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Modulating laser intensity profile ellipticity for microstructural control during metal additive manufacturing

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ABSTRACT

Additively manufactured (AM) metals are often highly textured, containing large columnar grains that initiate epitaxially under steep temperature gradients and rapid solidification conditions. These unique microstructures partially account for the massive property disparity existing between AM and conventionally processed alloys. Although equiaxed grains are desirable for isotropic mechanical behavior, the columnar-to-equiaxed transition remains difficult to predict for conventional solidification processes, and much more so for AM. In this study, the effects of laser intensity profile ellipticity on melt track macrostructures and microstructures were studied in 316L stainless steel. Experimental results were supported by temperature gradients and melt velocities simulated using the ALE3D multi-physics code. As a general trend, columnar grains preferentially formed with increasing laser power and scan speed for all beam profiles. However, when conduction mode laser heating occurs, scan parameters that result in coarse columnar microstructures using Gaussian profiles produce equiaxed or mixed equiaxed-columnar microstructures using elliptical profiles. By modulating spatial laser intensity profiles on the fly, site-specific microstructures and properties can be directly engineered into additively manufactured parts.

1. Introduction

Research in additive manufacturing (AM) has gained tremendous momentum over the past decade due to the prospect of directly building complex three-dimensional parts from computer-aided design (CAD) files. During laser powder-bed fusion (LPBF), processing parameters such as laser power, scan speed, scan pattern, and hatch spacing have typically been optimized to improve geometrical accuracy and reduce defect concentrations. In taking this macroscopic approach, however, the microstructure-property relationships underlying the performance disparities between conventionally machined and AM parts are often overlooked.

The ultimate goal of *a priori* parameter selection for tailored microstructures is in sight, with recent efforts made in e-beam and laser additive manufacturing [1–6]. Site-specific microstructural control has numerous practical applications, such as in improving the fatigue life of a part by imposing deliberate textures at surfaces or stress-concentrating features, or in manufacturing components with functionally graded mechanical properties. In 2014, Körner et al. investigated the effect of varying “cross snake” scan patterns every ten *versus* every single layer in Inconel tensile samples [1]. The authors found that columnar grains are formed when solidification occurs primarily in the building direction, while equiaxed grains are formed when the solidification direction varies frequently. In 2015, Dehoff et al. demonstrated localized microstructural control by developing highly misoriented equiaxed grains surrounded by columnar grains in an Inconel 718 block [2]. The researchers rapidly switched between point and line heat sources to manipulate local thermal gradients and solid/liquid (s/l) interface velocities. Some microstructural control has also been demonstrated in laser additive manufacturing by varying laser power up to 1000 W [3], using multiple laser sources [4], and varying scan strategies [5,6].

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In this work, beam ellipticity is pursued as a potential means for microstructural control during laser additive manufacturing. Commercial LPBF systems typically use circular Gaussian intensity profiles, although they may not be ideal for optimizing process control. During a build, beam ellipticity can be modulated on the fly by diverting the laser into a beam shaping optical element (e.g., an anamorphic prism pair). Since local temperature gradients are affected, it may be possible to engineer equiaxed or columnar grains at specified locations by modulating beam shape *in situ*. Elliptical beams have been explored for laser annealing semiconductors [7,8], but knowledge of their effects on metal solidification remains relatively limited, particularly with respect to metal AM. The present study explores the microstructures produced by circular and elliptical laser intensity profiles in 316L stainless steel single-tracks. Macroscopic features, such as track continuity, roughness, and melt depth are measured and discussed.

Since LPBF is a far-from-equilibrium processing technique, the classic temperature gradient (G) *versus* solidification rate (R) analysis may not fully capture the complexities of solidification in the aggressively dynamic melt. The Arbitrary Lagrangian-Eulerian 3D (ALE3D) massively-parallel multi-physics code was used to simulate the temperature gradients and melt flow velocities induced by the beam profiles used in this study. The model takes into account Marangoni convection, the recoil pressure, evaporative and radiative cooling. It has been used recently to successfully described several deleterious LPBF phenomena, including spatter, denudation, melt instability, and three mechanisms of pore formation [9–11].

The objective of this investigation is to determine the microstructures produced by circular and elliptical laser intensity profiles at different beam sizes, laser powers, and scan speeds. The purpose is to judge if changes in beam ellipticity could provide a route for site-specific microstructural control during laser additive manufacturing. ALE3D simulations support analyses of the experimental results.

