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A conceptual design of residual stress reduction with multiple shape laser beams in direct laser deposition

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A B S T R A C T

Residual stress is a major problem in metal parts fabrication with the direct laser deposition (DLD) process due to severe temperature gradient around a molten pool. A three-dimensional finite element analysis (FEA) model with a simplified substrate clamping fixture modeling method is proposed, validated, and then implemented with a novel DLD heat input strategy in Ti-6Al-4V thin-wall structure fabrication, which was applied with multiple beam shapes, including a super-Gaussian beam, Gaussian beam, and inverse-Gaussian beam, to reduce residual stress in the final part. A regression model of the heat input and final part residual stress was obtained via a three-factor two-level full factorial design. An optimized heat input strategy was achieved based on response surface contour plots of the regression model.

1. Introduction

In metal additive manufacturing (AM) process, residual stresses are generated from severe temperature gradient around a molten pool, which induces tensile stresses on top layers and compressive stresses below [1]. Many studies have investigated residual stress reduction methods with the help of finite element analysis (FEA) models. Indirect-coupled thermal-mechanical model is a commonly used method, which decouples the simulation process into thermal and structural part and the thermal results are applied as loads for the following structural simulation [2–5]. Idle time adjustment between layers is a simple method to modify cooling rate during the AM process, which will tailor solid-state phase transformation, stress evolution, and stress distribution in the deposit [6–9]. Scanning path strategy also has been investigated among different types of structures in various AM processes to explore a suitable scanning path for residual stress distribution and reduction optimization [9–11]. Except the in-process parameters study, initial conditions have shown impacts on the deposition also, such as the significant impacts that substrate size and initial temperature have on transient thermal history, microstructure, and residual stress of the part that is built atop [7,8,12–15]. Multiple approaches have been used for substrate preheating. For the whole part uniform preheating, furnace and induction has been tested and shown positive effects on residual stress reduction [16]. For localized preheating, a dual beam system has been introduced to the AM process to heat up the materials with a defocused low-power laser beam just before a focused Gaussian beam was applied to melt injected powders [16,17]. Research has shown that the uniform preheating has a greater effect on residual stress reduction than the localized preheating method [17]. Though uniform substrate preheating is superior to localized substrate preheating in residual stress control, the localized preheating is more feasible and convenient to implement compared to uniform preheating, especially for local features on complex shape parts. The localized preheating effect in residual stress reduction can be improved by a laser beam with a large diameter and almost uniformly distributed energy intensity scanning multiple times before real deposition. To reduce temperature gradient around deposit after deposition, a beam with less energy intensity around the beam center can be implemented for in situ post heat treatment to reduce temperature gradient between substrate and deposit, and thus indirectly result in residual stress reduction during cooling. The boundary condition like thermal interaction between base plate and clamping fixture can also be a critical factor to microstructure and residual stress evolution in the final part especially when the temperature of the base plate and fixture contacting surface rises above ambient temperature [18,19]. Here are two common methods to simulate the thermal interaction between the base plate and the clamping fixture in current direct laser deposition (DLD) process research. One is eliminating the clamping fixture model and simplifying it by using fixed base plate temperatures or artificial convection boundaries to mimic conduction heat losses between the base plate and the fixture [4,20–22]. The

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other method including a fixture modeled with its actual geometry in the simulation process [5,23,24], which requires extra modeling efforts and the increasing element number is also a negative factor for reducing simulation time.

Based on those ideals, to improve the existing knowledge, a three -dimensional FEA model implemented with a simplified modeling method for base plate clamping fixture is developed and validated. A new methodology with a combination of super-Gaussian beam (top hat beam), Gaussian beam, and inverse-Gaussian beam (donut beam) is proposed for the direct laser deposition (DLD) process. The super-Gaussian beam with uniform energy intensity is used for preheating, the Gaussian beam is designed for melting, and the inverse-Gaussian beam is used for post heat treatment. Due to the lack of available standard thermal-mechanical package for the DLD process simulation, an Ansys-based thermal-mechanical model is developed to maximize the feasibility of simulating DLD process at different experimental setups and to fulfill aforementioned research objectives. Herein, the design of experiment (DOE) and finite element analysis (FEA) methods are combined to explore an optimized energy input strategy for the three heat sources to reduce residual stress.

