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Evolution phenomena and surface shrink of the melt pool in an additive manufacturing process under magnetic field

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ABSTRACT

The control of evolution of flow and heat transfer in melt pool is a key concern and hot topic to improve the produce quality, e.g. fissure and roughness, during the additive manufacture process. Researchers focus on controlling the evolution of melt pool by changing energy balance in melt pool. However, the momentum drive is seldom presented in literatures but fully necessary to further improve the control efficiency. Therefore, a promising magnetic force source is introduced to investigate the controlling effect on melt pool evolution. Based on a developed and validated laser melt pool model, the evolution results of three different magnetic field arrangements and intensities are obtained and analysed compared with that without magnetic force. In addition, the surface shrink characteristics during quenching process are studied to further evaluate the benefit of the added source. Results show that the melt pool evolution is significantly affected by the additional magnetic force. The increasing downward y-component force promotes the transport in melt pool which makes the surface deformation larger, as well as the melt pool dimension. Inversely, with the increase of x-component force, both the surface deformation and the melt pool dimension gradually decrease due to the induced transport limitation. During quenching process, the surface roughness is continuously reduced with a certain increase of the magnetic intensity caused by the increased melt pool duration and slightly vigorous surface flow. However, the improvement effectiveness becomes bad as the magnetic force exceeds a critical value owing to the increased shrink instability.

1. Introduction

The manufacturing industry is fundamental to social production and quickly drives the development of human life quality. The common and traditional manufacturing techniques, including melting, casting and turning, etc., whose process is complicated and production period is long. Especially, for customer-tailored produce, the economic efficiency of the usage of traditional technique is negative due to the small production amount [1]. The additive manufacture (AM) technique, propelled by the advanced computer aided design (CAD) regime and characterized by layer-wised powder cladding and flexible and rapid fabrication, well covers the shortage of the traditional manufacturing technique and is widely used in many important industry, such as the aerospace, the biomedicine and the automation [2,3]. Furthermore, owing to the rapid melting and solidification during the fabrication process, the AM technique has quite higher cooling rate compared with the traditional technique, and the resultant produce has better microstructure and mechanical behavior [4,5]. However, with the extreme high heat flux input, the involved complicated heat and mass transfer also brings instability into the fabrication procedure and causes the produce quality reduction (such as fissure and roughness) [6]. During the process, not only the new delivered powder layer is melt, the front layer is also re-melt or the delivered power is not totally melting, which is easy to induce inhomogeneous thermal stress superposition and damage the formed microstructure. The vigorous transport phenomena cause surface deformation on the melting layer as well, and the added surface deformation leads to the continuously inhomogeneous increase of the powder feeding and melting and gives rise to the gas capture capacity of the melting surface which also induces production defects [4,6]. Therefore, how to modify the AM fabrication process and overcome the appearance of the above shortages is the key concern and hot topic to spread the technique to a higher stage.

It is well known that the feeding power is sinter by the high heat flux source, e.g. the laser beam, to structure the industrial product. The melt pool is the fundamental procedure which bridges the original material and the formed part during the AM fabrication process and absorbs high attentions. Based on clearly

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Nomenclature

C	volume fraction function
C_p	specific heat, J/(kg K)
d	distance from grid to interface, m
g	gravity, m/s^2
g_l	liquid fraction in melt pool
K_0	permeability coefficient
ΔH	latent heat of melting, J/kg
L_v	latent heat of evaporation, J/kg
p_r	vapor recoil force, N
P_{laser}	laser power, W
P	pressure, Pa
Q_{ct}	radiation energy at current time, W
Q_A	radiation energy of point A at 100 ms, W
t	time, s
T_0	ambient temperature, K
T_s	solidification temperature, K
T_{surf}	surface temperature of melt pool, K
T_m	melting temperature, K
$\vec{v}$	velocity, m/s
x, y	coordinate directions, m
δx	distance between the adjacent grid point

Greek symbols

β	coefficient of volume expansion
κ	interface curvature
μ	dynamic viscosity coefficient, Pa s
γ	surface tension coefficient, N/m
ϕ	level set function
ε	emissivity
ε_0	transition region thickness
σ	Stefan Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4)
ζ	small number
τ	radiation ratio
η	absorptivity coefficient

