Numerical investigation of thermocapillary-induced deposited shape in fused-coating additive manufacturing process of aluminum alloy

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Abstract

In varying polarity gas tungsten arc welding (VP-GTAW) based metal fused-coating additive manufacturing (AM), the surface topographies of deposited layer are more complex than conventional welding, therefore, the distribution of the electromagnetic force in molten pool, arc pressure, plasma shear stress and heat flux on thermocapillary-induced deposited shape are not the same as the conventional welding. A three-dimensional numerical model was developed to investigate the transient thermal-fluid behaviors and the shape evolution of deposited layers in fused-coating AM process of aluminum alloys. Various driving forces of thermocapillary-induced melt flow including arc pressure, Lorentz force, arc plasma drag force and surface tension were taken into account in the model. Numerical prediction regarding the solidified shape and size of a single-track deposited layer is compared with the corresponding experimental data, showing that there is a good qualitative agreement between the two, which indicates that the established numerical model is capable of simulating the complex heat and mass transfer phenomena in the VP-GTAW based additive manufacturing. The thermo-physical process in fused-coating additive manufacturing process is systematically analyzed. Trends in deposition width and height with two major process parameters are captured. It is found that the shape of single-track deposited layers is strongly influenced by substrate moving speed. With an increase in the gap height between the substrate and fused-coating head, there are approximate changing trends in the height and width of deposited layers. The parametric study is prime important to understand and control the metal behavior in a layered deposition format.

Nomenclature

\[ A_x, A_y, A_z \] fractional area opening to flow
\[ a, b, c \] heat source parameters (mm)
\[ C_p \] specific heat capacity (J kg\(^{-1}\) K\(^{-1}\))
\[ d \] diameter of the inner flow channel of fused-coating head (mm)
\[ D \] diameter of the end-face of fused-coating head (mm)
\[ F \] volume of fluid function
\[ I \] arc current (A)
\[ k \] thermal conductivity (W m\(^{-1}\) K\(^{-1}\))
\[ L \] thickness of workpiece (mm)
\[ h \] the gap height between substrate and fused-coating head (mm)
\[ h_A \] heat transfer coefficient between the liquid metal and substrate
\[ h_{id} \] latent heat of fusion (J kg\(^{-1}\))
1. Introduction

In recent years, the additive manufacturing (AM) technologies have drawn tremendous attention as a very promising process for the fabrication of complex 3D structures in various materials. Especially, the development of advanced metal AM processes is extremely demanding. However, there are also various challenges impeding and slowing the application of this technology\cite{1, 2}. The primary restrictive factors for the development of metal AM are deposition efficiency and cost-effectiveness, especially for the powder feedstock-based AM process\cite{3}.

Aluminum (Al) is gradually becoming more attractive for structural components characterized by its high strength-to-weight ratio, good corrosion resistance, ease of machinability and usability\cite{4}. Al alloys are in high demand for AM processing\cite{5}, but, there are a few characteristics of the metal need to be faced and solved. Firstly, the aluminum 3D components produced today using AM processes in most cases are still limited to weldable Al–Si alloys\cite{6}, but, many applications require significantly higher strength aluminum alloys\cite{7, 8}, such as 2000 and 7000 series. However, suffering from hot tearing during solidification makes them difficult for processing in additive manufacturing. Secondly, Al exhibits high reflectivity at the laser wavelengths\cite{9–11}, which can be seen as an important obstacle for aluminum components produced by laser-based AM process. Due to the aluminum’s high reflectivity and high thermal conductivity, the deposition rate of Al and its alloy via laser AM is very low. Although wire arc additive manufacturing (WAAM) has proven its capability of fulfilling demands of production of medium–to-large-scale components made up of aluminum, at present, types of filler wires are very limited. Thirdly, the physical properties of Al alloys are less favorable for the fabrication of
repeatable and reliable parts, with factors including surface oxide, high thermal conductivity, large solidification shrinkage [12] and the vaporization of volatile alloying elements [13].

