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Thermal modeling of Inconel 718 processed with powder bed fusion and experimental validation using in situ measurements

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ABSTRACT

A model for predicting the thermal response of Inconel® 718 during laser powder-bed fusion processing (LPBF) is developed. The approach includes the pre-placed powder layer in the analysis by initially assigning powder properties to the top layer of elements before restoring the solid properties as the heat source traverses the layer. Different linear heat inputs are examined by varying both laser power and scan speed. The effectiveness of the model is demonstrated by comparing the predicted temperatures to in situ experimental thermocouple data gathered during LPBF processing. The simulated temperatures accurately capture the measured peak temperatures (within 11% error) and temperature trends. The effect of neglecting the pre-placed powder layer in the simulations is also investigated demonstrating that conduction into the powder material should be accounted for in LPBF analyses. The simulation neglecting the powder predicts temperatures more than 30% higher than the simulation including the powder.

1. Introduction

The laser powder bed fusion (LPBF) additive manufacturing (AM) process allows for the rapid production of net shape metallic parts directly from a digital drawing file. The LPBF process operates by first spreading a thin layer of powder (on the order of 10's of μm) across a build plate. Next a laser melts the material which then cools and solidifies to form a fully dense geometry. The build plate then lowers, a recoater spreads a new layer of powder, and the process is repeated allowing for parts to be additively constructed on a layer-by-layer basis. During the process large thermal gradients arise causing unacceptable levels of residual stress to build up in the part, frequently leading to failure by cracking or delamination from the build plate. Current efforts to deal with this issue utilize a costly trial and error approach where parts are manufactured several times until an acceptable final product results. Finite element model (FEM) predictions can be used to circumvent the costly trial and error process assuming that they accurately capture the necessary process physics.

In situ experimental measurements have been used to thoroughly validate FE models of AM processes as they provide more insight into the process than could be realized using only post-process measurements. Lundbäck and Lindgren performed in situ distortion and temperature measurements during single wall depositions using a gas tungsten arc welding process and used the results for FEM validation [1]. Ocelik et al. used digital image correlation (DIC) to validate a predictive FE model by measuring in process strain during laser cladding of single and multi-bead Nanosteel, Eutroloy 16012, and MicroMelt 23 on C45 steel and 301 stainless steel substrates [2]. Peyre et al. used thermocouples and thermal imaging to validate numerical predictions of the directed energy deposition (DED) thermal response [3]. Plati et al. used thermocouples to monitor in situ temperatures during laser cladding and validated a 3D FE model using the results [4]. Heigel et al. developed a thermo-mechanical FE model of the laser engineered net shape (LENS) processing of Ti-6Al-4V which includes the effect of forced convection from the inert gas jets [5]. In situ temperature measurements performed using thermocouples were used to validate the model and to illustrate that the numerical predictions neglecting forced convection were insufficient. Gouge et al. implemented forced convection measurements in a thermal FE model to accurately capture the thermal response of laser clad Inconel® 625 [6].

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The results were validated against in situ measurements taken with thermocouples. While each of these studies offers an in depth validation of numerical models of AM processes, none focuses on the LPBF process.

From a modeling standpoint the primary differences between the previously discussed DED AM processes and the LPBF process include the presence of the pre-placed powder layer and a smaller laser spot size (as little as 70 μm). The pre-placed powder may affect the thermal response. A smaller spot size necessitates strict spacial and temporal discretization requirements. To reduce lengthy computation times imposed by the discretization requirements associated with LPBF researchers have attempted removing the build plate from the analysis [7] or using a 2D model [8]. Others have neglected the powder in thermal analyses of LPBF processes [7,9,10], essentially assuming that the powder is a perfect insulator. The effect of this assumption is unknown.

Several other approaches to modeling the powder layer have been presented that are not intended to reduce computational expense. Dai and Shaw [11,12] assumed that the powder material in LPBF processes has the same thermal properties as its matching solid material in a 3D thermomechanical powder bed model. In other LPBF research the conductivity of the powder is scaled by a porosity dependent factor [13,14]. Another common strategy [15–19] involves assigning the metallic powder thermal properties based on powder–solid relationships developed by Sih and Barlow [20–22]. Some of these works on LPBF modeling provide no model validation [11,12,15,14], while others validate the developed models against measured relative densities [16], weld track width [17], microstructure and melt pool dimensions [19,18], or post process residual stress [10]. None of the aforementioned models have been validated against in situ temperature measurements.