Subscripts

1	liquid phase
2	gas phase
i, j	index of point
surf	surface

Abbreviations

AM	additive manufacture
SLM	selective laser melting
CSF	continuum surface force

understanding the evolution phenomena of melt pool and clarifying the effects of various parameters on that evolution process [7–9], researchers focused on controlling and optimizing the flow and heat transfer in melt pool and gained good reward on improving the produce quality. Wang et al. [10] numerically revealed that the resultant get fine grain as the laser power decreased or the scan speed increased, since the convection in melt pool was weakened, the distortion sharply decreased [11] and the cooling rate at the liquid/solid interface increased. Dai et al. [12] also validated that result using a selective laser melting (SLM) sinter experiment. Criales et al. [13] found that the cross-sectional morphology (i.e. the free surface profile) of the melt pool strongly depended on the laser spot diameter, the resultant built quality and the structural integrity reduced significantly with decreasing laser spot diameter due to the continuously increased sharp top. Sun et al. [14] directly active-controlled the input energy strategy and a stable free surface (keyhole) was established during welding process, the product quality was also proved to be better than that of an unstable process. The above approach changes the energy input into the melt pool through changing the process parameters to control the evolution morphology of melt pool, which is common used in the realistic fabrication to improve the resultant product quality. In fact, the melt pool is formed by continuous energy and momentum transport, and the morphology of melt pool (especially for the free surface) is sensitive to the energy changes, as well as the momentum [15]. However, the investigation of the momentum effect on the controlling of melt pool evolution is seldom presented in literatures, which is also fully necessary to further improve the AM product quality.

As is known recently, the magnetic force is a utility additional momentum source which is proportional to the magnetic susceptibility of the fluid and approximately proportional to the gradient of the square of magnetic induction. Furthermore, magnetic force has received more attention in many engineering operations [16], such as casting, crystal product, and electrolysis, for various purposes, e.g. natural convection and heat transfer enhancement [17,18]. Moreover, the applications of magnetic force on controlling of the melting and solidification process were also be attempted. Wang et al. numerically studied the effect of electric-magnetic field on controlling of a WC particles distribution [19] and melting suppression [16] in the surface processing and reinforcement. Bachmann et al. [20] and Chen et al. [21] found that the magnetic field had significantly effect on controlling of the welding full-penetration process as it could accelerate or brake the fluid flow during melting period. Li et al. [22] revealed that the magnetic force had good controlling efficiency on the dendrite growth of magnetic material when the suppressed natural convection and induced magnetic convection got proper balance. In AM industry, the magnetic force can also be a useful momentum source to control the laser melt pool evolution, since the original manufacturing

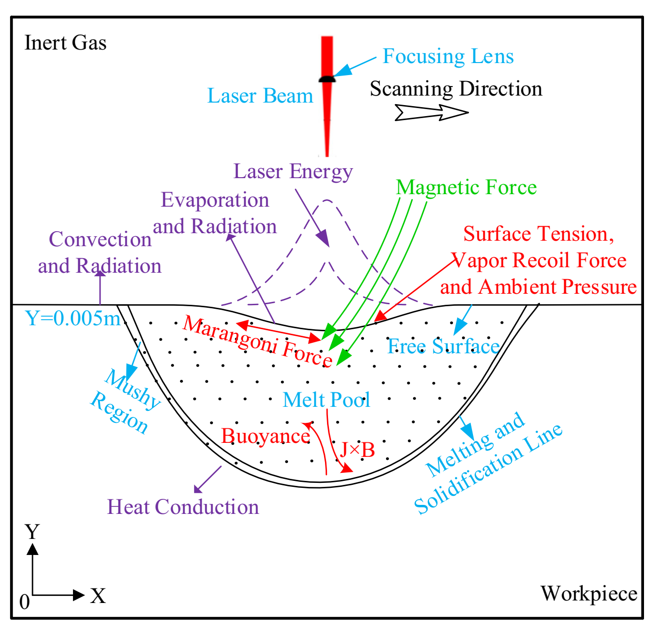

Fig. 1. The schematic physical melt pool model.