To solve the primary problems of low deposition rate, high-cost material, and limited welding wire type in aluminum additive manufacturing, a novel metal AM process called as fused-coating additive manufacturing (FCAM) has been proposed previously [14]. In the early studies on feasibility of laser for FCAM of aluminum using the 7075 alloy, the flow and heat/mass transfer behaviors of liquid metal was discussed [15]. However, the oxide inclusions in as-deposited structure were observed, which have a negative impact on the overall quality and integrity of the deposited part. At present, an improved MFCAM integrates induction melting and variable polarity gas tungsten arc welding (instead of laser) as a guiding heat source to create a shallow molten pool, which have not been able to accommodate in the previous models. Higher deposition rate and lower the costs of feedstocks and equipment make the high-efficiency and low-cost additive manufacturing of high-strength aluminum alloys possible, which is especially suitable for low and medium complexity components. During the aluminum FCAM process, in order to avoid oxide inclusion, the previously deposited surface layer need to be cleaned from oxides by a variable polarity welding arc established between a non-consumable electrode and a previously deposited layer. The mechanical performance and microstructure of a deposited part are greatly dependent on the solidification and crystallization process. Further, the final shape of deposits is mainly determined by the liquid metal flow patterns. Many experiments are required to optimize the fused-coating deposition process, but they are time consuming and costly, numerical investigations are helpful to lower the cost of optimization process. Accurate prediction of the deposition ability of FCAM process requires a thorough knowledge of the liquid metal flow patterns, thermal cycles, and the shape evolution process of deposited layers.

The final shape of deposited layers is intricately correlated to the thermocapillary-induced melt flows, which can be usually calculated based on the volume of fluid (VOF) method [16] in numerical modelling. The thermal-force effects of variable polarity welding arc are able to significantly affect the thermal-flow behaviors in molten pool. Recently, significant progress has been achieved on the modelling of the molten pool dynamics under the direct current gas tungsten arc welding (GTAW) process. A computational model was established by Kim and Na et al [17] to study heat transfer, melt flow and phase change in pulsed current GTAW. A mathematical model considering the influences of Marangoni, Lorentz, and buoyancy forces was developed to study the molten pool dynamics [18]. Only few results have been published in the three-dimensional (3D) study. And, either the surface tension gradient is assumed to a constant value [19, 20], or the molten pool surface is kept flat [21]. Furthermore, a 3D model was established to describe the heat transfer and fluid flow in the interfacial region between the GTAW arc and molten pool [22]. It can be noted here that almost all works above-mentioned, the position of electrode was considered perpendicular to the workpieces surface. However, this is not the case in fused-coating deposition process. In the literature [23], tilted electrode has obvious influence on the shape of thermocapillary-induced liquid metal and the transient thermal distribution in the local deposition region. Up to now, only few works [24–26] have been reported in the aspect of tilted electrode for GTAW process.

In this paper, a 3D numerical model for fused-coating AM process focusing on the thermocapillary-induced deposited shape is presented. The thermocapillary-induced spreading of liquid metal on a solid substrate is discussed in detailed. In section 2, the principle of FCAM process is firstly introduced. Then, the modelling assumptions and related governing equations are described in section 3, while a comparison with an experiment is carried out to assess its capabilities in section 4. In section 5, the formation mechanism of thermocapillary-induced spreading in FCAM process was illustrated, and the shape evolution of a deposited layer and the flow patterns of fluid metal are discussed. The effects of the speed of moving substrate and the gap height between substrate and fused-coating head on the shape of single-track deposited layers are also analyzed.

