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Prediction of Residual Stress and Part Distortion in Selective Laser Melting

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Abstract

Selective laser melting (SLM) is widely used to make functional metal parts. The high-temperature process will produce large tensile residual stress (RS) which leads to part distortion and poor product performance. Traditional modeling approaches are not practical to predict residual stress and part distortion due to the exceedingly high computational cost. In this study, two efficient multiscale modeling methods have been developed to across microscale laser scan, mesoscale layer hatch, and macroscale part buildup for fast prediction of residual stress and part distortion. A concept of equivalent heat source has been developed from the microscale laser scan model. In the "stress-thread" method, the local residual stress field was predicted by the mesoscale layer hatch model using the equivalent heat source, then the residual stress field is imported, i.e., "stress-thread", to the macroscale part buildup model to predict residual stress and part distortion. In the temperature-thread method, the powder–liquid–solid material transition has been incorporated. A body heat flux obtained from the microscale laser scan model is applied, i.e., "temperature-thread", to the hatch layer. Then multiple hatches are sequentially "deposited" in the macroscale part buildup model with different scanning strategies. The predicted part distortions by both methods were compared and compared with the experimental data.

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Keywords: residual stress; selective laser melting; distortion, multiscale modeling; selective laser melting; additive manufacturing

1. Introduction

1.1. SLM process and part distortion

Selective laser melting (SLM) is capable of producing functional parts in a layer upon layer fashion directly from CAD data [1]. Parts by SLM are near full density and have mechanical properties comparable to bulk materials [2, 3]. In a typical SLM system, a fine powder layer is placed on a substrate inside an inert chamber and is fully melted by a laser. After one layer is deposited, another layer will be placed and melted until a part is produced. Several defects usually exist in a SLM part. High thermal stress would lead to part distortion and cracks. The balling effect may result in poor surface finish [4]. Also, residual gas content, unmelted powder, and oxidized particles may lead to porosity of the component [5, 6].

The uneven heat input as well as the rapid cooling of the process generates large amounts of tensile residual stresses in the component. It not only reduces the part geometrical accuracy but also and detrimentally affects the functional performance of the end-use parts. Simulation work [7, 8] has been done to predict residual stress and distortion of SLM parts on the micro or mesoscale, in which only single tracks or multi-tracks were considered. Some studies [9, 10] predicted residual stress and part distortion in SLM on the macroscale. In these models a constant heat flux was applied to heat an entire scan line or an entire layer at the same instant to predict the temperature and residual stress distribution of macro part.

1.2. Pressing issues and research objective

A coupled thermal-mechanical analysis for several single scans with a fine mesh model is very time consuming. A practical SLM part on the macroscale requires millions of microscale laser scans which dramatically increases the computational load for the calculation of a coupled analysis. Thus, it is impossible in practice to predict the distortion of a practical SLM part if every scan is simulated.

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The objectives of this study are to develop and compare temperature-thread based and stress-thread based multi-scale approaches for efficient prediction of part distortion and residual stress by: (a) developing a novel equivalent heat source in mesoscale layer hatch from a microscale laser scan; (b) calculating the residual stress field and distortion of a practical part at macroscale; and (c) compare the predicted distortion results with the experimental data.

2. SLM experiment conditions

The laser source in this study is a continuous Nd:YAG laser with a wavelength of 1064 nm. The process parameters are listed in Table 1[3].

This study aims to predict part distortion and validate with the experimental data using the lab-made iron-based powders, but the material properties are not available, so a commercial powder with similar chemical composition is used instead as an approximation, it would be a future research subject to investigate the effect of temperature-dependent material data on model accuracy. The temperature-independent mechanical and thermal material properties are [11]: the elastic modulus is 130 GPa, the Possion's ratio is 0.41, the tensile and yield stress is 600 and 400 MPa, the melting point is 1330 ^{o}C, the coefficient of thermal expansion is 9 × 10^{-6}/K, the thermal conductivity is 13 W/m·K, and the specific heat is 375 J/kg·K.

