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Modeling the effect of beam shaping at selective laser melting

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Abstract

The influence of the laser-beam radial distribution of the energy flux density is theoretically studied for the Gaussian distribution (mode TEM_{00}), and doughnut distribution of TEM_{01*} mode for the values of the Peclet number from 0 to 3. The model of linear thermal conduction in the target indicates that profile TEM_{00} is the best for thermo-activated treatment processes that can be accomplished in a wide temperature range and profile TEM_{01*} can be advantageous for a narrow range of the permissible processing temperature. If the phase transitions of melting/solidification and evaporation are included into the model, the estimate of the width of the laser-treated band is reduced but the tendencies predicted by the linear model are not changed.

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Keywords: thermal conductivity; melting/solidification; evaporation; Peclet number;

1. Introduction

The drawback of selective laser melting (SLM) is the non-uniform thermal conditions in the zone of laser treatment. In the center of the laser spot material can be overheated, which can initiate chemical decomposition and evaporation with useless losses of mass and energy, while at the periphery of the spot material may not attain the melting point, so that the energy is essentially lost by heat diffusion[1]. At present laser beams of commercial SLM machines have bell-like radial profile, which approximately corresponds to TEM_{00} mode of the optical resonator. Such a profile is not optimal because the energy flux attains its maximum in the center of the laser spot, which is favorable for the highly non-uniform temperature distribution over the spot. Nowadays optical tools for laser beam shaping are available. They were tested for SLM. Some differences in the obtained microstructure of materials were reported[2]. The objective of this study is to calculate thermal fields and to estimate the optimal laser beam profile.

The conventional distribution of the energy-density flux over radius r in the focus of a SLM machine is the bell-like one[3] and can be approximated by the Gauss distribution corresponding to the fundamental Laguerre-Gauss mode TEM_{00} of the optical resonator,

$$q = (P/\pi r_0^2)\exp(r^2/r_0^2)\ , \qquad (1)$$

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Nomenclature

B	width of the treated band
C	specific heat
$d_{1/2}$	diameter at half-maximum
H	enthalpy
L_{mass}	mass loss rate
m	molecular mass of vapor
P	laser beam power
Pe	Peclet's number
P_e	evaporation loss
q	energy flux density
Q	latent heat
r	radius
r_0	tentative radius
$r_{1/2}$	radius at half-maximum
T	temperature
T_a	ambient temperature
u_s	scanning speed
α	thermal diffusivity
γ	parameter of the temperature range
λ	thermal conductivity
ρ	density
∇	operator nabla
Subscripts	
b	boiling
l	liquid
m	melting
s	solid

where P is the beam power and r_0 the tentative radius. For photo-activated processes like photolithography, the optimal radial beam profile would be the top-hat one assuring the uniformity of the radiation flux. The typical mechanisms of powder consolidation at SLM are thermo-activated ones. This is why the objective is not obtaining a uniform irradiation flux q, but a uniform temperature field T induced by the irradiation. It is known from the half-space conduction problem[4] that the temperature over a circular laser spot is uniform and equal to

$$T_0 = P/(4\lambda r_0)\,, \tag{2}$$

where λ is the thermal conductivity, if the radial distribution is

$$q = P/(2\pi r_0^2)/\sqrt{1-r^2/r_0^2}\,, \tag{3}$$

Suppose that a massive body is treated, the conduction is the principal mechanism of heat transfer, and the laser radiation is absorbed on the surface. Then profile (3) would be the best for SLM. Below, this profile is referred to as TFT (energy-density flux profile assuring a flat-top temperature distribution). Profile TFT is difficult to obtain because of a discontinuity at the beam boundary $r = r_0$. The donut-like distribution of the first overtone TEM_{01*} could be a reasonable compromise, where

$$q = \frac{P}{\pi r_0^2}\frac{r^2}{r_0^2}\exp\left(-\frac{r^2}{r_0^2}\right). \tag{4}$$