2. Principle of the FCAM process

Figure 1 shows the schematic illustration of the FCAM process. The system of FCAM includes an induction heating unit with crucible, a pressure controller with a lifting lever, gas protection device and a movable machine platform. According to the basic principle of AM process, the FCAM can produce aluminum components by synchronized controlling the motion of the movable platform based on sliced data and the extrusion of the high-temperature liquid metal. The movable platform is controlled by a programmable multi-axis controller (PMAC). A CCD camera, image acquisition card and computer were applied to build a process monitor system. Under the combined action of moving push rod, surface tension, gas and hydrostatic pressure, the liquid metal will flow through the inner flow channel of fused-coating head. When the liquid metal contacts with the surface of substrate or previously deposited layers, non-equilibrium solidification would take place at the interface of substrate and liquid metal (or previously deposited layers). Rapidly solidified deposition layers in motion will stay in motion with the same speed and direction. A metallurgical bonding is obtained between the deposited layers by the pulsed variable polarity GTA welding arc, the shallow molten pool created by the welding arc will
spontaneously fuses together with the fused-coating liquid metal. In addition, variable polarity GTAW arc has a two-fold effect in the fused-coating process: First, for Al alloys, the aluminum oxide on the surfaces of deposited layers must be removed timely. Fortunately, variable polarity gas tungsten arc welding (VP-GTAW) has been proved as a feasible method for the enhanced surface cleaning of oxide film. Second, the heat input by the VP-GTAW is also favorable to delaying the solidification process in the local deposition region, which is convenient for obtaining the larger end-face of fused-coating head, thus, the deposition rate can be further improved. The relative position between the variable polarity welding arc and fused-coating head keeps tunable.

Figure 2 shows the experimental equipment for the FCAM of Al alloys.

3. Governing equations

Modelling of the VP-GTAW based fused-coating AM process is a complex phenomenon and involves a lot of interactive physical phenomena, such as the effect of magnetic field and the impact of liquid metal being coated. To increase the accuracy in numerical simulation, we need to establish and verify the model of the weld pool firstly in the horizontal plane. Then the impact of liquid metal being coated would be integrated into the developed previously model of weld pool dynamics in VP-GTAW. A multiphysics model accounting for the coupling between electromagnetism, heat transfer, and fluid metal flows by thermocapillary-induced is derived.
in this section. The governing equations are solved using the FLOW3D commercial code with the extended subroutine code modifications. The electric arc is modelled by an electric current applied to the upper surface of the substrate below the tilted (60°) torch, a resulting heat flux, and an induced arc pressure. The problem reduces then to the fused-coating assembly, on which the distributions of the modelled electric arc quantities are assumed Gaussian. The substrate moving speed is assumed constant and the problem is defined in the coordinate system attached to the tilted torch, so that a steady solution can be sought. The electromagnetic, continuity, momentum equations are solved in the thermocapillary-induced flows. The liquid metal is assumed Newtonian, its fluid flow remains laminar, and the Boussinesq’s approximation is used. The factorial experiment was designed by Prachya [27] to investigate the influence of shielding gas parameter on the mechanical properties and microstructures of heat-affected zone and fusion zone in GTAW of aluminum alloy AA 5083. The result showed that the type of shielding gas and flow rate interaction hardness will affect the mechanical properties and microstructures of HAZ and fusion zone. However, the precise quantitative analysis of the effect of shielding gas on weld pool dimensions is still scarcely. Therefore, the argon gas flow is not considered for reducing the complexity of the model. Moreover, depending on the fused-coating position, the considered problem can possess the longitudinal vertical median plane as symmetry plane so the computational domain consists in this case of only one half plate.

3.1. Incompressible fluid flow model

Mass conservation equation:

\[
\frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z) = 0
\]  

(1)

where \( u, v \) and \( w \) are the velocity components along each of three coordinate axes. \( A_x, A_y, \) and \( A_z \) are the fractional area of the opening available for fluid flow.

