Coupling analysis of molten pool during fused coating process with arc preheating

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Abstract. Fused coating process with arc preheating is a new developing additive manufacturing technology. In addition to the high efficiency and low cost, it solves the spread difficulty of lightweight alloys such as aluminum alloy. In this paper, separating and coupling effect of driving forces exerted on weld molten pool caused by the arc is analyzed. Evolution of temperature field and flow field is described in detail. It is found that the magnitude order of the force's influence is surface tension>arc pressure> Lorenz force>drag force>buoyancy force. With the increase of the molten pool depth, the influence of the Lorentz force gradually increases and exceeds the surface tension at the bottom of the molten pool. Heat and mass transfer between the molten pool and externally added liquid metal is also calculated. External liquid metal rapidly flows into the molten pool at the moment of contact under the influence of surface tension and molecular affinity. Weld pool size and single pass morphology are measured and compared with the numerical simulation results to verify the accuracy of the model, and it turned out that the dimensional errors are all less than 10%.

1. Introduction

Additive manufacturing (AM) technology fabricates complex components layer by layer, which greatly reduced lead-times and made design changes easier. Conventional metal AM technique can be dived into two categories according to the form of raw materials: powder-feed process and wire-feed process. Powder-feed process mainly includes SLS (selective laser sintering) [1], SLM (selective laser melting) [2], LCD (laser cladding deposition) [3], EBM (electron beam melting) [4], while wire-feed process mainly includes WAAM (wire and arc additive manufacturing) [5], GMAW (gas metal arc welding) [6], GTA (gas tungsten arc welding) [7], LBW (laser beam welding process) and PAW (plasma arc welding process) [8]. Conventional metal AM technique usually have expensive equipment and low efficiency, which greatly limit its application and promotion. Compared with laser and electron beam, weld deposition based rapid prototyping is very competitive in energy efficiency [9], but the shape of material must be wire which is very difficult and expensive for some metal.
Fused coating process is a novel joining technique to build near-net component layer-by-layer in a simple and rapid way. Fused coating process uses a crucible and nozzle instead of a weld head and wire feeder to supply material, as a result, the shapes of the material are not confined to powder or wire, bars and blocks can also be used. Researchers in Xi’an JiaoTong university have studied this process with Sn63Pb37 material [10]. However, it is very different with aluminum alloy since the surface tension coefficient of the latter is much greater while the density is much smaller. Consequently, the liquid aluminum alloy is easier to agglomerate. In addition, high melting point also increases the difficulty of aluminum alloy forming process. Taking the energy absorption rate of aluminum alloy into consideration, tungsten inert gas arc welding is adopted as the preheating heat source. Many researchers [11] have studied the arc heat source and molten pool dynamics without consideration of the arc force or the arc force is considered, but the deformation of the weld pool surface is neglected. The driving forces in the arc molten pool were calculated separately in this paper, and then they are combined together with the fused coating process.

2. Mathematical model

Fused coating process with arc preheating contains two physical parts: arc preheating and coating. Driving forces exerted on weld molten pool mainly include surface tension, arc pressure, Lorenz force, buoyancy force and drag force [12-14]. In this paper, the molten metal is assumed as incompressible flow, laminar flow, and Newtonian fluid.

In order to improve the simulation accuracy, double ellipsoid heat source model is chosen, which suits better for large impact force situation.

Surface tension results from the fact that atoms near a free surface have partially unfilled coordination shells, which require that they be in higher energy states than atoms in the bulk of the solution. It depends not only on the composition of material but also on the temperature. Surface tension can be expressed as equation (3) [15]:

\[
\gamma(T) = \gamma_m^0 - A(T - T_m) - \frac{RT\Gamma_s}{\lambda} \ln(1 + k_1 a_1 e^{-M_p^0/\lambda R})
\]  \hspace{1cm} (1)

\[
a_1 = M_s 10^{(-94.2/T + 0.0396)M_{Cr}}
\]  \hspace{1cm} (2)

