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An inherent strain based multiscale modeling framework for simulating part-scale residual deformation for direct metal laser sintering

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A B S T R A C T

Residual distortion is a major technical challenge for laser powder bed fusion (LPBF) additive manufacturing (AM), since excessive distortion can cause build failure, cracks and loss in structural integrity. However, residual distortion can hardly be avoided due to the rapid heating and cooling inherent in this AM process. Thus, fast and accurate distortion prediction is an effective way to ensure manufacturability and build quality. This paper proposes a multiscale process modeling framework for efficiently and accurately simulating residual distortion and stress at the part-scale for the direct metal laser sintering (DMLS) process. In this framework, inherent strains are extracted from detailed process simulation of micro-scale model based on the recently proposed modified inherent strain model. The micro-scale detailed process simulation employs the actual parameters of the DMLS process such as laser power, velocity, and scanning path. Uniform but anisotropic strains are then applied to the part in a layer-by-layer fashion in a quasi-static equilibrium finite element analysis, in order to predict residual distortion/stress for the entire AM build. Using this approach, the total computational time can be significantly reduced from potentially days or weeks to a few hours for part-scale prediction. Effectiveness of this proposed framework is demonstrated by simulating a double cantilever beam and a canonical part with varying wall thicknesses and comparing with experimental measurements which show very good agreement.

1. Introduction

Powder bed fusion (PBF) additive manufacturing (AM) process, including direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM), has drawn unprecedented attention from both academia and industry due to its capability to manufacture functional parts with complex geometry and internal structures in a layer-by-layer fashion. In laser-based powder bed fusion process, the recoater blade spreads a thin powder layer from the reservoir to the build plate, and the laser beam melts the powders and welds them with the previously deposited layers according to the sliced layer shape and predefined scanning pattern. Then, the build platform moves downwards by a distance equal to the layer thickness, and the process repeats itself every layer until the part is built completely. Rapid melting and cooling occur everywhere within the build layer due to localized and point-to-point laser scanning, and repeated thermal cycles are induced by subsequent layer deposition. These extreme thermal events introduce high temperature gradient to each layer and generate high residual stress and distortion. Although the powder bed fusion process is widely used in aerospace, automobile and biomedical industries, this undesired residual distortion and stress is one of the main critical issues that prevent broader applications. To address this issue, a deep understanding of the detailed mechanisms responsible for residual stress and distortion is necessary. Various experimental studies have been performed to investigate the mechanisms and stress profile by means of X-ray diffraction or neutron diffraction [1–4]. However, these experiments are usually time-consuming and expensive.

Fast and accurate simulation of residual stress/distortion in AM-processed parts is a promising method for ensuring manufacturability and improving component quality. Considering the limited computational speed, early simulation efforts for powder bed fusion mainly focus on models on the order of millimeter or even smaller scale such as single track. Dai and Shaw [5,6] developed a 3D finite element model to investigate the effect of fabrication sequences, laser scanning patterns, and laser scanning rates on residual stress and distortion. Similarly, Cheng et al. [7] explored residual stress and deformation subject to different scanning strategies in selective laser melting, where eight different scanning strategies were simulated. Fu and Guo [8] used a

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micro-scale SLM model with surface moving Gaussian heat flux to study the temperature gradient mechanism within the molten pool. Prabhakar et al. [9] proposed a layer-by-layer finite element based modeling approach to study residual stress and deformation of the electron beam melting process. Hussein et al. [10] implemented a non-linear transient thermo-mechanical analysis to study the temperature and stress profile of a single layer deposition process consisting of multiple laser scanning tracks. In this way, part-scale distortion and residual stress prediction requires thermo-mechanical analysis with millions of time steps. With very small laser spot size and thin layer thickness, simulation of powder bed AM process requires prohibitively large number of elements and high computation cost. Various techniques have been proposed to make AM process simulation model more efficient lately. For instance, layer scaling, which simultaneously models a number of layers grouped together, is a common method used by the majority of simulation work to reduce element number and computation cost [11–15]. Others have attempted uniform thermal load [12], stress [13], or temperature field [14] from detailed micro-scale analysis and pass the results to macro-scale analysis with scaled up layers for distortion and stress prediction. Simulation results of these methods show good agreement with experimental measurements. Several faster and more robust commercial simulation tools have also been developed for industrial applications, such as AutoDesk Netfabb, 3DSim (now part of ANSYS), MSC Simufact, GE GeonX, and Amphyon Works. Dynamic adaptive mesh refinement and coarsening algorithm has been developed by Pan Computing Cube (now part of Netfabb) [16–18] and 3DSim [19,20] to reduce computation expense in performing part-scale simulation.