The velocity components \((u, v, w)\) of the fluid metal can be expressed as follows:

\[
\frac{\partial u}{\partial t} + \frac{1}{V_f} \left( \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z} \right) = \frac{1}{\rho} \frac{\partial p}{\partial x} + f_x
\]  

(2a)

\[
\frac{\partial v}{\partial t} + \frac{1}{V_f} \left( \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z} \right) = \frac{1}{\rho} \frac{\partial p}{\partial y} + f_y
\]  

(2b)

\[
\frac{\partial w}{\partial t} + \frac{1}{V_f} \left( \frac{\partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z} \right) = -\frac{1}{\rho} \frac{\partial p}{\partial z} + f_z + G
\]  

(2c)

where \( V_f \) is the volume fraction in a cell in the VOF method. \( f_x, f_y, f_z \) are viscous acceleration rates as equation (3).

In equation (2), \( t \) is the time, \( \rho \) is the density of the fluid metal, \( p \) is the pressure, \( G \) is the acceleration by body force. The body force term in equation (2) is the sum of Lorentz force and buoyancy force.

\[
\rho V_f f_x = w_{sx} = \left[ \frac{\partial}{\partial x} (A_x \tau_{sx}) + \frac{\partial}{\partial y} (A_y \tau_{sy}) + \frac{\partial}{\partial z} (A_z \tau_{sz}) \right]
\]  

(3a)

\[
\rho V_f f_y = w_{sy} = \left[ \frac{\partial}{\partial x} (A_x \tau_{sx}) + \frac{\partial}{\partial y} (A_y \tau_{sy}) + \frac{\partial}{\partial z} (A_z \tau_{sz}) \right]
\]  

(3b)

\[
\rho V_f f_z = w_{sz} = \left[ \frac{\partial}{\partial x} (A_x \tau_{sx}) + \frac{\partial}{\partial y} (A_y \tau_{sy}) + \frac{\partial}{\partial z} (A_z \tau_{sz}) \right]
\]  

(3c)

where \( \tau \) is the viscous stress, the terms \((w_{sx}, w_{sy}, w_{sz})\) are wall shear stresses.

An enthalpy-based continuum method is employed to taking into account the solid-liquid phase change, the internal energy equation is:

\[
\frac{\partial h}{\partial t} + \mathbf{v} \cdot \nabla h = \frac{1}{\rho} \cdot (k \nabla T)
\]  

(4)

where \( h \) is the enthalpy, \( k \) is the thermal conductivity, \( T \) is the local temperature. As shown in the following equation,
\[
    h = \begin{cases} 
    \rho_s C_s T, & (T \leq T_s) \\
    h(T) + h_d \frac{T - T_s}{T_f - T_s}, & (T_s \leq T \leq T_f) \\
    h(T_f) + \rho_f C_f (T - T_f), & (T \leq T_f) 
    \end{cases}
\]

(5)

where \( \rho_s \) and \( \rho_f \) are solid and liquid density, \( C_s \) and \( C_f \) are specific heat of solid and liquid phases, \( T_s \) and \( T_f \) are solidus and liquidus temperatures, and \( h_d \) is the latent heat of fusion.

The free surface tracking of the fluid metal flow in FCAM process is modeled using the volume of fluid (VOF) method developed by Hirt and Nichols [28].

The VOF equation:

\[
    \frac{\delta F}{\delta t} + \frac{1}{V_F} \left[ \frac{\partial}{\partial x} (FA_x u) + \frac{\partial}{\partial y} (FA_y v) + \frac{\partial}{\partial z} (FA_z w) \right] = 0
\]

(6)

where \( u, v \) and \( w \) are the velocity components in \( x, y, z \) directions.

In VOF method, the scalar function \( F \) is defined as the fraction of a cell volume occupied by fluid; \( F \) is assumed to be one when a cell is fully occupied by the fluid and zero for an empty cell. The cells with values of \( 0 < F < 1 \) contain a free surface.