Where \(\gamma_m^0\) is the surface tension at the melting point of the metal, \(A\) is a constant which expresses the variation of surface tension of pure metal at temperatures above the melting point. \(T_m\) is the melting point, \(\Gamma_s\) is the surface excess at saturation, \(k_1\) denotes entropy of segregation, \(a_1\) is the mass percentage of surface activation factor, and \(\Delta H^0\) is the standard heat of adsorption. \(M_s\) and \(M_{Cr}\) are weight percentage of sulphur and chromium. Buoyancy is caused by changes in density after metal melting and it can be expressed as:
\[ F_p = -\rho_0 \alpha (T - T_0) g \]  \hspace{1cm} (3)

Where \( \alpha \) is the coefficient of linear thermal expansion of the liquid molten metal, \( \rho_0 \) is the density of the molten liquid metal at the reference temperature \( T_0 \). Normally, room temperature is taken as the reference point. Arc pressure usually expressed by a Gauss function as:

\[ P_{arc} = \frac{\mu_0 I^2}{4 \pi r_A^2} \exp\left(-\frac{x^2 + y^2}{2r_A^2}\right) \]  \hspace{1cm} (4)

where \( \mu_0 \) is the magnetic permeability of free space, \( r_A \) is the effective radius and \( I \) is the electric current density. The Lorentz force \([14]\) is generated by the electric current density and self-induced magnetic field, and it can be described as:

\[ F = J \times B \]  \hspace{1cm} (5)

Electromagnetic force in the direction of X Y and Z axis is respectively:

\[ F_x = -\frac{\mu_0 I^2}{4 \pi \sigma_j r} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right] \left(1 - \frac{z}{z_L}\right)^2 \frac{x}{r} \]  \hspace{1cm} (6)

\[ F_y = -\frac{\mu_0 I^2}{4 \pi \sigma_j r} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right] \left(1 - \frac{z}{z_L}\right)^2 \frac{y}{r} \]  \hspace{1cm} (7)

\[ F_z = \frac{\mu_0 I^2}{4 \pi z_L r^2} \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right] \left(1 - \frac{z}{z_L}\right)^2 \]  \hspace{1cm} (8)

\[ r = \sqrt{(x-v_0 t)^2 + y^2} \]  \hspace{1cm} (9)

Where \( \sigma_j \) is current distribution parameter, \( z_L \) is the thickness of the substrate. Drag force \([16]\) is generated due to the collision of arc plasma jet whose direction is flow outwards from the arc center, and it can be expressed as:

\[ \tau = \frac{\rho_0 \mu_0}{\rho_p \mu_{o}^2} \operatorname{Re} \left[ \frac{1}{2} \left( \frac{H}{D} \right)^2 \right] = g_2 \left( \frac{r}{H} \right) \]  \hspace{1cm} (10)

Where \( \tau \) is the shear stress, \( \rho_0 \) and \( u_0 \) is respectively the plasma density and initial velocity, \( r \) is the radius from the center, \( g_2 \) is the universal function, \( H \) is the nozzle height from the substrate surface and \( D \) is the electrode diameter.

Flow3D software is used to calculate whole process, and all of the driving forces are programmed in Fortran. 2024 aluminum alloy is selected for calculation and the initial values of processing parameters are shown in table 1: The coating gap refers to the height between the end face of the nozzle and the substrate or the last coating layer.

| parameter | current density (A) | 3D platform velocity (mm/s) | pressure in crucible (kPa) | substrate temperature (K) | liquid metal temperature (K) | coating gap (mm) | nozzle diameter (mm) |
|-----------|---------------------|-----------------------------|---------------------------|---------------------------|-----------------------------|----------------|---------------------|
| value     | 200                 | 5                           | 1                         | 293.5                     | 973                         | 0.8            | 1                   |

3. Results and discussion

Solid fraction and velocity field at cross section of the molten pool driven by separated force are shown in Fig.2. Fig.2 from (a) to (e) are the results of surface tension, buoyancy, arc pressure, Lorenz, and drag force applied alone.
It can be seen from Fig. 2 that two circulations are formed in all the molten pools. The circulation direction of Fig. 2(a) point from the surface arc center to surround since the surface tension decreases with the increase of temperature, which is called Marangoni convection. As Fig. 2(b) shows the flow direction in the weld pool is clockwise when only buoyancy force applied. Arc pressure makes the weld pool surface depressed and the circulation direction is opposite to the Marangoni convection. The direction of the Lorentz force is determined by the magnetic field and the current direction. Lorentz force in the center of the pool is vertical down and the direction of the entire circulation will make the molten pool deeper. From the causes of drag force can be seen that the flow direction must be from the center to around at the molten pool surface.