Most of the aforementioned commercial software packages utilize different variants of the so-called inherent strain method to simulate residual stress/distortion at part-scale. This highly efficient method, also called applied plastic inherent strain method, was first proposed by Ueda [21] and has been widely used in welding distortion and residual stress simulations [22–25]. In this method, high resolution thermo-mechanical analysis is first performed on smaller specimen to obtain the plastic strain tensor components when the weldment has cooled down to ambient temperature. The plastic strain tensor obtained is then applied to a real welding part through a linear elastic analysis. This method drastically reduces computation time, and due to the similarity of the underlying physical process, the potential of applying plastic strain to AM process simulation has been explored [26–28]. However, the original inherent strain model for welding distortion simulation is not accurate for modeling AM processes since the multi-layer effects in AM are not considered in the model. To address this issue, Setien et al. [29] has proposed an empirical method based on classical laminate theory to determine the inherent strain in powder bed fusion AM process. Some of the aforementioned software packages, such as MSC Simufact and GE Amphyon, also employ experimental calibration to determine the applied inherent strain components, while Pan Computing and 3DSim packages extract plastic strains from micro-scale thermo-mechanical simulations. However, since these are commercial software packages, detailed description of the underlying algorithms developed is not publicly available. Most importantly, it is not known exactly how the inherent strains are being extracted and how these strains are applied to the part-scale model in their algorithms.

A modified inherent strain model [30,31], which has no loose parameters, has recently been proposed by the authors of the present paper to extract inherent strains from detailed AM process simulations. In that work, the accuracy and efficiency of the modified inherent strain model have been shown by comparing with detailed simulations and experimental results for several single-walled structures processed by the laser engineered net shaping (LENS) process. However, the modified inherent strain model has not been applied to more complex structures involving multiple scan lines in the same deposition layer as in typical laser powder bed fusion AM process. Following our previous work, this paper presents in detail a multiscale process modeling framework for efficiently and accurately simulating residual distortion and stress at the part-scale for the DMLS process. In this framework, inherent strains are extracted from a micro-scale detailed process simulation based on the modified inherent strain model [30,31] and then employed in the part-scale simulation through a quasi-static equilibrium finite element analysis (FEA). Different from the aforementioned methods, this multiscale model is for part-scale prediction and entirely based on the real printing process, where the process parameters, scanning strategy, and powder-to-solid transition are accounted for. Another important feature that is worth mentioning is that once the inherent strain values for a given material under a certain set of process parameters have been obtained, residual stress and distortion prediction can be directly performed without repeating the micro-scale detailed process simulation. This paper is arranged as follows: Section 2 is a brief introduction of the proposed multiscale modeling framework. Section 3 presents the detailed process simulation model, modified inherent strain model, and their linkage for performing part-scale simulation of residual stress/distortion. Additionally, validation experiments for the models at two different scales will also be presented. Section 4 presents the distortion and residual stress prediction results obtained from the proposed multiscale model and comparison with experimental measurements. Conclusions are given in Section 5.

2. Multiscale simulation framework

Considering the high time and computational cost of a detailed simulation, a multiscale process modeling approach is proposed to integrate accurate micro-scale modeling with part-scale distortion prediction. The procedure of the multiscale process model developed in this study is shown in Fig. 1 and summarized below:

- A micro-scale detailed process model is employed to extract inherent strains based on the modified inherent strain model
- Residual distortion and stress prediction at the part scale is performed using the inherent strains extracted in the layerwise inherent strain method

3. Multiscale modeling approach

3.1. Governing equations for detailed process simulation

The governing equation for thermal analysis in the detailed process simulation is the heat conduction equation:

$$\rho c_p \frac{dT}{dt} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + Q \tag{1}$$

where ρ is the material density, T is the temperature, c_p is the temperature dependent heat capacity, t is time, k is the temperature dependent thermal conductivity of material, and Q is the volumetric heat input term.