### 3.2. Arc heat source model

Double-ellipsoidal volumetric heat with Gaussian distribution of heat intensity is one of the most popular heat source model used in fusion welding process simulations. Several investigators report the use of the 3D double-ellipsoid model proposed by Goldak et al [29]—an example including the complete formulation can be found in [30] to model the heat source gas welding with good results. Others successfully apply conical models with laser beam welding [31]. So, the double-ellipsoid volumetric heat with Gaussian distribution of heat intensity was adopted in this paper to predict the weld pool shape and size. However, the major difficulty of this kind of heat source model is to define the parameters before start of simulation. For a modified process of variable polarity gas tungsten arc welding without the addition of filler metal, it is common practice to define the heat source parameters from experimental measurement of weld dimensions for a particular welding condition that meet the demand of two parameters i.e. weld width and penetration. But the length of the front and rear ellipsoid again it should be estimated by trial and error method to meet the computed results, which enhances the accuracy level of calculation. Arc deflection can be treated just like weldment deflection. The energy distribution of the tilted arc is still denoted by the literature [32].

The power density distributions inside the front and rear quadrants of the heat source can be described by equations (7) and (8), respectively,

\[
    q_r = \frac{6 \sqrt{3} Q f_r}{\pi a_r b c \sqrt{\pi}} \exp \left( -3 \left( \frac{x^2}{a_r^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right) \right)
\]

(7)

\[
    q_f = \frac{6 \sqrt{3} Q f_f}{\pi a_f b c \sqrt{\pi}} \exp \left( -3 \left( \frac{x^2}{a_f^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right) \right)
\]

(8)

where \( f_r \) and \( f_f \) are the front and rear fraction of the heat flux; \( a_r, a_f, b \) and \( c \) are the parameters obtained from by standard metallography and optical microscopy analysis of welding sample. \( Q \) is the total heat input.

### 3.3. Arc pressure model

The distribution of the arc pressure is assumed to follow the distribution of current density. The arc pressure could be modeled by a Gaussian model [33], which has the same effective heating radius of the arc.

\[
    P_{arc} (x, y) = \frac{\mu_0 I^2}{4\pi^2 \sigma_r} \exp \left( - \frac{x^2}{2\sigma_r^2} \right)
\]

(9)

where \( \mu_0 \) is the magnetic permeability of free-space, \( I \) is the arc current, \( \sigma_r \) is the Gaussian pressure distribution parameter.

### 3.4. Electromagnetic force

As another body force, the electromagnetic force (EMF) that is generated by the arc current is considered by equation (2). Simplified electromagnetic force in the fluid metal can be expressed by the following equation set [34, 35]. Equations (10)–(12) use the same effective radius for the arc heat flux.
where $F_x$, $F_y$, and $F_z$ are the three components of the body force, $\mu_0$ is the magnetic permeability of the workpiece material, $I$ is the arc current, and $L$ is the thickness of the workpiece.

### 3.5. Arc drag force

The arc drag force by the plasma flow is always directed from the arc axis outwards, which is tangential to the free surface of fluid metal. The arc shear stress acting on the molten pool is greatly dependent on the arc current, the shielding gas composition, and the tip angle of non-consumable tungsten electrode. For the present study the effect of arc drag force is considered as a spatial boundary distribution. The following function represents the arc drag force distribution [36].

\[
P_{\text{Drag}}(r) = P_{\text{Max}} \sqrt{\frac{r}{r_{\text{Shear}}}} \exp\left(-\frac{r}{r_{\text{Shear}}}\right)^2
\]

where $r_{\text{Shear}}$ is the arc drag force distribution parameter.

### 3.6. Boundary conditions

The arc heat flux, arc plasma drag force and arc pressure are acting on the boundary of the fluid metal. The welding arc was considered as the internal boundary conditions on the top free surface of the fluid metal can be described as equation (14).

\[
\kappa \frac{\partial T}{\partial h} = Q - h_A(T - T_\infty) - \sigma \varepsilon (T^4 - T_{\infty}^4)
\]

where $h_A$ is the heat transfer coefficient between liquid metal and ambient; $\varepsilon$ is radiation emissivity; $T$ and $T_\infty$ are the temperature for fluid metal and ambient, respectively.