Table 1 SLM process parameters [3]

Laser power	Beam dia.	Scan speed	Scan spacing	Layer thickness
300 W	600 µm	50 mm/s	100 µm	150 µm

3. Multiscale simulation approaches

Two types of multi-scale finite element methods have been developed and compared, i.e., the stress-thread based and temperature-thread based methods. Detailed procedure for both methods is shown in Fig. 1. For both methods, the powder material is melted by a moving heat flux to capture the thermal data of a melt pool in the microscale laser scan model. In the stress-thread method, the temperature field of the melt pool is recorded. In the temperature-thread method, the entire thermal history of the melt pool is recorded. Second, two types of equivalent heat sources are developed based on the thermal data in the microscale scan model for both methods, the heat load is directly applied to the mesoscale hatch model. Third, the thermal history of one hatch layer is applied to the macroscale part model, and each hatch layer is activated one by one until the whole part is built.

3.1. Micro laser scan model

Model dimensions

In the microscale scan model, a thermal analysis was conducted using the FEA package ABAQUS/Standard to predict the temperature field in the melt pool. The powder layer with thickness of 0.15 mm was placed on the substrate. The powder layer was 5 mm in length, 0.3 mm in width and 0.15 mm in thickness. The substrate was 5 mm in length, 0.3 mm in width and 5 mm in height. The initial temperature of the whole model was set to room temperature 20 °C.

Laser heat source modeling

A moving Gaussian distributed heat flux is developed to model the heat input of the scanning laser in the microscale model. The temperature field of the melt pool was captured when the laser travelled to the center point of scan track, and this field was used to develop equivalent heat source for stress-thread based method. The thermal history (heating and cooling) of the center point of scanning track was recorded for equivalent heat source development for temperature-thread based method.

Temperature data output

Fig. 2(a) shows the temperature field of the cross-section of the melt pool when the laser is located at the center of the scan track. This temperature field will be extended on a larger scale with scan spacing considered, used for mesoscale model in stress-thread method. Fig. 2(b) shows the thermal history of the melt pool center which will be used for developing an equivalent heat source for temperature-thread method.

3.2. Meso layer hatch model

Scan spacing is an important SLM process parameter and defined as the length of overlap between two neighboring scan tracks. In this study, the scan spacing was incorporated in the equivalent heat source in the mesoscale hatch model for both the stress-thread and temperature-thread methods.

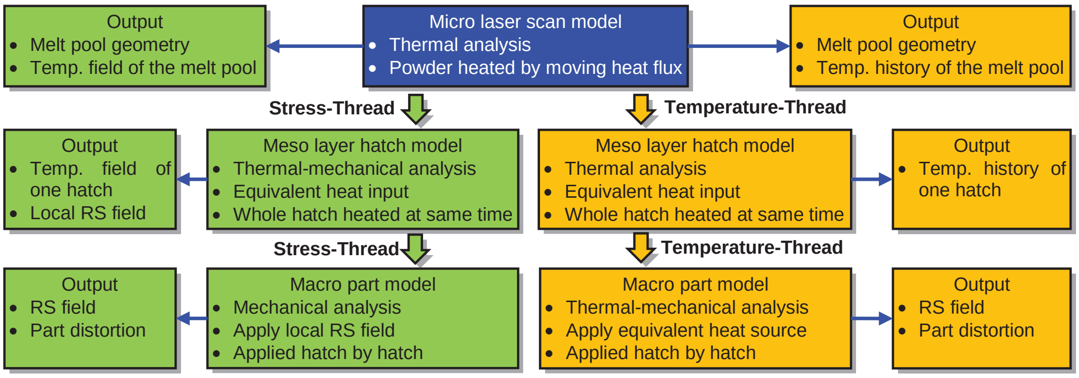

Fig. 1 Stress-Thread based and Temperature-thread based method for the prediction of distortion of SLM parts.