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ScienceDirect

Applied Surface Science 254 (2007) 975–979

applied surface science

www.elsevier.com/locate/apsusc

Heat transfer modelling and stability analysis of selective laser melting

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Available online 30 August 2007

Abstract

The process of direct manufacturing by selective laser melting basically consists of laser beam scanning over a thin powder layer deposited on a dense substrate. Complete remelting of the powder in the scanned zone and its good adhesion to the substrate ensure obtaining functional parts with improved mechanical properties. Experiments with single-line scanning indicate, that an interval of scanning velocities exists where the remelted tracks are uniform. The tracks become broken if the scanning velocity is outside this interval. This is extremely undesirable and referred to as the ''balling'' effect. A numerical model of coupled radiation and heat transfer is proposed to analyse the observed instability. The ''balling'' effect at high scanning velocities (above ~20 cm/s for the present conditions) can be explained by the Plateau–Rayleigh capillary instability of the melt pool. Two factors stabilize the process with decreasing the scanning velocity: reducing the length-to-width ratio of the melt pool and increasing the width of its contact with the substrate.

Keywords: Selective laser melting; Radiation transfer; Heat transfer; Capillary instability

1. Introduction

Selective laser melting (SLM) is a technique for rapid layer-by-layer fabrication of functional parts from powders [1]. Powder binding is assured by local heating and melting by a laser beam scanning over the surface of a thin powder layer deposited on a previously treated layers. Fig. 1 shows the elementary step of SLM as laser scanning of the powder layer on a deep dense substrate. Complete remelting of the powder in the scanning zone and its good adhesion to the substrate ensure obtaining functional parts with improved mechanical properties [2]. The process of SLM is sensitive to a number of parameters as the powder layer thickness, the energy density and the diameter of the laser beam and the scanning speed. The objective of this work is to estimate the influence of the process parameters on the local temperature distribution in the laser-powder interaction zone. A single-line scan on a layer of unconsolidated powder is studied.

2. Model

The substrate is implied to be solid and thermally thick. A Cartesian coordinate system moving with the laser beam is used with axis (OX) opposite to the scanning direction and axis (OZ) along the inward normal to the surface, where the heat conduction equation is

$$\frac{\partial H}{\partial t} - v\frac{\partial H}{\partial x} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + U, \quad (1)$$

where volumetric enthalpy H is related with temperature T by the thermal equation of state

$$T = \begin{cases} H/C_s & , \; H \le C_s T_m \\ T_m & , \; C_s T_m < H < C_s T_m + H_m \\ T_m + (H - C_s T_m - H_m)/C_l & , \; H \ge C_s T_m + H_m \end{cases}, \quad (2)$$

C_s and C_l are the specific heats in solid and liquid phases, respectively, T_m is the melting point, H_m the latent heat of melting, t the time, v the scanning velocity, k the thermal

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doi:10.1016/j.apsusc.2007.08.074

