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Analytical description of the surface temperature for the characterization of laser welding processes

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ABSTRACT

The simplified model of a point source on the top surface of a plate with finite thickness is used to describe the temperature field outside the melt pool during the welding process with concentrated energy input (laser or electron beam welding). Two limit regions defined by Rosenthal (1946) depending on the distance to the source are analyzed by deriving explicit analytical expressions for the size of these regions on the plate surface. An important outcome is how a finite plate thickness influences the temperature field on the surface, which is representative of the heat transport of information from the inside to the surface. The simplified model is further used to characterize the temperature field of the top surface by geometrical quantities of the melt pool and quantities describing the temperature decay in the heat affected zone outside the melt pool. In the limit regions the values of these quantities are derived analytically. Their scaling behavior with the feed rate and the source power is confirmed in a typical process regime by experiments with thermographic imaging during a laser welding process.

1. Introduction

During a welding process the material is heated by a moving source leading to a melt pool, which solidifies and leaves a cooling seam track. Under certain assumptions the resulting temperature distribution can be described with a simplified analytical model with a point source and the solution of the stationary heat conduction differential equation with an additional advection term [1]. In our work this common method to model the temperature distribution during the process is used for characterizing the surface temperature with respect to the incident power and feed rate of the moving source.

Analytically obtained temperature fields for concentrated heat sources are used in various publications [1–8]. There are also numerical solutions with moved Gaussian distributions representing for example the laser beam [9,10]. The transient heat differential equation can be used to investigate the heating and cooling process [11,12]. With numerical techniques a higher number of physical processes can be taken into consideration to obtain the temperature fields during the laser welding process [13]. A general overview over thermal modeling of welding processes in metals is given in the literature review of Mackwood and Crafer [14].

A valid analytically solvable model has the advantage to understand the main scaling behavior during the welding process, if it takes the most dominant processes into account. During laser welding the heat conduction in the solid phase is generally the dominant process. Although for concentrated heat sources the temperature at the source diverges, in regions outside the melt pool a good approximation for the temperature distribution can be obtained in many cases [15].

For a one-phase model with the assumption of constant material properties Rosenthal solved the heat conduction differential equation analytically in the stationary state [3]. This allows explicit expressions of the temperature field for a moving point or line source in infinitely large and by using the method of mirror sources also in bounded plates. Grosh investigated the effect of temperature dependent material properties in a one dimensional heat conduction problem [16,17]. Christensen compared geometric quantities of the melt pool obtained experimentally by cross sections with values obtained numerically with the point-source solution in an infinite thick workpiece [18]. Swift-Hook and Gick used a moving line source and estimated the width of the molten material as a function of the laser power and the feed rate [19]. Their approach to analyze the melt pool width is also used in this manuscript to characterize the welding process in different limit cases defined by the distance from the source.

The main goal of this manuscript is to derive the main scaling behavior of characteristic quantities of the melt pool and the tem-

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Nomenclature

Latin

c	heat capacity [J kg^{-1}] K^{-1}
c_0	speed of light [m s^{-1}]
c_R	radiation constant Planck's Law [K m]
$\boldsymbol{e}_x, \boldsymbol{e}_y, \boldsymbol{e}_z$	unit vectors in x, y, z-direction
$\mathcal{F}$	far field region
$\mathcal{F}_\mathrm{I}$	inner far field
$\mathcal{F}_\mathrm{O}$	outer far field
h	plate thickness [m]
h_P	Planck's constant [J s]
I_0	proportionality factor for sensor signal
I_R	radiant intensity
K	modified Bessel function of second kind
k_B	Boltzmann constant [J K^{-1}]
L	decay length [m]
$\mathcal{L}$	heat trace along the x-axis
l	trailing length of the melt pool [m]
l_0	length scale [m]
$\mathcal{M}$	melt pool region
$\mathcal{N}$	near field region
$\mathcal{N}_\mathrm{I}$	inner near field
$\mathcal{N}_\mathrm{O}$	outer near field
$\boldsymbol{n}$	normal vector oriented outwardly
P	constant input power [W]
P_c	convective heat loss [W]
Pe	$\mathrm{Pe} \equiv 2h/l_0$, Peclet-number
P_l	heat loss at the plate surfaces [W]
P_r	radiative heat loss [W]
q_adv	advective heat flow density [W m^{-2}]
q_diff	diffusive heat flow density [W m^{-2}]
$\dot{q}(\boldsymbol{x})$	power density of point source [W m^{-3}]
r	radial coordinate [m]
$r_\mathcal{F}$	radius of the far field region [m]
r_M	radial coordinate of the melt pool width [m]
$r_\mathcal{N}$	radius of the near field region [m]
T	temperature difference to ambient temperature [K]
$\tilde{T}$	$\tilde{T} = T/T_0$ dimensionless temperature
T_0	temperature scale [K]
T_A	ambient temperature [K]
T_L	temperatur field of a line source [K]
T_M	melting temperature [K]
T_P	temperatur field of a point source ($h \to \infty$) [K]
T_R	radiation temperature [K]
T_S	arbitrary temperature scale [K]
v	scalar feed rate [m s^{-1}]
$\boldsymbol{v}$	feed rate vector
W	decay width [m]
w	maximum melt pool width on the surface [m]
x	x-coordinate [m]
$\boldsymbol{x}$	position vector
x_M	x-coordinate of the melt pool width [m]
$\tilde{\boldsymbol{x}}$	$\tilde{\boldsymbol{x}} \equiv \boldsymbol{x}/l_0$, dimensionless position vector
y	y-coordinate [m]
y_M	y-coordinate of the melt pool width [m]
z	z-coordinate [m]

