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Numerical modeling of the thermal behavior and residual stress in the direct metal laser sintering process of titanium alloy products

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ABSTRACT

In this paper the heat transfer and residual stress evolution in the direct metal laser sintering process of the additive manufacturing of titanium alloy products are studied. A numerical model is developed in a COMSOL multiphysics environment considering the temperature-dependent material properties of TiAl6V4. The thermo-mechanical coupled simulation is performed. 3-D simulation is used to study single-layer laser sintering. A 2-D model is used to study the multi-layer effects of additive manufacturing. The results reveal the behavior of the melt pool size, temperature history, and change of the residual stresses of a single layer and among the multiple layers of the effects of the change of the local base temperature and laser power etc. The result of the simulation provides a better understanding of the complex thermo-mechanical mechanisms of laser sintering additive manufacturing processes.

1. Introduction

Additive Manufacturing (AM) has received increased attention in recent years due to its ability to produce near-net shape parts directly from computer-aided design (CAD) files without the retooling cost associated with conventional manufacturing processes [1]. Direct Metal Laser Sintering (DMLS) is an additive manufacturing process that creates parts through the layer-by-layer addition of materials. The DMLS process uses a high-intensity laser source to create a melt pool on a layer of spread powder. The melt pool solidifies and cools to an ambient temperature; thus adding a solid layer. Then another layer of powder is spread on top and the process repeats to add a new layer, progressively building the part. The resulting complex thermal history influences the residual stress, the material properties, and the distortion of the final product. DMLS has many potential applications, including the production of functional prototypes, short-run component fabrication, and the fabrication of functionally-graded materials. It is particularly attractive for the fabrication of titanium aerospace components because it can greatly reduce the amount of raw materials required to produce a finished part, the lead time for production, and cost.

Unfortunately, the presence of large thermal gradients during the metal sintering process results in undesirable residual stress and product distortion [1]. An improved scanning strategy could reduce the distortion and residual stresses; however, it is usually not clear[AG1]. It is also difficult to record the fast changing temperature history under the laser point via an experimental method. As of today, as indicated by some manufacturers, it usually takes an average of three trials to make a reliable product. To optimize the build plan without the expensive trial-and-error iterations, and to better understand the heat transfer in DMLS processes, an accurate predictive model is needed. In an effort to understand this phenomena, researchers have developed various analytical models [2,3] to describe the residual stress and distortion, while many others have used finite element analysis (FEA) to model the direct metal laser sintering process and study its effects on the part [1,4–7]. Mercelis and Kruth [3] presented a simplified analytical model to determine residual stress for parts produced using stainless steel powder (316L). Their model predicted the evolution of residual stress along the build direction but neglected the effect of base plate width. Vasinonta et al. [4] developed a 2D thermo-mechanical model for a thin-walled structure but neglected the convective and radiative heat exchange with the surroundings, making conduction the only mode of heat transfer. Additionally, they considered the base plate to be a constant temperature a boundary condition. Labudovic et al. [5] developed an improved modeling technique by considering the convection and radiation for a MONEL 400-alloy product. For the application of titanium alloy, a number of early efforts have been undertaken to develop its laser additive manufacturing processes [8–11]. These were mostly experimental studies seeking to deter-

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Nomenclature

c_p	Specific heat (J/kg-K)
E	Young's Modulus (Pa)
H	Latent heat (J/kg)
k	Thermal conductivity (W/k-m)
L	Length of the model element (mm)
P	Total laser power (J/s)
T	Temperature (K)
s	Thickness (mm)
r	Radius (mm)
Q	Energy absorbed (J)
ϵ_H	Hole emissivity (1)
ϵ_S	Solid emissivity (1)
T_{base}	Base temperature (K)
T_{init}	Initial temperature (K)
V_{laser}	Laser scanning speed (m/s)
σ_Y	Yield strength (MPa)
ϵ	Emissivity (1)
φ	Porosity (1)
ρ	Density (kg/m3)
A_H	Area fraction of emitting holes (1)
σ	Stress (MPa)
α	Thermal expansion coefficient (1)
C	Stiffness tensor (K^{-1})
f	Yield function (MPa)

mine the effect of the process parameters on the microstructural properties of final product. Some researchers have focused on the material phase change caused by AM such as predicting the resulting microstructure of the Ti-6Al-4V product [12–15]. Peyre et al. [15] developed a three step analytical and numerical approach to predict the melt pool dimensions and simulate thermal loading cycles for the addition of 25 layers. Roberts et al. [16] neglected convection and radiation heat losses in their thermal model and found that the heat was conducted much faster than two successive layer additions. They also concluded that residual stress concerns arise due to rapid thermal cycling. Other works have also focused on predicting the thermal behavior in the laser and electron beam deposition process [17,18]. Most of the previous research has focused on the material property measurement, laser-powder interaction, and metallurgical research; however, in-depth thermal history and thermo-mechanical coupling and the physics of multi-layer effects are lacking.

