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The Marangoni effect on microstructure properties and morphology of laser-treated Al-Fe alloy with single track by FEM: Varying the laser beam velocity

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ABSTRACT

Laser workpiece surface treatment of Al-1.5 wt% Fe alloy with single track was performed with a 2 kW Yb-fiber laser (IPG YLR-2000S). A 3D thermal FEM model has been built to calculate the temperature field and fluid flow field in the molten pool cross-section. Results of numerical simulation, experimental of the micrographs and morphologies were presented, discussed and checked. By FEM the fluid flow due to the Marangoni effect presents two symmetric vortices corresponding to the molten pool center line. The Marangoni effect can lead to mass transfer and interfacial turbulence, when this phenomenon is considered, maximum values of the flow velocity and as well as thermal gradient occur around on the workpiece surface, smaller velocity and thermal gradient occur in the melt pool-substrate interface, thus, the Marangoni effect was more noticeable in lower than in high laser beam velocities. This phenomenon influences and controls the quality, such as, properties of the microstructure, morphological characteristic and as well as quality of laser-treated workpiece tracks, therefore, at low laser beam velocities the morphology is higher and quality of track presents many defects than at high laser beam velocities. Simulation results were assessed with the experimental data, their results were fairly coherent.

1. Introduction

Historically several authors have discussed the Marangoni effect. Between them, Siwek [1] argued that the model takes into consideration thermophysical and metallurgical properties of the remelting steel, laser beam parameters and boundary conditions of the process. As a result of heating the material, in the area of laser beam operation a weld pool was created, whose shape and size depends on convection caused by the Marangoni force. Moreover, the Marangoni effect is a frequently observed phenomenon of enhancement of interphase mass transfer in liquid–liquid systems. Such effect, originating from the hydrodynamic instability induced by surface tension sensitivity and surface concentration of transferred solute, which was discussed by the authors Bergman and Keller [2]. In addition, they stated that, the local variation in solute concentration at the interface in liquid–liquid solvent extraction systems would cause local increase or decrease of interfacial tension, and thus induce additional convection at the interface (so-called interfacial turbulence). According to authors Mao and Chen [3], the Marangoni effect is a phenomenon of interfacial turbulence provoked by surface tension gradients that might be induced by gradients in temperature, concentration and surface charge through the interface, still, it is known that this effect effectively enhances the rate of mass transfer across the interface.

According to Gan et al. [4], they affirmed that numerical simulation has previously offered a tool of effective evaluating the thermal behavior during the direct laser deposition process and numerical simulation has offered an effective tool in prediction the thermal behavior and mass transport in direct laser deposition. However, numerical simulation, in general, is a powerful tool to obtain complete understanding of the physical phenomena and the underlying mechanisms of welding processes, as emphasized by Murphy [5]. Yang et al. [6] investigated numerical simulation of heat transfer and fluid flow during laser beam welding, according to authors, the calculated weld pool geometry basically had in good agreement with the experimental results, therefore, these same authors affirmed, to better use this innovative technology, a thorough physical understanding of the associated molten pool phenomena is critically important.

Purpose of this work was to study behavior of the temperature field and fluid-velocity field in the molten pool cross-section involving the Marangoni effect. Results of numerical simulation and microstructure were presented, discussed and checked. More-

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over, result of influence of the Marangoni effect were shown on surface morphology through SEM and atomic force microscopy (AFM).

2. Mathematical model

A mathematical model involving heat transfer, fluid flow and mass transfer in laser surface remelting (LSR) was proposed. Simplifying assumptions are the following:

1. The fluid flow in the molten pool is assumed to be Newtonian, laminar and incompressible.
2. The thermophysical properties of Al-1.5 wt% Fe alloy were assumed to be temperature-dependent.
3. The laser heat flux is assumed to be a Gaussian distribution.
4. There is no diffusion transport in solid phase.

2.1. Governing equations

Equations of conservation of mass, momentum-transport and thermal energy are formulated in Eqs. (1)–(4). These Equations were proposed by Gao et al. [7] and Gan et al. [4].

Continuity equation,

$$\rho\nabla\cdot(u) = 0 \quad (1)$$

where u is the velocity vector of fluid flow in weld pool.

Momentum equation,

$$\rho\frac{\partial u}{\partial t} + \rho(u\cdot\nabla)u = \nabla\cdot[-pI + \mu(\nabla u + (\nabla u)^T] + F \quad (2)$$

where ρ is density, u is the velocity, p is the pressure, I is the identity matrix, T is the temperature and F is the force.