Temperature dependent thermal properties of bulk Inconel 718 can be found in [32]. For metallic powder, various thermal conductivity models have been developed to account for the porosity effect [33–35]. Powder thermal conductivity from these simple models is much larger than real value, since thermal conductivity is mainly dictated by the surrounding gas embedded within the voids. The model above which accounts for the surrounding gas effect has been developed [36] and utilized in thermal analysis:

$$k_{eff} = \frac{\rho_R k_s}{1 + \phi k_s / k_g} \tag{2}$$

where k_{eff} is the effective thermal conductivity of the powder bed, k_s and k_g are the temperature dependent thermal conductivities of the solid material and surrounding gaseous environment, respectively; ρ_R is the initial relative density of the powder; and the empirical coefficient $\phi = 0.02 \times 10^{2(0.7-\rho_R)}$.

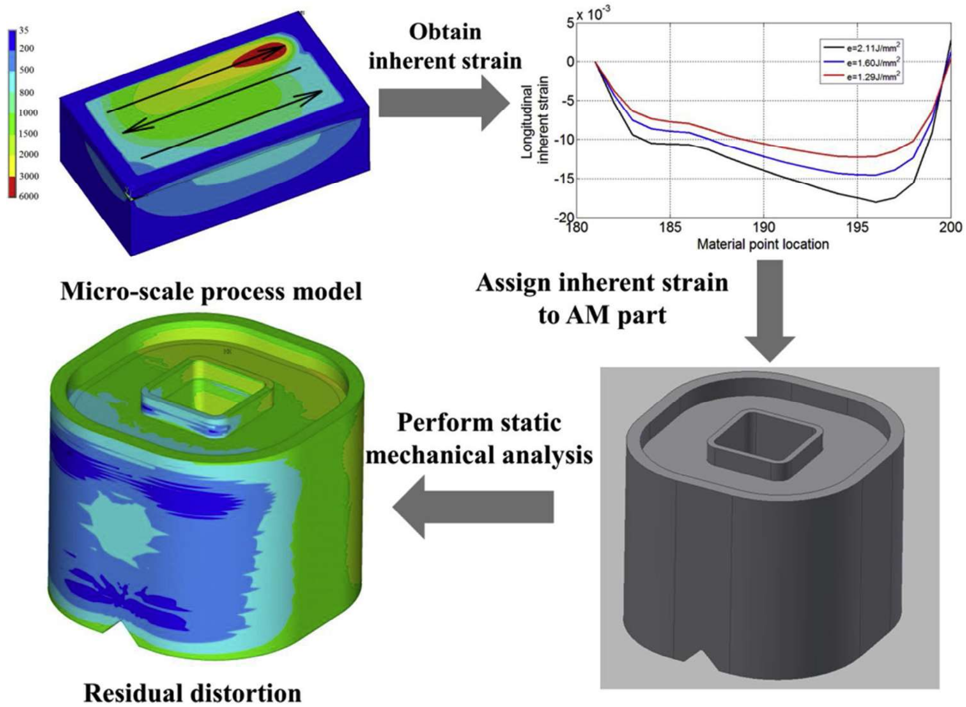

Fig. 1. Proposed multiscale process simulation framework.

Initial condition and boundary conditions of the governing equation are shown in Eqs. (3)–(6), respectively:

$$T(x, y, z, t_0) = T_0,\ (x, y, z) \in \Omega \tag{3}$$

$$T = \bar{T},\ (x, y, z) \in \partial\Omega_D \tag{4}$$

$$-k\nabla T \bullet \boldsymbol{n} = h(T - T_0),\ (x, y, z) \in \partial\Omega_R \tag{5}$$

where T_0 is the initial temperature. Since there is powder preheating, the initial temperature equals to 80 °C in detailed process modeling. Eqs. (4), (5) define the Dirchlet boundary $\partial\Omega_D$ and Robin or convection boundary $\partial\Omega_R$, respectively, and $\partial\Omega = \partial\Omega_D \cup \partial\Omega_R$.

The heat loss due to radiation is given as:

$$-k\nabla T \bullet \boldsymbol{n} = \sigma\zeta(T^4 - T_0^4) \tag{6}$$

where σ is the Stephan-Boltzmann constant and ζ is the emssivity.

