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Localized melt-scan strategy for site specific control of grain size and primary dendrite arm spacing in electron beam additive manufacturing☆

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ABSTRACT

In addition to design geometry, surface roughness, and solid-state phase transformation, solidification microstructure plays a crucial role in controlling the performance of additively manufactured components. Crystallographic texture, primary dendrite arm spacing (PDAS), and grain size are directly correlated to local solidification conditions. We have developed a new melt-scan strategy for inducing site specific, on-demand control of solidification microstructure. We were able to induce variations in grain size (30 μm−150 μm) and PDAS (4 μm - 10 μm) in Inconel 718 parts produced by the electron beam additive manufacturing system (Arcam®). A conventional raster melt-scan resulted in a grain size of about 600 μm. The observed variations in grain size with different melt-scan strategies are rationalized using a numerical thermal and solidification model which accounts for the transient curvature of the melt pool and associated thermal gradients and liquid-solid interface velocities. The refinement in grain size at high cooling rates (>10^4 K/s) is also attributed to the potential heterogeneous nucleation of grains ahead of the epitaxially growing solidification front. The variation in PDAS is rationalized using a coupled numerical-theoretical model as a function of local solidification conditions (thermal gradient and liquid-solid interface velocity) of the melt pool.

1. Introduction

New additive manufacturing (AM) technologies are revolutionizing the manufacturing sector and are being adapted to fabricate critical components in the aerospace, automotive, defense and medical industries [1]. The mechanical properties (fatigue, yield strength, ultimate tensile strength, ductility, and creep) of engineering components are primarily dictated by their (a) design geometry, (b) surface roughness, and (c) microstructure. In this process-structure-property-performance (PSPP) linkage, understanding the process-structure relationship is important to obtain the desired mechanical performance of parts fabricated through AM. The microstructure of the fabricated component can be controlled by the (a) liquid-solid and (b) solid-solid phase transformations of the alloy system during complex thermal history created by the processing conditions. In this work, we focus on controlling the liquid-solid phase transformation by modifying the scanning pattern of the electron beam with objective to enable site specific, on-demand control over the grain size and PDAS.

Transient characteristics (direction and magnitude) of the velocity vector of the heat source are defined by the melt-scan strategy used during the fabrication. Variants of raster melt-scan are the most common in commercial AM machines. The effect of changes in the orientation of the raster melt-scan between alternate layers on the

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direction of epitaxial columnar grains has been investigated by Wei et al. [2] and Dinda et al. [3]. Lee et al. [4] studied the effect of fluid convection on dendrite arm spacing in a single layer epitaxial laser melting process. Helmer et al. [5,6] studied the influence of raster melt-scan parameters on the solidification microstructure in electron beam AM. Gockel et al. [7] used experimental process mapping of raster melt-scans to control melt pool shape and microstructure.

One of the unattained potentials of AM is the ability to fabricate components with tailored, site-specific microstructures and mechanical properties. Comprehensive work [8–16] has been done on modeling and rationalization of microstructure formation in beam and arc welding processes. However, none of the existing AM investigations were extended utilizing the knowledge from welding literature and developed melt-scan strategies for on-demand microstructure control. Dehoff et al. [17] introduced a new melt-scan strategy and demonstrated the feasibility of growing misoriented equiaxed grains on-demand. Raghavan at al. [18] further extended the study using numerical modeling and experiments, and demonstrated bulk columnar-to-equiaxed transition (CET) in the parts fabricated via electron beam AM.

In addition to controlling anisotropy by CET, the ability to have site-specific control of columnar grain size is also vital to modify local mechanical properties of components. For room temperature applications, the material yield strength is inversely proportional to the square root of grain size (Hall-Petch relationship) [19]. In materials used at or below the homologous temperature, the mechanical properties (yield strength, fracture toughness, fatigue life) are benefited by an increase in grain boundary area per unit volume (grain size refinement). Conversely, in high-temperature materials, such as Nickel-base superalloys, the reduction in the grain size is detrimental to the creep and stress rupture properties [20,21]. The PDAS has a strong impact on the high cycle fatigue life [22].

Our goal is to design new melt-scan strategies to achieve explicit, site-specific control of the grain size and PDAS within the epitaxially solidified columnar microstructure. Using the proposed scan pattern as the design variable decouples other process parameters from the geometry of the part being fabricated. We developed a numerical model to simulate and interpret the observed variations in PDAS and grain size based on three-dimensional and temporal variations of thermal gradient (G) at the liquid-solid interface and the velocity (R) of the liquid-solid interface, during the solidification of the melt pool. These simulation results were coupled with the existing phenomenological solidification models [16,23] to quantitatively predict the PDAS and to rationalize variations in grain size as a function of processing conditions.

