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A scalable predictive model and validation for residual stress and distortion in selective laser melting

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ABSTRACT

The unique thermal cycle of rapid melting, solidification, and melt-back in selective laser melting (SLM) induces steep residual stress gradients which lead to part distortion. However, it is extremely difficult to predict residual stress in SLM due to complex multi-physics phenomena and scale-up of millions of laser scans. This paper has developed a geometry scalable predictive model across microscale laser scan, mesoscale layer hatch, and macroscale part build-up to fast predict residual stress in different scanning strategies. The predictions were validated using the L-shaped bar and bridge structures. The geometry scalability law provides an effective tool for optimizing part designs.

1. Introduction

Selective laser melting (SLM) may manufacture functional metal parts by melting metal powders layer by layer directly from a digital model [1]. SLM has a broad of applications in the aerospace, automotive, tool, biomedical, and energy industries in the past decade due to its potential of rapid manufacturing. However, the unique thermal cycle of rapid melting, cooling, and melt-back during SLM induces steep residual stress gradients which lead to microcrack, delamination, and part distortion which are major concerns in metal additive manufacturing (AM) community.

An experimental study on residual stress and part distortion induced by SLM is time-consuming and expensive, while a numerical simulation of residual stress and part distortion has the potential to avoid the tedious and costly trial-and-error efforts to improve the part quality. A reliable prediction of residual stress and part distortion before the actual SLM process would assure first-time-right of an SLM part since a practical sized part would take days or even weeks to print. Research efforts have been made to predict residual stress on the scale of a single or multiple track or layers, and practical parts. Hodge et al. [2] utilized a fully coupled thermo-mechanical finite element (FE) model considering twelve layers and material state changing to predict the residual stress field. Several researchers [3–5] used the super-layer method to accelerate the SLM build-up simulation in an FE model, in which several physical layers are bundled and melted simultaneously by an equivalent heat source determined by measurements or assumptions. However, the effects of scanning strategy are difficult to implement using the method. Other researchers [6,7] used a pure mechanical load to mimic the mechanical response of the thermal load in SLM to avoid complex coupled thermo-mechanical calculation. This approach allows the prediction of displacement contours of a SLMed part with scanning strategy effects. Commercial AM process simulation software developers such as Autodesk, GeonX, 3DSim, etc., have employed the above predictive methods to simulate residual stress and part distortion in a metal AM process. Sharing the similar simulation methodology, the commercial software developers have shown the advantages by integrating advanced algorithm such as adaptive mesh for reduced computational load, with physical phenomenon such as solid phase transformation to accurately capture the elasto-plastic response of materials in AM [8].

It is extremely expensive to calculate residual stress field of a practical part using the coupled thermo-mechanical FE model even on a powerful workstation since a practical part usually requires millions of laser scans. Thus, a scalable multiscale predictive model is needed to provide an efficient prediction of residual stress and distortion with acceptable accuracy and cost. However, very little work has been focusing on developing such a scalable model to simulate residual stress and part distortion in SLM. Therefore, the research objectives of this paper are to (a) develop a scalable multiscale FE model for fast prediction of residual stress and part distortion in SLM through accelerating the material deposition rate (MDR); (b) explore the effects of scanning strategies on residual stress and part distortion; and (c) validate the model predictions with the experiment data.

2. Predictive model development

2.1. Benchmark structures

Fig. 1 gives the dimensions of two structures which were selected as benchmark design for this study. The L-shaped bar (Fig. 1a) was made from stainless steel 316 powder and specially

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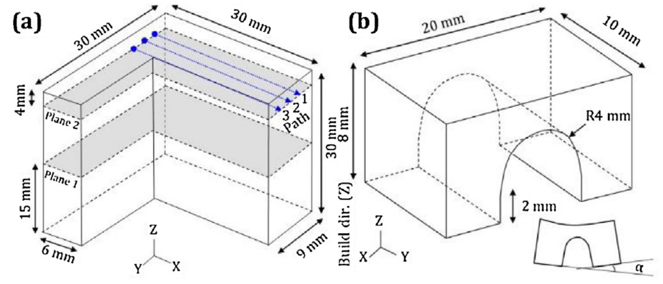

L-shaped bar/Bridge structure	
Laser power (w): 400/42	Scan spacing (μm): 100/74
Beam dia. (μm): 50/80	Layer thickness (μm): 30/30
Scan speed (mm/s): 1800/225	Gas: Argon

Fig. 1. (a) L-shaped bar dimensions and the cross-sections for residual stress measurement [9]; (b) Bridge structure dimensions and curling angle after substrate removal [11].

designed to facilitate residual stress measurement through neutron diffraction [9]. Ti–6Al–4V bridge structure (Fig. 1b) is an overhang structure which can be used to rapidly assess the residual stress magnitude of SLMed parts [10]. The key SLM process parameters for L-shaped bar and bridge structures are also shown in Fig 1. Post-process measurement was performed to examine the residual stress and distortion after the part was wire electrical discharge machined (EDM) from the substrate. For the L-shaped bar, residual stress was measured on the central surface (plane 1) and the near top surface (plane 2) as illustrated in Fig. 1a using the neutron diffraction and digital image correlation (DIC) methods. For the bridge structure, the curling angle α was measured to quantify the magnitude of residual stress.

