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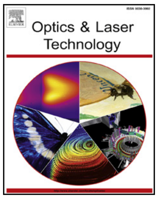

Full length article

Modeling and simulation of thermal field and solidification in laser powder bed fusion of nickel alloy IN625

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HIGHLIGHTS

- Simulation and modeling on laser powder bed fusion of nickel alloy IN625 powder material.
- Laser induced meltpool gets broader and more uneven at higher energy density.
- Laser induced spatter of the powder material is detected using thermal image monitoring.
- Phase field based solidification simulation shows dendrites forming into the meltpool.
- Solidification directions indicate the preferred growth direction is towards the built direction.

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ABSTRACT

Finite element modeling and simulation of laser powder bed fusion process (L-PBF) provides physical insight about the laser processing that is often not possible or highly difficult by in-situ monitoring or in-process measurements. A three-dimensional (3D) thermal field especially into depth direction that is not visible by a thermal camera can be obtained by solving the 3D heat transfer problem. Furthermore, microstructure growth can be modelled to predict the direction of solidification in the fabricated part. This paper presents 3D Finite Element Method (FEM) based simulation models developed for laser processing of single- and multi-tracks with different energy density levels dependent upon process parameters such as laser power and scan velocity. This 3D L-PBF process model is validated with in-situ thermal measurements and further improved by utilizing predicted spattering of powder material which is in turn included as a stochastic heat loss in the 3D FEM model. Thermal gradients extracted from these simulations utilized to compute the directions in the resulting solidification which are found to be in reasonable agreements with experimental observations. Finally, a phase field method based post processing is applied on the thermal solution to simulate the nucleation phenomenon and columnar dendrite formation during solidification.

1. Introduction

Metal additive manufacturing technology has been rapidly expanding its applications in various industries for functional parts with complex shapes, geometries, and structures. Laser powder bed fusion (L-PBF) also commercially known as selective laser melting (SLM) is a laser-based additive manufacturing process that allows the creation of three-dimensional (3D) parts by selectively melting and layer-by-layer fusing metallic powder materials followed by subsequent solidification. This process is especially advantageous in obtaining fully dense structures without a need for post processing but requires higher laser energy levels and lower scan velocities [47,18]. These high energy density levels that are applied to powder metallic material create undesirable situations such as meltpool instabilities and spattering [40], balling effects, material evaporation, and keyhole effects [24] resulting in unacceptable defects and hence loss of quality in fabricated parts. It is also difficult to control the resultant microstructure of the build part [2,44] especially for nickel-based alloyed Inconel 718 (IN718) or Inconel 625 (IN625) materials for mission critical aerospace applications [23].

The laser powder bed fusion process typically generates surfaces and microstructures through directional solidification that may be controlled or adjusted by scan strategies and selection of processing parameters. On the other hand, the modeling and simulation provides physical process insight that is often not possible or highly difficult by conducting in-situ/in-process measurements [14]. In literature, Dunbar et al. [10] investigated post-built distortion of experimental cylindrical

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builds obtained through a rotating scan pattern and a constant scan pattern in the L-PBF. These measurements were compared against the predictions using finite element method based simulations. Their results indicated about 12% percent error in distortion deformations as compared to experimental measurements. Denlinger et al. [8] developed a model for predicting the thermal response of nickel alloy IN718 during the L-PBF processing. Their model simulated peak temperatures within 11% error against the measured values and captured temperature trends. However, neglecting the pre-placed powder layer in their simulations resulted in predicting temperatures 30% higher than measured ones and they suggested including the placement of powder layer for more accurate predictions. Later, Dunbar et al. [11] conducted in-situ experimental measurements with a goal of gaining insight into the evolution of distortion in the powder bed fusion build process. Their experimental results showed that builds completed using nickel alloy IN718 distort between 50% and 80% more relative to titanium alloy Ti–6Al–4V depending on substrate size and build geometry. Wang et al. [45] used neutron diffraction to validate thermomechanical models developed to predict the residual stresses in nickel alloy IN625 walls fabricated by a laser based directed energy deposition process. Their residual stress calculations from neutron diffraction measurements showed strong dependency on the determination of stress-free lattice spacing.