As shown in Fig. 2, The maximum velocities from (a) to (e) are respectively 4.04e-2 m/s, 4.72e-4 m/s, 2.14e-2 m/s, 1.95e-3 m/s and 9.98e-4 m/s. As a result, the magnitude order of the force's influence is surface tension>arc pressure> Lorenz force>drag force>buoyancy force.

All the forces are integrated together and the coupling effect of driving forces is explored. Fig. 3 shows the evolution of temperature field and flow field over time along longitudinal section.

As shown in Fig. 3, in the initial stage the surface tension plays a leading role, the flow field is consistent with the direction of the Marangoni convection. With the increase of the molten pool depth, the effect of the surface tension at the bottom of the molten pool is gradually reduced. As a body force, the influence of the Lorentz force in the depth direction gradually increases and exceeds the surface tension. Starting from 1.8s, the direction of the flow field in the elliptical annotation area begins to change and then four circulations are gradually formed in the molten pool as Fig. 3(c) shows. The flow field and solid phase fraction of the molten pool at cross section when the molten pool is steady are shown in Fig. 4. It can be seen that four circulations are formed in the molten pool and the flow field is symmetrical.
Evolution of temperature field and flow field of fused coating process with arc preheating is shown in Fig. 5:

As shown in Fig. 5a, fluid from the nozzle and arc heat source does not affect each other before 0.14s, the fluid spreads around and rises along the nozzle. As the substrate moves, the fluid begins to contact the molten pool and quickly flows into the it. This is mainly because the molecular affinity between the fluids is much greater than the affinity of the fluid with the nozzle or with the solid substrate. As the substrate continues to move, the arc heat source begins to act on the thin layer of fluid and the coating layer begins to solidify.

The experimental cross-sectional morphology of the molten pool and single pass are observed with Nikon MA200 metallographic microscope, while the simulation results were obtained by software post processing.

It can be seen from Fig. 6(a) that the cross-section morphology of molten pool is slightly convex after solidification since along the direction of heat source scanning, the front half part of the molten pool is slightly concave under the action of the arc pressure. The maximum width and height of the...
molten pool and heat affected zone are measured. The simulation results are separately 9.28mm, 3.25mm and 3.97mm, 3.51mm, while the experimental results are separately 9.38mm, 3.27mm and 3.63mm, 3.33mm. As a result, the errors are respectively 1.1%, 0.6%, 9.3% and 5.4%.

Fig.6(b) shows the cross-sectional morphology of single pass. Measuring the width of single pass at every 1mm height and the results are shown in table 2.

| Table 2 Width at different height |
|----------------------------------|
| h=0    | h=1mm | h=2mm | h=3mm |
| Simulation width /mm | 7.88  | 8.02  | 7.12  | 4.91  |
| Experimental width /mm | 7.59  | 7.75  | 7.10  | 5.12  |
| error      | 3.8%  | 3.5%  | 0.3%  | 4.1%  |

As shown in table 2, simulation width and experimental width are compared at different height and the width error are all less than 5%.

4. Conclusion
Fused coating process with arc preheating contains two physical parts: arc preheating and coating. And they are analysed separately and then combined together.

(1) Separating and coupling effect of driving forces exerted on weld molten pool caused by the arc is analyzed. It is found that the magnitude order of the force's influence is surface tension>arc pressure>Lorenz force>drag force>buoyancy force.

(2) With the increase of the molten pool depth, the influence of the Lorentz force gradually increases and exceeds the surface tension at the bottom of the molten pool. Consequently, four circulations are gradually formed in the molten pool.

(3) As the substrate moves, the fluid begins to contact the molten pool and quickly flows into it. This is mainly because the molecular affinity between the fluids is much greater than the affinity of the fluid with the nozzle or with the solid substrate.

(4) Weld pool size and single pass morphology are measured and compared with the numerical simulation results to verify the accuracy of the model, and it turned out that the dimensional errors are all less than 10%.

Acknowledgement
This project supported by the State Key Development Program Research of China (Grant No. 2017YFB1103201). †: these authors contributed equally to this study.

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