The objective of this work is to develop a thermal model of the LPBF process and validate the predicted thermal response against in situ temperature measurements. A thermal finite element analysis is performed using a modified version of the quiet element approach [23]. The modified approach permits the metallic powder material to have a thermal conductivity and emissivity based off of the solid–powder material property relationships developed by Sih and Barlow [22]. Prior to processing all melted and solidified elements are given powder properties, however when the heat source is applied to the elements their solid properties are restored. The necessary number of degrees of freedom (DOF) in the model imposed by the required spacial discretization requirement is reduced by applying condensation and recovery [24]. The effectiveness of the approach is demonstrated by simulating the LPBF processing of a single layer 100 laser track Inconel® 718 build. Experimental model validation is performed by comparing the model to the measured thermal response of actual LPBF processed builds of the same geometry. The model results are also compared to numerical cases where the powder elements are removed from the analysis.

2. Modeling approach

The temperature history is calculated using a 3D Lagrangian transient thermal analysis accounting for both solid and powder properties of the metallic material.

2.1. Transient thermal analysis

The governing transient heat transfer energy balance in the entire volume of the material is given as:

$$Q(\boldsymbol{x}, t) - \nabla \cdot \boldsymbol{q}(\boldsymbol{x}, t) - \rho C_p \frac{dT}{dt} = 0 \tag{1}$$

where ρ is the material density, C_p is the specific heat capacity, T is the temperature, t is the time, Q is the internal heat generation rate, $\boldsymbol{x}$ is the relative reference coordinate, and $\boldsymbol{q}$ is the heat flux.

The initial condition for Eq. (1) is:

$$T(\boldsymbol{x}, t_0) = T_\infty \tag{2}$$

where T_∞ is the ambient air temperature. The Fourier heat flux constitutive relation is given by:

$$\boldsymbol{q} = -k\nabla T \tag{3}$$

which depends on temperature dependent thermal conductivity k.

Thermal radiation q_{rad} is accounted for using the Stefan–Boltzmann law:

$$q_{rad} = \varepsilon\sigma({T_s}^4 - {T_\infty}^4) \tag{4}$$

where ε is the surface emissivity, σ is the Stefan–Boltzmann constant, and T_s is the surface temperature of the workpiece. The Stefan–Boltzamnn equation can be linearized and put into heat transfer coefficient form:

$$q_{rad} = h_{rad}(T_s - T_\infty) \tag{5}$$

where the heat transfer coefficient for radiation h_{rad} is calculated as [6]:

$$h_{rad} = \varepsilon\sigma(T_s + T_\infty)({T_s}^2 + {T_\infty}^2) \tag{6}$$

Newton's law of cooling describes the heat loss due to convection q_{conv}:

$$q_{conv} = h(T_s - T_\infty) \tag{7}$$

where h is the convective heat transfer coefficient.

2.2. Powder-bed conductivity and emissivity

The properties of the metallic Inconel® 718 powder are assigned based on powder–solid relationships developed by Sih and Barlow [22]. The conductivity k_p of the Inconel® 718 powder consisting of spherical particles can be calculated as follows:

$$k_p = k_f \left[(1 - \sqrt{1-\phi}) \left(1 + \phi \frac{k_r}{k_f} \right) + \sqrt{1-\phi} \left(\frac{2}{1 - \frac{k_f}{k_s}} \left(\frac{2}{1 - \frac{k_f}{k_s}} \ln \frac{k_s}{k_f} - 1 \right) + \frac{k_r}{k_f} \right) \right] \tag{8}$$

where k_f is the thermal conductivity of the Argon gas surrounding the particles, ϕ is the porosity of the powder bed, k_s is the conductivity of the solid, and k_r is heat transfer attributed to the radiation amongst the individual powder particles.

$$k_r = \frac{4}{3}\sigma T^3 D_p \tag{9}$$

where D_p is the average diameter of the powder particles.

The emission of radiation from the heated porous powder surface is caused by emission from the individual particles as well as from cavities present in the powder bed. The emissivity ε_p of the Inconel® 718 powder bed can be calculated as:

$$\varepsilon_p = A_H \varepsilon_H + (1 - A_H)\varepsilon_s \tag{10}$$

where A_H is the porous area fraction of the powder surface:

$$A_H = \frac{0.908\phi^2}{1.908\phi^2 - 2\phi + 1} \tag{11}$$