3D-Computer Simulation of Physical Transfer Process in Laser Molten Pool

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Abstract: The physical mathematic model for heat transfer and convection in laser molten pool established. 3D-computer simulation of temperature and fluid fields has been completed with finite difference method. It is shown that in laser molten pool there is a strong fluid flow, which is symmetrical in XY plane and anti symmetric in XZ plane. Due to effects of convection and heat transfer laser molten pool is widen. Surface tension gradient is the main drawing force for convection.

1. Introduction

Laser materials processing has been widely used in many industries. There is melting phenomenon in laser welding, cladding, alloying and melt-solidification. In laser molten pool, there are three important physical process of transfer heat, transfer mass and convection. It is shown that energy transfer determines the rate of heating and cooling, convection and mass transfer determine the extent of mixing and final composition. Specially, convection in laser molten pool can strongly affect the quality of laser welding and cladding. Some computer simulations of heat transfer and mass transfer have been reported [1,2]. In recent work, some new phenomena of convection in laser molten pool have been observed [3,4,5,6]. In order to examine convection mechanism in theory, 3D computer simulation of convection and transfer heat in laser molten pool is need.

2. Physical model

The main physical process in laser molten pool is as follows: some of the incident beam is absorbed while the rest is reflected. If the absorbed heat exceeds the threshold, the molten pool will be developed. In static melting, molten pool shape and absorbability are constant. Two driving forces for fluid flow in laser pool are considered: the surface tension gradient and the buoyancy force. The surface tension gradient is represented as follows: $\partial\gamma / \partial x = \partial T / \partial x \cdot \partial\gamma / \partial T$.

The buoyancy force is: $\vec{F_b} = -\rho\beta\Delta T\vec{g}$

The basic assumptions are as follows:

1. Quasi-steady state, semi-infinite domain.

2. The dependence of surface tension on temperature is assumed to be linear, but the rest properties of liquid and solid metal are constant, independent of temperature.

3. The effects of plasma and gas shield are ignored.

The rectangular pattern of laser beam with width 2b and length 2l is selected to simulate the distribution of temperature and convection fields in laser molten pool.

The relationship between a stationary laser beam with 2b*2l sizes and specimen is shown in Fig.1, in which laser beam moves at a constant speed U in x-direction.

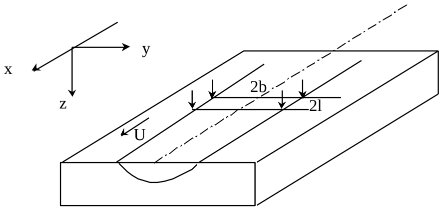


Fig.1 Schematic diagram of laser beam melting process

3. Mathematical equation and boundary condition

The following equations describe the temperature and velocity fields inside and out side of laser pool in moving coordinate system.

The continuity equation: $\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{V} = 0$ -------------------------------------(1)

The momentum equation: $\rho\left[\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla\right)\vec{V}\right] = \mu \nabla^2 \vec{V} - \nabla P + F_b$ -----------------(2)

The energy equation: $\frac{\partial \vec{T}}{\partial t} + \left(\vec{V} \cdot \nabla\right) T = \alpha \nabla^2 T$ -------------------------------(3)

The boundary conditions are as follows:

(1) Top surface (z=0)

$$\begin{cases} w = 0 \\ \mu \frac{\partial u}{\partial z} = -\frac{\partial T}{\partial x}\frac{\partial \gamma}{\partial T} \\ \mu \frac{\partial v}{\partial z} = -\frac{\partial T}{\partial y}\frac{\partial \gamma}{\partial T} \\ k\frac{\partial T}{\partial z} = \begin{cases} -Q_0 = -\frac{\varepsilon q}{2b \cdot 2l} \\ 0 \end{cases} \end{cases}$$

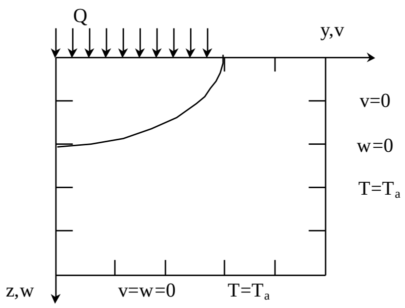


Fig.2 The boundary conditions in yz plane

(2) Center plane (y=0): $v = 0$, $\frac{\partial u}{\partial y} = \frac{\partial w}{\partial y} = \frac{\partial T}{\partial y} = 0$.

(3) Side surface and bottom surface: u=v=w=0, T=Ta.

(4) Melting boundary (solid-liquid interface): T=Tm, u=v=w=0.

The boundary conditions in yz plane are shown in Fig.2.

Where $\vec{V} = u\vec{i} + v\vec{j} + w\vec{k}$,

V: Total velocity of fluid, u, v and w are components of V in x, y and z direction respectively.

U: speed at which specimen moves in x-axis. ρ: mass density, α: thermal diffusivety.

μ: viscosity. γ: surface tension. β: volumetric thermal expansion coefficient.

g: gravitational acceleration. T: temperature. P: pressure.

Q: laser power delivered to the specimen. ε: absorbability 0.75.

The finite difference method was employed for the calculation of temperature and velocity fields.

The grid system used in this paper actually consists of four different grids, three for u, v, w and one for T and P. Such a grid system is required for numerical stability in fluid flow calculation, and is called the "staggered grid". 50*150 grid system was used in this paper. M-160 computer was employed to carry out the computation. The iterative procedure was continued until the following convergence criterion was satisfied: $\sum_{p} \varphi - \varphi^{old} / \sum_{p} \varphi < 10^{3}$.