Energy equation,

$$\rho\left(\frac{\partial h}{\partial t} + V\cdot\nabla h\right) = \nabla\cdot(k\nabla T) \quad (3)$$

where h is the enthalpy of material, k is the thermal conductivity.

Equation of heat transfer in fluids:

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u\cdot\nabla T + \nabla\cdot q = Q \quad (4)$$

$$q = -k\nabla T$$

where ρ is the density, C_p is the heat capacity at constant pressure, u is the velocity, k is the thermal conductivity, q is the heat flux and Q is the heat.

The Marangoni Effect, Comsol [8]

$$\left[-pI + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla\cdot u)I\right]n = \gamma\nabla T \quad (5)$$

where p is the pressure, I is the identity matrix, μ is the coefficient of viscosity, ∇u is the gradiente of the velocity, T is the temperature, γ is the temperature derivative of the surface tension and ∇T is the gradient of the temperature.

Non-isothermal flow, Comsol [8]

$$-n\cdot q = \rho C_p C_\mu^{\frac{1}{4}} k^{1/2}\frac{T_w - T}{T_{amb}} \quad (6)$$

where n is the coordinate normal to the wall, q is the heat flux, ρ is the density, C_p is the heat capacity at constant pressure, k is the thermal conductivity, T_w is the reference temperature of the wall, T_{amb} is ambient temperature and T is the temperature.

2.2. Boundary and initial conditions

The laser heat flux input at liquid/laser beam interface is as follow, Pariona et al. [9]

$$\rho\frac{\partial(C_P T)}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + (1 - rf)I_0 \times \exp\left(-\frac{x^2 + y^2}{a^2}\right)exp(-\delta z) \quad (7)$$

On the free liquid surface, Yang et al. [6]:

On the bottom of the workpiece:

$$k\frac{\partial T}{n} = -h_d(T - T_{ref}) \quad (8)$$

On the other surfaces:

$$k\frac{\partial T}{n} = -h_c(T - T_{ref}) - \varepsilon k_b(T^4 - T_{ref}^4) \quad (9)$$

where h_c is the convective heat transfer coefficient, h_d is the heat transfer coefficient between the workpiece and workbench, ε is the materials emission and k_b is the Stefan-Boltzmann constant.

3. Materials and methods

3.1. Experimental characterization

3.1.1. Preparation of samples

The casting assembly used in solidification experiments consists of water-cooled mold with heat being extracted only from the bottom. It promotes a vertical upward directional solidification and this directional solidification apparatus was used to obtain an Al-1.5 wt% Fe alloy cylindrical casting, with 60 mm diameter and 100 mm length. This alloy was prepared with pure raw materials. The laser surface treatment was performed with a 2 kW Yb-fiber laser (IPG YLR-2000S). The laser beam was focused by a 160 mm lens on sample surface, while the laser wavelength was λ = 1.06 μm and the its intensity at initial moment was I(0) = 1.81×10^9 W·m^{-2}. The power density was of 4.8×10^5 W·cm^{-2} with multiphase distribution of energy with an approximately Gaussian profile. For this experiment, the sample was positioned 3 mm above the laser focus (out-focusing), using a laser beam diameter of about 600 μm. This laser treatment without an assisting gas jet was applied to propitiate the formation of alumina and nitride on laser-treated surface and to promote the formation of a passive oxide layer in contact with the environment and these phases present high hardness, as discussed by Pariona et al. [9].

3.1.2. Characterization techniques

For the metallographic characterization of cross-section, small samples were cut and sanded with 600, 800, 1200 grit SiC sand paper, and polished with colloidal silica in a semi-automatic polishing machine (AROTEC Ind. e Com., Brazil). Micrographs were recorded by an optical microscopy (OM, Olympus-BX51) and by a scanning electron microscopy (SEM, Shimadzu SSX-550 microscope). Atomic force microscopy analysis was performed in a Shimadzu SPM-9600 microscope with 400-nm minimum resolution, equipped with a 125-μm scanner operating in non-contact mode, according to Pariona et al. [9].

3.2. Numerical implementations

The coupled governing equations were numerically solved employing the commercial software COMSOL [8], optimized by Multigrid technique and the thermophysical properties of Al-1.5 wt.%Fe alloy were assumed to be temperature-dependent, as