2. Experimental

2.1. Laser powder-bed fusion experiments

Single-track laser melting experiments were completed using 316L stainless steel powder (Concept Laser) on 316L stainless steel substrates (McMaster-Carr). Prior to use, the ~27-μm powders were vacuum dried at 623 K and stored in a desiccator thereafter. The surfaces of the 3.175-mm (1/8-in) thick substrates were bead blasted. A 50-μm thick powder layer was manually spread onto each substrate using a glass microscope slide prior to single powder layer melting.

In the LPBF testbed, the output of a 600 W fiber laser (JK600 FL, JK Lasers) was first collimated using a 50 mm FL lens and then directed through an anamorphic prism pair (Thor Labs) to adjust beam ellipticity. The modified beam was then directed through a 2-5x reducer (Thor Labs) which controls the beam size to a galvanometer scanner (Nutfield Technologies), and through the high purity fused silica window of a 15 × 15 × 15 cm^3 vacuum chamber. For each experiment, the chamber was evacuated using a turbomolecular pump and back-filled with argon. During laser melting, the Ar pressure was maintained at 750 Torr.

The circular and elliptical beam profiles were studied at three sizes, each (Fig. 1, Table 1). The nominal $1/e^2$ diameters of the circular beams were $w_b = 100, 175, 250$ μm. These sizes will hereon be referred to as S (small), M (medium), and L (large), respectively. The major and minor axes of the elliptical beams were calculated from S, M, and L to deliver equivalent peak irradiances (based on average geometric beam diameters) at an aspect ratio of ~3.7:1. Size S was limited by the smallest minor axis achievable using the current setup. The elliptical beams were scanned with the major axes parallel ("longitudinal", LE) and perpendicular ("transverse", TE) to the scan direction, and compared to circular (C) beam scans. The intensity profiles are named by geometry and size (e.g., LE-M refers to a longitudinal elliptical beam of Size M).

Experimental parameters were selected based on Kamath et al. [12] and King et al. [13]. An energy density (Q) equation common in laser welding was adapted to scale laser power (P), scan speed (v), powder layer thickness ($t = 50$ μm), and beam size (w_b):

$$Q = \frac{P}{vtw_b} \tag{1}$$

The energy density ranged from 80 to 260 J/mm^3 at 60 J/mm^3-intervals. Since nominal laser power was varied from 50 to 550 W at 100-W intervals, scan speed (15–1375 mm/s) was calculated based on Q, P, t, and w_b. Overall, 216 combinations of beam shape, beam size, power, and scan speed were studied.

2.2. Characterization

Wide-field height maps of the single-tracks were generated by laser confocal microscopy (Keyence) to assess macroscopic morphological features. Height and line roughness were measured along the centerline of the middle ~0.8 cm of each 1.0-cm long track. Track continuity was categorized according to Childs et al. [14], with example tracks shown in the Supporting Information (Table S1).

After sectioning, the samples were mounted, ground using 120–1200 grit metallographic silicon carbide paper, and then polished with 1-μm polycrystalline diamond suspension. At this point, the samples were checked by optical microscopy for pores and voids. Immediately before etching, the samples were polished with 0.05 μm aluminum oxide. The samples were swabbed with a modified Carpenter's reagent, which contained an additional 5 mL of HNO_3 for each 100 mL of stock solution, for less than 1 min. The

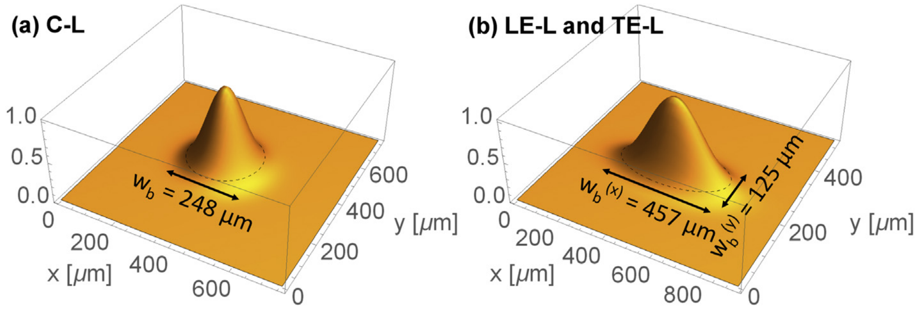

Fig. 1. Numerical fits of measured spatial intensity profiles for the (a) circular Gaussian and (b) elliptical beam shapes at Size L.