2.2. Multiscale model description

The scalable multiscale model in this study includes three sub-models, namely, microscale scan model, mesoscale hatch model, and macroscale part model. The thermal history of the melt pool and heating rate, heating time, and melt pool depth was calculated in the microscale scan model. A Gaussian distributed heat flux as shown in Fig. 2a was used to model the moving laser beam heat source. Heat conduction, convection, and radiation were considered as thermal boundary conditions. The initial temperature of the powder bed and substrate was set at 20 °C.

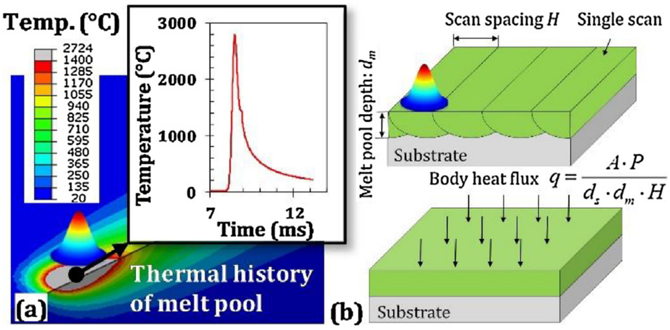

Fig. 2. (a) Temperature history output in the microscale laser scan model; (b) equivalent heat source model in the mesoscale hatch model.

The thermal history calculated in the microscale model was then used to determine an equivalent heat source for the mesoscale hatch model where the scan spacing was considered. The scan spacing for both structures (Fig. 1) is on the same level as the melt pool size. The shape of melt pool in the mesoscale model was simplified to a cuboid characterized by laser spot diameter, hatch spacing width, and melt pool depth. The equivalent body heat flux q (W/m^3) defined in Fig. 2b is a function of laser power (P), laser absorption rate (A), beam diameter (d_s), melt pool depth (d_m), and scan spacing (H).

The concept of block layer (Fig. 4a) is defined in the macroscale part model to accelerate the layer build-up simulation in SLM. A number of physical powder layers were bundled together to form one block layer. In this study, different block layer thickness for both L-shaped bar and bridge structures was chosen to investigate the simulation scalability on residual stress and distortion in SLM. Four levels of block layer thickness were chosen for both cases: 3 mm (10 block layers), 1.5 mm (20 block layers), 1 mm (30 block layers), and 0.75 mm (40 block layers) for the L-shaped bar; and 1.6 mm (5 block layers), 0.8 mm (10 block layers), 0.53 mm (15 block layers), and 0.4 mm (20 block layers) for the bridge. The cooling time for each block layers was set to 10 s.

2.3. Material properties and boundary conditions

The temperature-dependent thermal and mechanical properties of stainless steel 316L and Ti–6Al–4V used in this study are shown in Fig. 3 [9,11]. Strain hardening was ignored for the plasticity of both materials. Solid phase transformation induced strain for Ti–6Al–4V was not considered in this study and isotropic thermal and mechanical properties were used for both materials.

Thermal boundary condition in the macroscale part model was similar to the microscale scan model, in which heat loss of the system was achieved through conduction to the substrate and the powder bed, and heat convection and radiation to the surroundings (see Fig. 4a). The bottom surface of the substrate was fixed. The part building up process was achieved by a series of element deactivation and reactivation. The elements in each block layer were deactivated first and then reactivated layer by layer. Moreover, each reactivated block layer was heated by the equivalent heat flux q simultaneously. As illustrated in Fig. 4a, a layer of elements was deactivated to mimic the cut-through process of part removal by wire-EDM. For the bridge structure, the curling angle between two bottom surfaces after cut-through was calculated to measure the distortion. To study the effects of different scanning strategies on residual stress and distortion, four scanning patterns were considered in the bridge structure case as

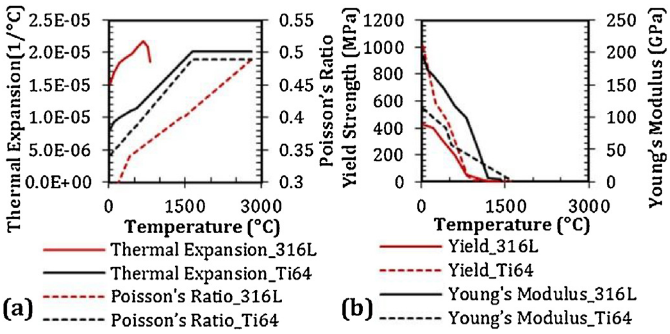

Fig. 3. Temperature-dependent material properties of SS316L and. Ti–6Al–4V (a) thermal expansion, (b) yield strength and Young's modulus.

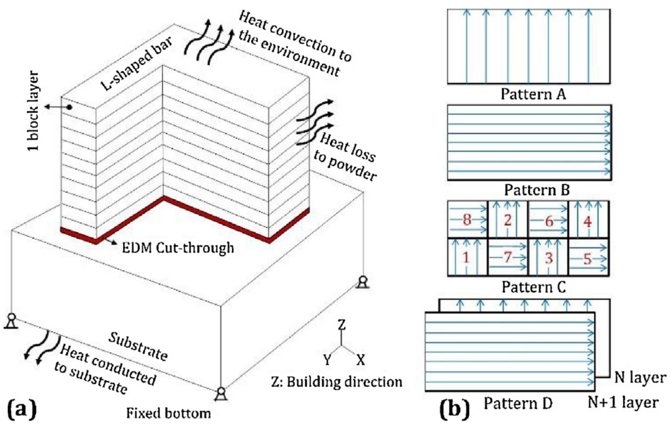

Fig. 4. (a) Thermal and mechanical boundary conditions of macroscale part model, (b) Scanning strategies.