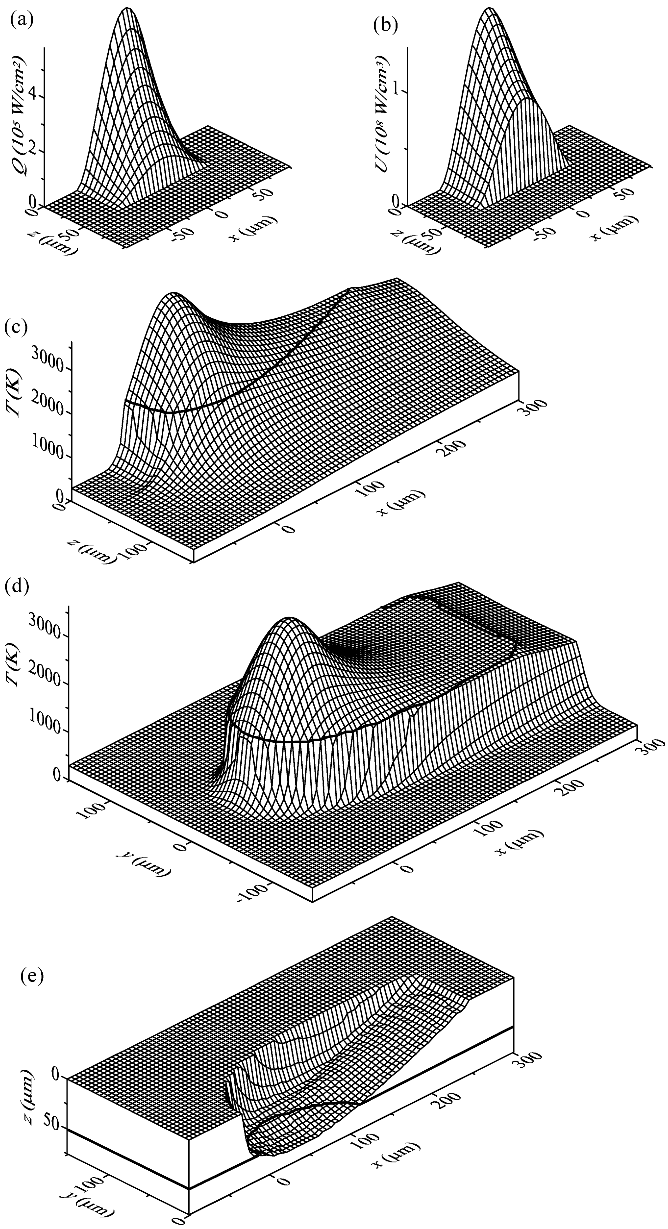

Fig. 1. Laser beam scanning of a 50 μm powder layer with optical thickness λ = 2 at the incident laser power of 30 W, the laser beam FWHM of 60 μm, and the scanning velocity of 20 cm/s. Distributions at the symmetry plane $y = 0$: (a) normal component of net laser radiation flux density Q; (b) volumetric heat source due to absorption of laser radiation U; (c) temperature T. Temperature T at the top powder surface $z = 0$ (d). Melt pool shape (e). Isotherms in diagrams (c) and (d) show the melting point $T_m = 1700$ K. The level in diagram (e) is the powder-substrate interface.

conductivity, and U the heat source due to volumetric absorption of laser radiation. Experimental visualization of the Marangoni convective flow in the melt pool indicates that the flow is important at low scanning velocities while it disappears at the scanning velocities above ~ 10 cm/s. Therefore, the convection is not taken into account in the present model applied at high scanning velocities.

In case of metallic powder, laser radiation penetrates into the powder bed by the open pore system and can be described by a radiation transfer equation with the isotropic scattering term [3]:

$$\mu\frac{\partial I(z,\mu)}{\partial z} = \beta\left\{\frac{\rho}{2}\int_{-1}^{1} I(z,\mu')\mathrm{d}\mu' - I(z,\mu)\right\}, \quad (3)$$

where $I(z, \mu)$ is the angular radiation intensity, μ the cosine of the angle between the direction of radiation propagation and axis (OZ), β the effective extinction coefficient of the powder bed, and ρ the reflectivity of dense material. Radiation flux in z-direction per unit surface Q and the volumetric source U can be found as:

$$Q = 2\pi\int_{=1}^{1} I\mu\,\mathrm{d}\mu, \quad U = -\frac{\mathrm{d}Q}{\mathrm{d}z}. \quad (4)$$

The two-flux moment method [3] applied to Eq. (3) with the boundary conditions of normally collimated incident flux Q_0 at $z = 0$ and specular reflection with reflectivity ρ at the substrate surface $z = L$ gives radiation penetration profile:

$$\begin{aligned}\frac{Q}{Q_0} = {} & \frac{\rho a}{(4\rho-3)D}\{(1-\rho^2)e^{-\lambda}[(1-a)\mathrm{e}^{-2a\xi} + (1+a)\mathrm{e}^{2a\xi}] \\ & - (3+\rho\mathrm{e}^{-2\lambda}) \times \{[1+a-\rho(1-a)]\mathrm{e}^{2a(\lambda-\xi)} \\ & + [1-a-\rho(1+a)]\mathrm{e}^{2a(\xi-\lambda)}\}\} \\ & - \frac{3(1-\rho)(\mathrm{e}^{-\xi} - \rho\mathrm{e}^{\xi-2\lambda})}{4\rho-3}, \end{aligned} \quad (5)$$

where

$$\begin{aligned} D = {} & (1-a)[1-a-\rho(1+a)]\mathrm{e}^{-2a\lambda} \\ & - (1+a)[1+a-\rho(1-a)]\mathrm{e}^{2a\lambda}, \\ a = {} & \sqrt{1-\rho}, \end{aligned} \quad (6)$$

$\xi = \beta z$ is the dimensionless depth, L the powder layer thickness, and $\lambda = \beta L$ its optical thickness.

3. Results and discussion

Calculations are made for stainless steel type 316 L with the parameters taken from [4] and listed in Table 1. Thermal conductivity of this alloy considerably increases with temperature above the room temperature. The temperature range about the melting point and above, is the most important for the studied problem where there is no reliable experimental data, so that a constant value of $k_d = 20$ W/(m K) is accepted, which is obtained by extrapolation to the melting point. The effective thermal conductivity of loose metallic powders is

Table 1
Thermal parameters of steel 316 L used for calculations

Parameter	Value
Melting point, T_m	1700 K
Latent heat of melting, H_m	2.18 GJ/m^3
Specific heat of the solid phase, C_s	4.25 MJ/(m^3 K)
Specific heat of the liquid phase, C_l	5.95 MJ/(m^3 K)
Thermal conductivity of dense material, k_d	20 W/(m K)
Thermal conductivity of powder, k_p	0.3 W/(m K)