Greek

α	thermal diffusivity [m^2 s^{-1}]
α_B	constant heat transfer coefficient [W m^{-2} K^{-1}]
α_c	heat transfer coefficient for convection [W m^{-2} K^{-1}]
$\alpha_l(T)$	temperature dependent heat transfer coefficient [W m^{-2} K^{-1}]
$\alpha_r(T)$	temperature dependent heat transfer coefficient for radiation [W m^{-2} K^{-1}]
α_{rB}	upper bound for the heat transfer coefficient for radiation [W m^{-2} K^{-1}]
Γ	work piece region
$\partial\Gamma$	work piece surface
γ	Euler–Mascheroni constant
Δ	difference
$\delta(\boldsymbol{x})$	Dirac distribution [m^{-3}]
$\tilde{\delta}(\boldsymbol{x})$	$\tilde{\delta}(\boldsymbol{x}) = l_0^3\delta(\boldsymbol{x})$ dimensionless Dirac distribution
ε	relative deviation
ϵ	relative deviation regarding the length scale
λ	thermal conductivity [W m^{-1} K^{-1}]
λ_0	detection wave length [m]
ρ	density [kg m^{-3}]
ρ_k	distance to source [kg m^{-3}]
ρ_n	distance in spectral space [kg m^{-3}]
σ	Boltzmann constant [W m^{-2} K^{-4}]

perature field on the top surface outside the melt pool. We demonstrate the method for the case of a point source on the plate surface.

We investigate how the temperature field of the plate surface generated by a point source is influenced by the plate thickness, based on analytical expressions for limit approximations of the temperature field given by Rosenthal [3]. In the vicinity of the source the reflected heat on the bottom side is negligible (near-field region), while with increasing distance from the source the temperature field approaches the field generated by a line source (far-field region) [3]. Within the Rosenthal model, summarized in Section 2, we derive analytical expressions for the size of these regions (Section 3).

The temperature field on the top surface of the workpiece is easily accessible for measurements and can be observed, for example, by coaxial thermographic imaging of the process [20,21]. We characterize the temperature field on the top surface by geometric values of the melt pool and the cooling welding seam (Section 4). In Section 5 we use the defined asymptotic temperature fields, to compute these geometric properties and derive their dependence on the process parameters and the material properties. Their scaling behavior with the laser power and the feed rate are confirmed by experiments (Section 6).

2. Model

2.1. Model equations

A common strategy to model the laser process is to focus on the dominant heat conduction in the solid phase and neglect all other heat processes such as convection, radiation and latent heat [1–8,14]. This can be accomplished by substituting the fluid phase of the melt pool and the energy input into the capillary by a solid phase and substituted heat sources, where the heat sources are chosen in such a way that the resulting melt pool is a good approximation of the melt pool generated by the real process. Using this strategy the loss of power at the surface of the capillary and the melt pool has to be incorporated into the total power of the substituted heat sources, i.e. the total power flowing through the melt pool boundary equals the total power of the substituted heat