Recent efforts in predictive modeling for laser melting and powder bed fusion processes have been directed into understanding the relationship between material and process parameters, in particular, the effect of rapid heating and quick cooling times in the resulting microstructure [2,48,46,23,24]. Therefore, temperature distribution plays a significant role in the resulting properties of the parts manufactured through the L-PBF process. For this reason, accurately describing the temperature distribution during and after the process is vital to obtain high quality parts. The temperature distribution can be calculated using either an analytical solution approach or a numerical solution approach. Furthermore, a numerical solution can be obtained two-fold: with a finite element method (FEM) approach, and by means of applying the finite difference method (FDM). Rosenthal [38] was the first author to address the problem of the physics of a moving heat source and developed an analytical solution. Eagar & Tsai [13] attempted to find an analytical expression for the geometry of the meltpool produced by a traveling, Gaussian-distributed heat source. Goldak et al. [17] were the first to introduce a 3D heat source, by using a double ellipsoidal moving heat source to calculate the temperature field utilizing finite element method based modeling. Gusarov et al. [19] developed a model to calculate the thermal conductivity of a powder bed based on the molecular structure of the powder. Kolossov et al. [27] developed a thermal model utilizing finite element analysis. Their model incorporated the non-linear behavior of thermal conductivity and specific heat, due to the change in temperature and phase. Patil & Yadava [35] analyzed the effect of laser processing parameters such as power, beam diameter, laser on/off-time, and hatch spacing in the temperature distribution of a single powder layer using a FEM approach. Gusarov et al. [20] continued their investigations by developing an FEM model to analyze the effect of scanning velocity, concluding that an interval of scanning velocities exists in which the re-melted tracks due to scanning are uniform. Van Elsen et al. [42] provided both analytical and FDM numerical solutions to the heat conduction equation for a localized moving heat source. Roberts et al. [37] developed a 3D FEM model for predicting the transient temperature field for multiple layers of parts, using a death and rebirth technique. Yin et al. [48] developed a simulation of the temperature distribution and analyzed the effect of process parameters on temperature distribution and the geometry of the meltpool. An accurate temperature distribution is deemed necessary to predict the dimensions and characteristics of the meltpool. Aggarangsi & Beuth [1] studied the meltpool size utilizing an FEM approach and used Rosenthal's solution to validate their results. Pinkerton & Li [36] modeled the geometry of a moving laser meltpool utilizing energy and mass balance equations along with a one-dimensional heat conduction approach, thereby ignoring convective and radiation losses. Jahn et al. [22] developed an FEM model based on heat conduction, a free melt surface, a moving phase boundary to obtain meltpool geometry in solid-liquid-solid phase transition problems. Vasquez et al. [43] developed a 3D quasi-stationary FEM model to analyze multi-physics laser-material interaction. Cheng et al. [4] developed an FEM-based transient thermal model where a moving conical volumetric heat source is employed to model beam penetration into the material. Song et al. [41] performed a study on process parameter selection using temperature distributions obtained from FEM with solid elements, as well as experiments. Yadroitsev et al. [46] investigated the effects of the process on the microstructure by taking direct measurements of the surface temperature distribution. Shrestha & Chou [39] proposed 3D thermo-fluid model using temperature dependent physical properties and analyzed the dynamics of free surface of meltpool by taking into account the energy, volume fraction, and flow equations at the interface when heated by a moving heat source. Criales et al. [5] analyzed the effects of varying laser power, scanning speed, and the packing density of the powder material for selective laser melting of nickel alloy IN625 using FEM modeling. Arisoy et al. [3] investigated the L-PBF process with an aim to produce fully dense solid parts. They analyzed the microstructure of fabricated nickel alloy IN625 test cubes and measured average grain size and columnar growth directions by utilizing scanning electron microscopy (SEM) images on the electro-polished surfaces. They provided explanations on the microstructure formation including sizes of cellular grains and growth directions of the columnar grains. 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. Criales et al. [6,7] fabricated nickel alloy IN625 test coupons with different L-PBF process conditions and analyzed the process signatures such as meltpool geometry and shape in order to gain in-depth process understanding. They also performed in-situ thermal camera video recording and analyzed for measuring meltpool size, spattering, and heating and cooling rates during the processing of the nickel alloy IN625 powder bed. Multi-track processing is analyzed by using 2D finite element method. Du et al. [9] proposed a 3D FEM model for thermal behavior and microstructure evolution in multi-track laser melting deposition of nickel alloy IN625. They considered latent heat of phase change, multiple heat transfer, temperature dependent thermal physical properties for the thermal simulations. Their simulations for solidification microstructure used temperature gradient, solidification growth rate, and cooling rate predictions. They found that columnar dendrites mostly likely to form under the meltpool, while equiaxed dendrites were formed on the meltpool surface. Meanwhile due to the high temperature gradient to solidification growth rate ratio, columnar dendrites formed along the meltpool boundaries.

Lawerence et al. [30] states that nickel alloy IN625 laser consolidation process yields a microstructure with columnar grains towards the build direction. The directionality comes from rapid solidification during the process. Horizontal view reveals fine cells of 2–3 μm diameters. The results from X-ray diffraction show that laser consolidated nickel alloy IN625 maintains the same γ phase as the powder. Moreover, the solidification is observed to be towards the (1 0 0) plane of the crystal, which is commonly seen in dendritic growth of fcc grains. The directionality of the microstructure caused anisotropic mechanical behavior with a lower tensile strength in the build direction compared to the horizontal direction. The nickel alloy IN625 is reported to contain γ NiCr, γ″ Ni3Nb, Laves (usually Nb-rich) and δ Ni3Cb phases, along with different carbide precipitations, based on the temperature history with δ and Laves phases precipitating when the material is held at elevated temperatures for long durations [15]. DuPont [12] states that solidification of nickel alloy IN625 is initiated by γ dendrites, which upon growth enriches the interdendritic liquid in Nb to form the γ/Laves eutectic composition after which the solidification terminates by