The data used for steel in the calculations are given in Table 1.

Table 1

$P=7.8*10^3 Kg/m^3$	$K=31.2W/M\cdot$℃
$\mu= 15*10^{-3} Kg/m\cdot s$	$\alpha=0.87*10^{-5} M^2/s$
T_m=1200℃	T_a=20℃
$\partial\gamma / \partial T = -0.112*10^{-3} Kg / S^2 \cdot C$	q=1~10KW
$\beta=1.0*10^{-4}$/℃	$\varepsilon=0.75$

4. Results and Discussion

4.1 The fluid fields of surface gradient and buoyancy force

In order to compare the effects of surface tension gradient and buoyancy force, their fluid fields in laser molten pool are simulated by computer as showing in Fig.3 and Fig.4, respectively. It is seen from Fig.3 that in the center of molten pool the fluid flow direction is that from bottom to top. On the surface of molten pool the fluid flow direction is that from center to edge, and in the interface of solid-liquid the fluid flow direction is that from top to bottom, so a circular flow is produced in the pool. Because $\partial\gamma / \partial T$ for liquid iron is negative, $\partial\gamma / \partial x$ in the pool center is lower than that in the pool edge, so liquid metal is drawn from center to edge, maximum flow velocity of on surface melted metal is about 840mmctiv/s, its corresponding Re (Regnolds number) is about 1200 (<critical Re=2000), so it belongs to a planar flow. The convection field pattern due to buoyancy force in Fig.4 is similar to that due to surface tension in Fig.3. It means they have the same flow direction from bottom to top in the pool center. However, the maximum flow speed on surface of molten pool due to buoyancy is about 10mm/s only. It is shown that convection in laser molten pool is mainly induced by surface tension gradient.

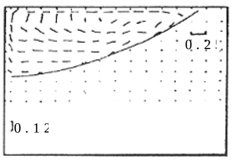


Fig.3 Convection pattern due to surface tension
P=2000w D: 5*4mm V=6mm/s

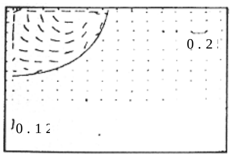
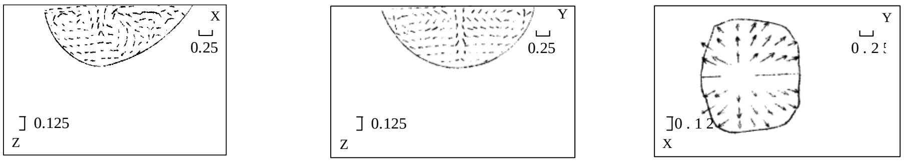


Fig.4 Convection pattern due to buoyancy
P=2000w D: 5*4mm V=6mm/s

4.2 3D-convection field distribution

3D convection field distributions of XZ, YZ and XY planes in laser molten pool are shown in Fig.5(a), Fig.5(b) and Fig.5(c) respectively, in which both surface tension gradient and buoyancy force are considered to calculate and simulate heat transfer and convection by computer. In the cross section of perpendicular to laser beam moving direction [Fig.5(b)], its convection pattern is similar to that only due to surface tension gradient, in which there are both left-hand flow cycle and right-hand flow cycle, they are symmetric to center plane, on surface of molten pool the fluid flow is drawn from center to edge, the flow speed is getting larger and larger, for example, in center line it is about 24mm/s, but in edge of the pool it became 870mm/s. Along the direction of laser beam moving [Fig.5(a)] there are two flow cycles which are anti symmetric to center line, one cycle is a left-hand direction, other one is a right-hand direction, all of them are drawn from center to edge, their maximum flow speed is about 580mm/s. On the top of molten pool [Fig.5(c)] there is not convection cycle, all of flow are from center to edge of the pool, it is evidenced from experiment in laser molten pool [5].



(a) In XZ plane (b) In YZ plane (c) In XY plane

Fig.5 3D convection simulated by computer in laser molten pool

P=2000w D: 5*4mm V=6mm/s

4.3 Temperature field distribution and its effect on molten pool shape

Fig.6 and Fig.7 are temperature fields in XZ plane and YX plane respectively. It is shown that in YZ plane temperature field simulated by computer distribution is symmetrical about center line, and in XZ plane temperature field distribution is anti symmetric about center line due to moving of laser beam. It is pointed out that due to convection effect hot fluid flow is drawn from center to edge in molten pool, as a result, width of molten pool became all the larger.

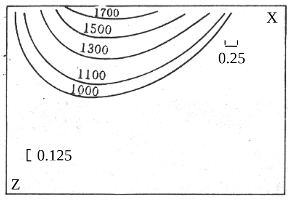


Fig.6 Temperature field distribution in XZ plane

P=2000w D: 5*4mm V=6mm/s

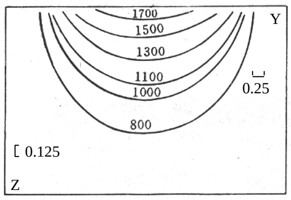


Fig.7 Temperature field distribution in YZ plane

P=2000w D: 5*4mm V=6mm/s

5. Conclusion

3D transfer heat and convection in laser molten pool has been simulated with computer. It is shown that in laser molten pool there is a strong convection and heat transfer. Surface tension gradient is the main drawing force. In perpendicular to moving direction of laser beam there are both left-hand and right-hand flow cycles which is symmetrical to center plane. In longitude section there are two anti symmetric convection cycles due to laser beam moving. Due to convection and transfer heat laser molten pool is widen. It is pointed that the results simulated by computer are consistent with experiment.

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