The objective of this study is to develop a numerical model for predicting the thermo-mechanical response of a Ti-6Al-4V workpiece built using a laser sintering system. This paper intends to reveal the fine details of the process and lead to the better consideration of the fabrication methods. The model described provides refined details of the process in good time. The microsecond resolution over micron scales in the structure interior cannot be obtained by current experimental methods and therefore has great importance to improve our understanding of the process. Although experimental validation is important, the experimental studies will be covered in a separate paper later. In this paper, workpiece thermal history, the size of the melt pool, and residual stress are modeled using a thermo-elastic-plastic finite element analysis. This research provides an effective computational model that provides guidelines for the settings used in practical laser-based additive manufacturing processes to maintain the proper melt pool size to avoid micro-defect and to ensure the quality of the product, as well as to control the residual stress-induced deformation within the acceptable tolerance. The results of this research could lead to the development of a promising tool to predict the microstructure and material phase transformation of products built by additive manufacturing [12–14].

2. Numerical model of direct metal laser sintering

The numerical method used in the simulation of Direct Metal Laser Sintering process is a thermo-mechanical transient phenomenon, which is a multi-physics coupled model. This is a weakly coupled model, which means the thermal history determines the mechanical response, while the mechanical response can be assumed to have little effect on the thermal history of the workpiece. As a result, a decoupled model, in which the heat transfer problem is solved first and the results are used as a thermal load input to the solid mechanics problem, could be used to get the approximate solution and greatly reduce the computational time without losing much accuracy. In the following section, the governing equations and corresponding constitutive equations are presented.

2.1. Thermal analysis

The governing equation for the heat transfer problem is the time-dependent energy equation:

$$\rho c_p \frac{dT}{dt} = -\text{div}\boldsymbol{q} + Q \tag{1}$$

where ρ is the density of the material, c_p is the specific heat, T is the temperature, t is the time, $d(\cdot)/dt$ is the material derivative, Q is the heat source, which is a function of time and spatial variables and considered to be zero in our model, assuming there is no interior heat generation or sink inside the bulk material. $\text{div}(\cdot)$ is the divergence operator. $\boldsymbol{q}$ is the heat flux vector governed by Fourier's Law

$$\boldsymbol{q} = -k\text{grad}T \tag{2}$$

where k is the thermal conductivity and assumed to be isotropic. $\text{grad}(\cdot)$ is the gradient operator.

The laser power is modeled as a heat flux boundary condition in the heat transfer problem, in which the moving laser power source is modeled as a moving round spot with radius r_0, and the center of V_{laser} the round spot moves with time on the surface of a workpiece with a constant speed

The distribution of the laser power is modeled in two different ways for the purpose of comparison, one is a uniform heating pattern, where the power is assumed to be constant within the moving circular laser-heating region, i.e.

$$q''_{\text{uniform}} = \frac{P}{\pi r_0^2} \tag{3}$$

where P is the total laser power. An alternative laser power distribution model widely used is the semi-spherical power distribution model, in which power is maximum at the center and decays radially to zero at the outer periphery, which is expressed as

$$q''_{\text{spherical}} = \frac{3P}{2\pi r_0^2}\sqrt{\left|1 - \frac{(x-x_0)^2}{r_0^2} - \frac{(y-y_0)^2}{r_0^2}\right|} \quad \text{for } |x-x_0| < r_0 \text{ and } |y-y_0| < r_0 \tag{4}$$

where x_0 and y_0 are the center of the laser spot in Cartesian coordinates. This distribution model gives better description to the real laser power, which is known to be non-uniform (high power at the center and low power close to the edge). Another laser distribution model commonly used by other researchers is the Gaussian power distribution. The comparison between the spherical power distribution and Gaussian distribution has been made in [15]. It