residual stresses [6,24] is also a major concern especially for additively manufactured parts in nickel alloy 718 or nickel alloy 625 that are considered for deployment in mission critical components in aerospace applications. After all these research studies, the influence of L-PBF process parameters on the quality measures such as density and process signatures such as meltpool shape and size is still not fully understood.

In literature, the overwhelmingly exploited quality measure is the density of the final part in addition to surface roughness and dimensional tolerances [16–18,24]. Meltpool geometry is also widely studied due to being a determinant of density and surface roughness [18,23].

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Kamath [17] claim that small meltpool depths make the system inefficient by increasing the processing time. On the other hand, large meltpools may yield vaporization of the substrate and causes pores in the structure that increase porosity [26]. To assure a stable meltpool, the meltpool dimensions are not allowed be too small or too large in order to avoid irregularities or droplets [24]. O'Regan et al. [28] classifies the parameters affecting such measures under four groups: feedstock, build environment, laser, and meltpool. Most of these parameters are predefined, that is, their values have to be adjusted before processing and some are controllable, that is, their values can be changed during processing. Lastly, some criteria are classified as undefined, that is, their values depend on other parameter adjustments. Control and optimization over L-PBF systems are achieved by changing predefined and controllable parameters. Even though laser power, scan velocity, hatch distance, and layer thickness have been known to be the most important parameters through experimentations, their relative importance are statistically analyzed in the recent study of Kamath [17]. According to this study, scan velocity is the most important parameters. A higher scan velocity causes the interaction between material and the laser beam to be short, which results in a narrow meltpool which also leads to rough surfaces, whereas decreasing the scan velocity causes excessive heating and vaporization. A very high scan velocity causes instability and droplet formation due to free cylindrical meltpool geometry. A very low scan velocity yields distortion and irregularities due to balling effect [18]. A low scan velocity is known to ensure a dense structure with the cost of rough surface. Hence, the optimal scan velocity is a trade-off between resultant density and surface quality [24].

Criales et al. [7] analyzed the effects of varying laser power, scan velocity, and the packing density of the powder material for selective laser melting of nickel alloy Inconel 625 using finite element simulations. A sensitivity analysis has been conducted to investigate the influence of material properties and process parameters on the predicted temperature profile along the center of the laser beam path. They found that the packing density (or porosity) significantly affects the temperature profile. The powder reflectivity has the greatest effect on the predicted peak temperature and melts pool geometry, followed by laser power and scanning speed. In a recent study, Arisoy et al. [5] investigated L-PBF of nearly fully dense nickel alloy 625. They observed that L-PBF generates a microstructure through directional solidification that can be controlled by scan strategies and selection of process parameters. They provided experimental investigations on microstructure formation including sizes of cellular grains and growth directions of columnar grains on the test coupons. They analyzed the main effects of process parameters including laser power, scan velocity, hatch distance, and scan strategy that produce various solidification cooling rates and thermal gradients during the process, which also contributed to understanding of the resultant microstructure.

2. Laser powder bed fusion of nickel alloy 625

Laser powder bed fusion (L-PBF) is an additive manufacturing process that enables direct fabrication of three-dimensional (3D) parts from computer models by scanning regions of a powder bed using a high energy laser beam that selectively melts and fuses cross-sectional geometry on each layer followed by subsequent solidification according to active ASTM terminology [1]. In L-PBF, the powder material is completely melted and solidified with an aim to achieve fully dense parts. A traditional L-PBF set-up typically requires a high power laser source (Fig. 1). Some of the key advantages of L-PBF over other manufacturing techniques include: (i) high flexibility in manufacturing complex shapes, (ii) quick process setup avoiding the need for tooling, and (iii) broad choice of materials including high strength superalloys. These advantages allow for quick transition between manufacturing products of different geometries within the same station.

The most attractive feature of L-PBF is the ability to use this process to produce highly complex geometries and structures that would normally not even be feasible using conventional production techniques. However, L-PBF has several major disadvantages: the laser heating process is known for its rapid heating times and unpredictable cooling times, which result in high localized residual stress, nonhomogeneous and anisotropic microstructure and material properties, as well as the formation of gas pores and voids in the microstructure, which often lead to reduced material density and mechanical properties such as strength, hardness, toughness, and fatigue resistance. Other than common concern of lack of fusion or gas induced porosity, dealing with structural defects such as residual stress, delamination, cracking are major challenges in L-PBF. The scan strategy, process temperature, powder mixture, build chamber atmosphere and many other inputs determine the occurrence and quantity of such defects [33].

In L-PBF, laser characteristics, process parameters, and material properties must be studied jointly to obtain a better understanding of the laser processing of powder metal materials. Laser characteristics are unique to the laser equipment such as maximum power, wavelength, beam spot diameter (or size), and beam energy distribution and usually cannot be modified by the end user. However, L-PBF involves a set of processing parameters that can be modified such as laser power (P), scan velocity (v_s), hatch distance (h), stripe width (w), and layer thickness (s) as shown in Fig. 2 and scan strategy rotation (SSR) as shown in Fig. 3.

In the L-PBF process, consecutive layers are built by processing powder material with a pre-specified powder layer thickness. These consecutive layers are processed slightly differently to ensure a robust build. More specifically, stripe orientation changes from layer to layer by a set margin. Two scan strategies available are a) 90° counter clockwise rotation, and b) 67° counter clockwise rotation between consecutive layers. Fig. 3 illustrates this concept for both of these laser scan strategies.

In L-PBF, the laser beam spot diameter is considered fixed (e.g., d=100 μm) with uniform or near Gaussian beam energy distribution, but laser power, scan velocity, hatch distance, and layer thickness can be altered to a desired energy density setting, which affect the resultant melt pool geometry, heat affected area, quality of fusion, cooling rate, formation of solidification microstructure on the powder bed. The effects of these process parameter settings together with powder material characteristics on the variations of the resultant part quality in terms of density, material properties, dimensional quality, surface roughness, and defects are not well understood.

3. Experimental design

An EOS M270[1] Direct Metal Laser Sintering (DMLS) machine was utilized for processing of experimental test coupons. This machine has a single-mode, continuous wave (CW) ytterbium fiber laser with maximum power of 200 W. An adequate quantity of commercial additive manufacturing grade nickel alloy 625 powder produced by gas atomized process with the average particle size of 35 μm was used and solid coupons in the shape of cubes (16 mm×16 mm×15 mm) were manufactured using an EOS M270 DMLS machine under nitrogen gas ambience at the National Institute for Standards & Technology (NIST) facility located in Gaithersburg, Maryland, USA. The powder material with −325 mesh size (particles that measure less than 44 μm) and atomized spherical morphology has a particle distribution of D60% =29.4 μm, D10%=13.5 μm, and D90%=43.0 μm. The chemical composition of the powder material in wt% was reported as follows: Cr 21.01%, Fe 0.85%, Mo 8.77%, Nb 3.35%, C 0.02%, Mn 0.36%, Si

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[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.