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Determination of melt pool dimensions using DOE-FEM and RSM with process window during SLM of Ti6Al4V powder

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ABSTRACT

Selective laser melting (SLM) shows a positive prospect as an additive manufacturing (AM) technique for fabrication of 3D parts with complicated structures. A transient thermal model was developed by the finite element method (FEM) to simulate the thermal behavior for predicting the time evolution of temperature field and melt pool dimensions of Ti6Al4V powder during SLM. The FEM predictions were then compared with published experimental measurements and calculation results for model validation. This study applied the design of experiment (DOE) scheme together with the response surface method (RSM) to conduct the regression analysis based on four processing parameters (exactly, the laser power, scanning speed, preheating temperature and hatch space) for predicting the dimensions of the melt pool in SLM. The preliminary RSM results were used to quantify the effects of those parameters on the melt pool size. The process window was further implemented via two criteria of the width and depth of the molten pool to screen impractical conditions of four parameters for including the practical ranges of processing parameters. The FEM simulations confirmed the good accuracy of the critical RSM models in the predictions of melt pool dimensions for three typical SLM working scenarios.

1. Introduction

Titanium alloys have very high tensile strength, light weight, good biocompatibility and superior corrosion resistance at even extreme temperatures [1,2]. For applications, titanium alloys have been broadly used in various fields such as aerospace, biomedical and automotive industries in recent years. However, titanium alloys are difficult-to-machine materials due to their high strength, low thermal conductivity and high chemical reactivity. Additionally, the slow solidification rates would produce the coarsened microstructures and the large degrees of segregation during the conventional casting processes [3]. As a result, further processing technologies are needed to maintain titanium components with great performance.

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is the process of direct fabrication for 3D objects in a layer-by-layer fashion. Selective laser melting (SLM) demonstrates a promising potential as a lately developed AM technique for fabrication of 3D parts with complex structures [4–7]. The SLM process can be also applied to precision part manufacturing [3,8]. In practice, SLM technology applied a high energy laser beam to selectively scan thin loose powder layers to generate melting and consolidation from a CAD model within milliseconds. As a result, the powders can be melted with higher-density parts formed by SLM, and thereby shape a final model with high mechanical properties [9]. SLM is usually performed in a neutral gas, nitrogen or argon gas, to protect the molten pool from oxidation. Considering as the concerned issues involving the operations of SLM, relocating a high energy density of laser beam on a powder bed can produce elevated thermal gradients, which may result in the undesired shrinkage variations, non-homogeneous thermal cracks and residual stresses distributed within consolidated layers [10].

The laser based SLM technique involves a complex process of heat and mass transfer including conduction, convection and radiation. Significant efforts were made to explore the thermal behavior and laser melting operational characteristics in the SLM process. Hussein et al. [11] and Craeghs et al. [12] analyzed the process parameters such as the laser power, scan velocity, preheating temperature and layer thickness affecting the formation of melt pool size as well as the dimension accuracy control and final features of SLM parts. The former found an increase in the

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Nomenclature

A	laser energy absorptance of a material
c	specific heat, J/kg K
c_f	specific heat of the fluid, J/kg K
D_P	average diameter of the powder particles, m
d	Hatch spacing, m
F_0	view factor
G_r	Grashof numbers
H	enthalpy, J/m^3
h	convective heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
k_{eff}	effective thermal conductivity of powder layer, W/m K
k_f	thermal conductivity of atmosphere, W/m K
k_r	thermal conductivity due to radiation, W/m K
k_s	thermal conductivity of solid, W/m K
l	length of scanning track, m
L	moving distance, m
N_t	number of track
N_u	nusselt number
P	laser power, W
P_r	Prandtl numbers
$\dot{Q}$	heat generated per volume
q	input heat flux, W/m^2
q_{con}	convection heat flux, W/m^2
q_{rad}	heat radiation heat flux, W/m^2
Ra_L	Rayleigh number
R	radius of the Gaussian heat source
r	radial distance from a point to the center of the laser beam, m
T	temperature, K
T_m	melting temperature, K
T_o	preheating temperature, K
T_P	temperature of powder particles, K
T_∞	ambient temperature, /°C
t	time, s
V	scan speed, m/s
x, y, z	Coordinates
β_f	volumetric expansivity, /°C
ρ	material density, kg/m^3
ρ_f	fluid density, kg/m^3
ρ_s	solid density, kg/m^3
ρ_p	powder density
ε	emissivity
μ_f	fluid viscosity, (Pa s)
φ	porosity of the powder bed
σ	Stefan-Boltzmann constant, W/m^2 K^4, (5.67×10^{-8} W/m^2 K^4)