2. Finite element modeling

A three-dimensional finite element model is developed to predict transient thermal history and residual stress in Ti-6Al-4V (Ti-64) thin-wall structure using ANSYS Parametric Design Language (APDL). ANSYS provides an indirect coupled-field method to solve thermomechanical problems, which performs two sequential analyses using thermal results from the first analysis as loads for the second mechanical simulation. All thermophysical and mechanical properties are considered to be temperature-dependent, as shown in Fig. 1 [25,26].

To simplify the FEA simulation with reasonable accuracy, six assumptions were used in the modeling and solving process:

1. During propagation in free space, the shape of the laser's intensity profile will not change.
2. In the FEA model, the thermal load is applied in the form of thermal flux density.
3. The width of the deposit is assumed to be the same diameter of the Gaussian beam.
4. The deposit and the substrate's thermophysical properties are equal and the latent heat of fusion was accounted for by modifying the specific heat.
5. The mechanical values are assumed to be constant above 1000 °C [23].
6. Due to limited material property data at high temperature, a linearly hardening situation after yielding is assumed in the residual stress simulation step and the tangent modulus is assigned to 5 GPa in the plastic range [26].

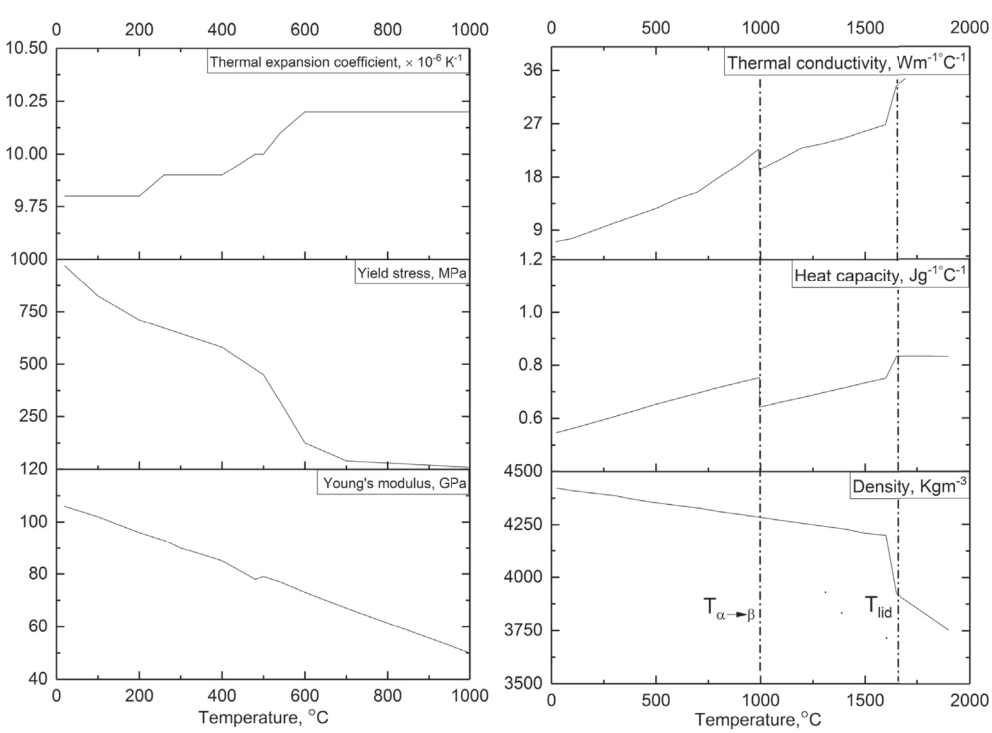
2.1. Thermal model

To simulate the DLD process, the first step is to solve the thermal history of the process with a three-dimensional transient thermal analysis. The governing equation of the transient process is written as in Eq. (1):

$$\nabla \cdot k\nabla T + \dot{q} = \rho c_P \frac{\partial T}{\partial t} \tag{1}$$

where T is temperature, t is time, c_P is specific heat at constant pressure, ρ is density, k is thermal conductivity, and ∇ is Hamilton operator, which equals to $(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$. There was no internal heat generation, so the $\dot{q}$ was set to zero. Latent heat of fusion is considered and included in the thermal model with a modified specific heat as shown in Eq. (2) [27]:

$$c_p^*(T) = c_p(T) + \frac{L}{T_m - T_0} \tag{2}$$



(a) mechanical properties (b) thermophysical properties

Fig. 1. Ti-64 temperature-dependent material properties.

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