2. Development of a new melt-scan strategy

The solidification grain size, morphology, and PDAS can be controlled by modifying the magnitude and direction of the thermal gradient (G) and velocity (R) of the liquid-solid interface during solidification. The feasibility of controlling solidification morphology (columnar or equiaxed) has been previously demonstrated [18] using a new melt-scan strategy in the Arcam® process. The most widely used melt-scan strategy in the current AM processes is similar to multi-pass welding. The heat source moves linearly from one end to the other with temporally varying current and velocity. The resulting epitaxial solidification of columnar grains within the melt pool and along the build direction is a well-known phenomenon [2,24]. The span of the raster scan depends on the geometry of the part being fabricated. Therefore, the local thermal history, solidification conditions, and solidification microstructure are significantly influenced by the part geometry. It is a complex challenge to obtain site-specific control over the solidification microstructure using the raster melt-scan strategy for arbitrary geometries.

Fig. 1(a) shows the proposed melt-scan strategy at a given layer (XY plane). The layer being melted is spatially discretized into smaller sections called "**domains**". The domains are melted sequentially. The numbers within each domain in Fig. 1(a) show the sequence in which they will be melted. X_1 and Y_1 are the variables that determine the distance between the domains in sequence along X and Y direction respectively. For example, in Fig. 1(a), the distance between domain 1 and 2 is X_1 and distance between domain 1 and 3 is Y_1. Each domain in Fig. 1(a) has 5 distinct spots within it where the electron beam heat source will be applied. Fig. 1(b) shows the distribution of spots and sequence of melting within one domain. These 5 spots within a domain can be moved closer together or away from each other. In Fig. 1(b), X_o and Y_o are called the "**internal point-offsets**" which dictates the distance of the 4 surrounding spots from the center spot in X and Y directions respectively. The rationale behind moving the spots closer or farther from each other is to gain control over the local solidification conditions (thermal gradient G, liquid-solid interface velocity R and cooling rate G*R) and hence microstructure. In addition, beam power and dwell time are control variables of the spots. This spot melting (Fig. 1) pattern is repeated layer-by-layer depending on the geometry.

3. AM processing, characterization and modeling

3.1. AM processing

Samples were fabricated using Inconel 718 (IN718) powder in an Arcam® S12 machine with a layer thickness of 50 μm and a bath temperature of 1050 °C. The dimensions of the samples were 2 × 2 × 2 cm. Using the layer thickness of 50 μm, there were 400 layers in the build. A layer of 2 × 2 cm was divided into 40 × 40 overlapping domains in the XY plane. The domains overlap laterally to avoid lack of fusion porosity through the build. The offset between domains, which ensures that solidification behavior is localized (i.e. solidification in domain 1 is independent of domain 2), is maintained at 3 mm along both the axes (X_1 and Y_1 in Fig. 1(a)). The offset value (3 mm) was chosen based on the predicted heat affected zone during solidification of a single domain. There are 8000 spots per layer per sample with 1600 domains and 5 spots per domain as shown in Fig. 1. At each spot, the electron beam power was maintained constant at 1200 W (20 mA, 60 kV) throughout the experiments, with a dwell time of 0.25 ms at each spot. A focus coil current of 0 mA was used to obtain a highly-focused beam (beam diameter ~200 μm). Accurate functional relationship between the beam diameter and the focus coil current is unknown but the beam diameter was found to have insignificant effect on the solidification conditions [20] within the practical limitations of the process.

3.2. Characterization

The samples were cut along the build direction (z-axis) and prepared for characterization by an optical microscope (Leica DM4000M) and a scanning electron microscope (JEOL 6500). To reveal the dendrites, the samples were etched using a mixture of nitric acid, acetic acid and hydrochloric acid in equal proportion (1:1:1). An optical microscope was used to analyze the primary dendrite arm spacing (PDAS). Electron Back Scattered Diffraction (EBSD) was performed using SEM to analyze the grain orientation, morphology, and size.

3.3. Numerical model

3-D numerical thermal simulations were carried out using a continuum mimetic finite difference code – Truchas [25,26]. New user subroutines have been written and integrated into the code to adapt it for AM process simulation, to define the new melt-scan