predicted length of the melt pool at higher scan speed with both width and depth of the melt pool decreased. High VonMises stresses were also noted in the consolidated layers due to the cyclic melting and cooling rates in the scanned tracks. With the use of static processing parameters at downfacing planes, the latter observed bad surface quality at these planes on account of the outsized melt pool. Childs et al. [13] investigated the relationship of the processing parameters with molten mass for a CO_2 laser beam focused to 0.55 mm and 1.1 mm diameters, scanning over those beds made from M2 and H13 tool steel and 314S-HC stainless steel powders in the SLM development. It was noted that the structure of the powder bed and size of particles could affect penetration of radiation into the bed and the consequent densification in the partial melting regime. Zaeh and Branner [14] described that those SLM parts (using tool steel 1.2709, X3NiCoMoTi18-9-5 alloy) with a thinner layer thickness were susceptible to deformation because of elevated temperature variations. The initial platform temperature was identified to be the major influence on the occurring deformations of the shaped cantilever. The scanning strategy and the layer size were indicated as a minor impact with larger layer sizes of 70 μm produced additionally reduced deformations. The layer-based detail model was found to be an essential requirement for determining the deformations and residual stresses with an augmented precision. Mumtaz and Hopkinson [15] experimentally examined the selective laser melting of Inconel 625 by an Nd:YAG pulsed laser to produce thin wall parts with minimum top surface and side surface roughness. Higher peak powers tended to reduce both top surface roughness and side roughness as recoil pressures flatten out the melt pool and ease balling formation by increasing wettability of the melt. Nevertheless, higher repetition rate and lower scan speed reduced top surface roughness but increased side roughness. Using a two-dimensional (2D) formulation, Ilin et al. [16] adopted the Goldak's heat source model to predict the melt pool size and the temperature distribution of the 316L-steel bulk and powder materials. The increasing width of the melt pool near the border was perceived by the local increasing of the powder amount in the vicinity of the fusing zone. The further numerical analysis also showed the attainment of decreasing the melt pool width via increasing the scanning speed for stabilizing the laser beam melting process and enhancing the accuracy of the sample dimensions. From the predictions of unsteady temperature field for TiAl6V4 powder layers during the additive layer manufacturing (ALM) process, Roberts et al. [17] indicated rapid thermal cycles with commensurate thermal stress cycles occurred at laser heated regions.

In fact, the experimental measurements of SLM practice are considered to be difficult since it involves many details of localized laser heating, superfast melting and solidification. Numerical simulation has become a powerful tool to comprehend the underlying mechanisms behind the phenomena of SLM. The finite element method is the widely used computational method for predicting temperature and stress fields in the SLM procedure. Using a 3D finite element model to resolve the temperature field, Dai and Shaw [18] investigated the effect of the volume shrinkage due to transformation from a powder compact to dense liquid on the temperature field, size and shape of laser-densified dental porcelain bodies. Different criteria were proposed to judge the state of element by considering the possible occurrence of volume shrinkage associated with the powder conversion process during laser densification. Germain et al. [19] carried out the finite element method (FEM)-based thermal numerical simulations by Abaqus/Standard® to resolve the shape and size of heat affected zone (HAZ) in two metals (100Cr6/AISI52100 and Ti6Al4V) all over moving laser irradiation. It was observed that the surface roughness was not affected by the laser power. Yang et al. [20] presented a 3D FEM model to predict the HAZ in the Ti6Al4V plate work piece by a moving Gaussian laser beam. The size of the HAZ was found to be closely related to the laser power, speed, and spot size. Foroozmehr et al. [21] conducted the FEM computations to simulate laser melting of a single layer of stainless steel 316L on a thick powder bed at scan speeds of 80, 100, and 150 mm/s. The results showed that the melt pool dimensions reached a steady condition after