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Full length article

Numerical and experimental analysis of the effect of volumetric energy absorption in powder layer on thermal-fluidic transport in selective laser melting of Ti6Al4V

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HIGHLIGHTS

- Volumetric heat source has been used in modeling of SLM of Ti6Al4V.
- Simulation of moving single scan and multi-scan.
- Porosity is estimated and compared with the experiment.
- Porosity forms due to improper melting in the powder bed.
- The solidification parameters are calculated to estimate solidified grain structure.

ARTICLE INFO

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ABSTRACT

A volumetric heat source is used in numerical modeling of selective laser melting (SLM) of Ti6Al4V powder. Single track and multi-track SLM simulations are performed by varying the two key process parameters-laser power and scan speed. The model is validated with the published experimental results for melt pool shape, size and temperature. The predictions are in good agreement with the experiments at low to medium energy density. The validated model is used for investigating the thermo-fluidic transport during SLM of Ti6Al4V and examining the dependence of the melt pool characteristics on the process parameters. As-solidified porosity is calculated numerically for the multi-track simulations and its formation is delineated with the transport phenomena. The predicted porosity compares reasonably well with the experimental values. Solidification parameters, such as temperature gradients and cooling rate are calculated at the instantaneous location of the solidification front and analyzed. This analysis suggests the formation of fully columnar grains of different sizes along the width and depth of the melt pool. Overall, the model provides a good description of thermo-fluidic transport in SLM of Ti6Al4V powder and the resulting temperature field, melt pool characteristics, as-solidified porosity and the expected grain structure. Based on the current analysis, an optimum processing window of 50–70 $\mathrm{J\,mm^{-3}}$ energy density is suggested for SLM of Ti6Al4V powder.

1. Introduction

Selective laser melting (SLM) can offer the metal manufacturing industries the much-needed ability to produce parts without being concerned of design complicacies. It has the potential to help in reducing the longer lead times involved with the traditional manufacturing of intricate parts or products such as scaffolds, turbine blades etc. SLM is a laser assisted powder layer fusion based additive manufacturing process. It uses a focused laser beam to melt the metal powder layer to form one layer or cross section of the part being manufactured. The process is repeated till the complete part is built layer by layer. The SLM produced parts have shown unique microstructures and mechanical properties that are unlike the conventional manufacturing processes [1]. Along with these, the very high energy and material efficiency of SLM makes it highly cost-effective for single and small batch production. These aspects have helped this process gain considerable interest from industries like aerospace, automobile, tooling, biomedical and jewelry. However, there exist several issues that impede the large scale commercial utilization of the SLM process, such as (i) Inadequate understanding of the various observed defects, such as porosity,

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Nomenclature

α	absorptivity
α_m	mass fraction
a, b	coefficients of equation
β_T	coefficient of thermal expansion
c_p	specific heat capacity at constant pressure
c_{pS}	specific heat capacity of solid at constant pressure
c_{pL}	specific heat capacity of liquid at constant pressure
δ	powder layer thickness
D_L	diffusion coefficient
ε	emissivity
E	energy density
$\vec{F}$	source term in the momentum conservation equation
f_L	liquid fraction
$\vec{g}$	acceleration due to gravity
γ	surface tension coefficient
G	temperature gradient magnitude
GR	cooling rate
G/R	interface stability factor
h	convective heat transfer coefficient
k	thermal conductivity
k_P	thermal conductivity of powder layer
k_L	thermal conductivity of liquid
k_S	thermal conductivity of solid
λ	scan spacing
L	latent heat of melting
μ	dynamic viscosity
n	exponent
ω	Mushy zone constant
p	pressure
P_L	laser power
Pe	Peclet number
Φ	powder layer porosity
q	heat source
q_{loss}	heat loss flux
R	solidification front velocity
R_L	laser beam spot radius
Re	Reynolds number
ρ	density
ρ_P	density of powder layer
ρ_S	density of solid
ρ_L	density of liquid
S	absorption depth (Optical penetration depth)
σ	Stefan-Boltzmann constant
t	time
T	temperature
T_S	solidus temperature of Ti6Al4V
T_L	liquidus temperature of Ti6Al4V
T_∞	ambient temperature
T_{ref}	reference temperature for Boussinesq approximation
T_β	beta transition temperature of Ti6Al4V
T_{max}	maximum (peak) temperature
$\vec{u}$	molten metal flow velocity field
$\lvert\vec{u}\rvert_{max}$	maximum (peak) magnitude of molten metal velocity field
u	x-component of molten metal flow velocity
v	y-component of molten metal flow velocity
vol.	melt pool volume
V_L	laser beam scan speed
x	x- coordinate
ξ	Mushy zone constant
y	y-coordinate
z	z-coordinate
z_0	maximum height of domain in z-direction

delamination, cracking and thermal distortion; (ii) Lack of sufficient know-how of SLM manufacturability of different materials; (iii) Very high cost of the SLM equipment and raw materials. In addition, the SLM parts are seldom used as-built and require considerable post processing such as heat treatment etc. further obstructing the large scale commercial utilization. This has resulted in a significant amount of resources being invested in SLM research in recent times, both in industries and academia.

A number of interconnected thermal and physical phenomena occur during SLM (Fig. 1), which control the solidified microstructure and mechanical properties of the end product. This includes laser-matter interaction, rapid heating and solidification, conduction-convection-radiation heat transfer and Marangoni and buoyancy driven flow of molten metal [2]. The process parameters and material properties play a significant role in controlling these phenomena. Therefore, for a particular material, the desired microstructure and mechanical properties in the end product can be obtained by using the optimum process parameters. The SLM process has a number of process parameters-laser

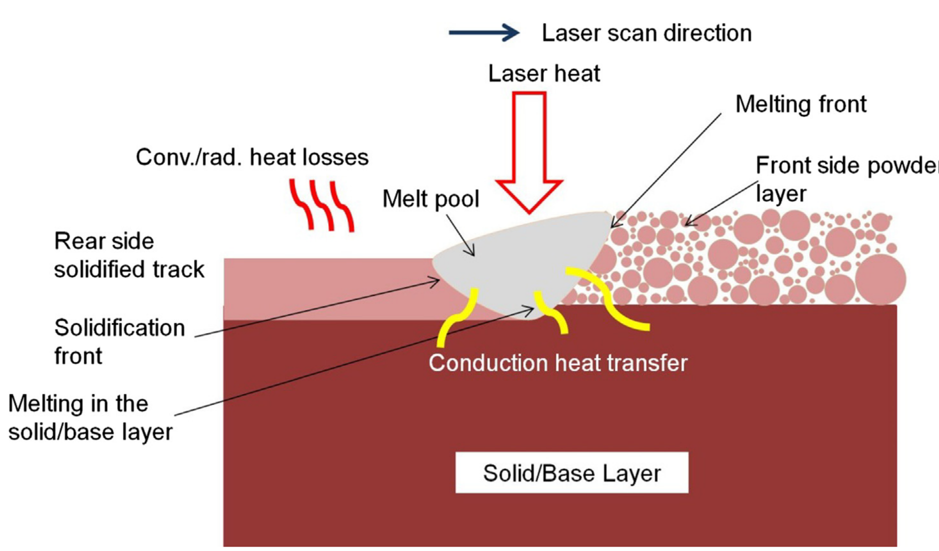

Fig. 1. Schematic of thermal and physical phenomena occurring during SLM.