A quasi-static mechanical analysis is conducted in sequential thermal load steps using the temperature history obtained to solve the mechanical response. The governing equation for the mechanical analysis is the stress equilibrium equation written as:

$$\nabla \bullet \boldsymbol{\sigma} + \rho \boldsymbol{b} = 0 \tag{7}$$

where $\boldsymbol{\sigma}$ is the stress tensor and $\boldsymbol{b}$ is the body force per unit volume and the boundary condition is defined as:

$$\boldsymbol{U} = \bar{\boldsymbol{U}},\ (x, y, z) \in \partial\Gamma_u \tag{8}$$

$$\boldsymbol{\sigma} \bullet \boldsymbol{n} = \bar{\boldsymbol{t}},\ (x, y, z)) \in \partial\Gamma_t \tag{9}$$

where the displacement vector $\boldsymbol{U}$ on boundary $\partial\Gamma_u$ is specified as $\bar{\boldsymbol{U}}$ and the surface vector on boundary $\partial\Gamma_t$ is defined as $\bar{\boldsymbol{t}}$. In mechanical analysis, the material constitutive model is assumed to be elastic and perfect plastic with J2-von Mises plasticity law:

$$\boldsymbol{\sigma} = \boldsymbol{C}: \boldsymbol{\varepsilon_{elastic}} \tag{10}$$

$$\boldsymbol{\varepsilon_{total}} = \boldsymbol{\varepsilon_{elastic}} + \boldsymbol{\varepsilon_{plastic}} + \boldsymbol{\varepsilon_{thermal}} \tag{11}$$

$$\boldsymbol{\varepsilon_{thermal}} = \boldsymbol{\alpha} \bullet \Delta T \tag{12}$$

$$f^{yield} = \sqrt{\frac{3}{2}\sigma_{ij}\sigma_{ij} - \frac{1}{2}\sigma_{kk}\sigma_{kk}} - \sigma_Y \tag{13}$$

where $\boldsymbol{C}$ is the fourth order stiffness tensor and $\boldsymbol{\varepsilon_{elastic}}$ is the elastic strain tensor. The stress tensor can be expressed as the double-dot product of the stiffness tensor and elastic strain tensor. Total strain $\boldsymbol{\varepsilon_{total}}$ is the sum of elastic strain $\boldsymbol{\varepsilon_{elastic}}$, plastic strain $\boldsymbol{\varepsilon_{plastic}}$ and thermal strain $\boldsymbol{\varepsilon_{thermal}}$, $\boldsymbol{\alpha}$ is the temperature dependent coefficients of thermal expansion (CTEs) and ΔT denotes the change in temperature. When $f^{yield} = 0$, yielding occurs and then generates plastic strains. Temperature dependent mechanical properties of Inconel 718 in mechanical analysis can be found in Refs. [37,38].

3.2. Single layer detailed process model

In order to calibrate the thermal finite element model, process simulation for a $40 \times 10 \times 0.04\ mm^3$ layer of Inconel 718 is performed, and the thermal histories obtained for the far-field points located on the bottom surface of the substrate are compared with experimental measurements by thermocouples. Here, it is worthy to emphasize that using thermocouples, it is not feasible to obtain near-field temperature history since thermocouples are limited to temperature range far below the melt pool temperature. However, thermal model calibration based on thermocouple measurement in the far-field has been used for decades to develop process model to predict residual deformation and stress for welding and more recently for additive manufacturing [38–41]. The reasons why this method works well are 1) past experiences have shown that the Goldak's model is effective for modeling residual stress/deformation for welding and AM process, and 2) the heat source model affects far-field temperatures just as much as it does on near-field temperatures. Hence, model calibration by far-field temperature histories would yield a heat source model with high fidelity, e.g., laser power and velocity, absorptivity and penetration depth, and finite element model with calibrated boundary condition setup which finally ensure the prediction accuracy for near-field temperature and residual deformation. The one layer of rectangle is deposited on a $101.6 \times 101.6 \times 3.18\ mm^3$ substrate using the EOS M290 DMLS with the default core-skin scanning strategy. The substrate is mounted by screws onto four short columns deposited onto the build platform *a priori* as shown in Fig. 2(a). Three Omega SA1XL-K-72 thermocouples,