To model Marangoni flow, the shear stress balance as boundary condition on the free surface is described as

\[
\mu \frac{\partial \gamma}{\partial n} = -\frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial r}
\]

where $\gamma$ is the dynamic viscosity, $\gamma$ is the tangential velocity vector, $n$ is the normal to the free surface, $\partial \gamma / \partial T$ is the surface tension gradient, and $r$ is the tangential direction on the free surface.

The pressure boundary conditions can be implemented by equation (16)

\[
-p + 2\mu \frac{\partial \gamma}{\partial h} = -P_{\text{arc}} - \frac{\gamma}{R_c}
\]

Here, $\gamma$ is the normal velocity vector, $\gamma$ and $R_c$ are the surface tension coefficient and the curvature radius of free surface, respectively. The outflow boundary conditions are applied for all other boundaries of the calculation domain.

### 4. Numerical model

Figure 3 shows a 2D symmetric longitudinal section of the 3D numerical model for the FCAM process. The front and rear walls of the substrate are defined as a continuative mesh boundary condition. In the model, the inner diameter in fused-coating head $d$ is 1.2 mm; the outer diameter of the endface of fused-coating head $D$ is 4 mm; the fixed substrate-to-head (gap) height $h$ is 1.2 to 2.4 mm; the substrate thickness is 6 mm. The distance from the arc centerline to the outside edge of fused-coating head is about 5.5 mm.
In the double-ellipsoidal heat source model, the parameters $a_f$, $a_r$, $b$ and $c$ can be determined through the metallographic analysis of the welded joint. The $q_f$ and $q_r$ values were given as the inputs to the model by a Fortran subroutine. The corresponding parameters used in the heat source model are listed in Table 1. For different processing conditions without the addition of filler metal, these dimension parameters need to be remeasured.

In present study, the peak current $I_p$ (voltage) and the base current $I_b$ (voltage) are 220 A (18.2 V) and 183 A (16.7 V), respectively. The proportion of peak current time in one cycle is 0.5. As shown in figure 2, the position of fixed electrode is tilted 60° ($\theta$) to the positive x axis. Arc pressure of 350 N·m$^{-2}$, arc pressure $p_r = 3.4$ mm and the characteristic radius of the electric current $r_0 = 3.2$ mm have been used. The initial conditions and thermo-physical properties of the 2024 aluminum alloy are listed in Table 2. The solidification contact angle is assumed to be 90°.

Temperature dependent material properties for 2024 aluminum alloy, including density, surface tension coefficient, liquid metal viscosity and thermal conductivity, are plotted in figure 4.
5. Verifications: comparison to experiments

Detailed compositions and weight percentages of 2024 aluminum substrates are shown in table 3. The thickness of 2024 aluminum substrates are 12 mm, length and width are 260 mm and 240 mm, respectively. The diameter and the conical angle of cathode are 3.2 mm and 60°, respectively. The welding arc length is controlled at 3.5 mm. Argon gas is introduced at the flow rate of 12 L min⁻¹ from the gas nozzle, the inner diameter of gas nozzle is 12.2 mm at the upper boundary. The gas flow is assumed to be laminar. The oxide films on the surface

| Cu  | Si  | Mn  | Mg  | Zn  | Ti  | Al  |
|-----|-----|-----|-----|-----|-----|-----|
| 4.52| 0.16| 0.61| 1.4 | 0.08| 0.05| Remain|

Figure 4. Temperature dependent thermo-physical properties of 2024 Al alloy.
of substrate were polished off firstly, the polished surface was then cleansed with acetone. Owing to the high reactivity of Al alloys, the oxides would wildly regenerate after the GTAW arc. In order to avoid heat sinks, the substrate was thermally insulated from the fixtures.

Single track experiments were performed to verify the numerical model, the relative thermal properties and process parameters are listed in table 2. The top view on a single-track deposited layer without VP-GTAW arc is shown in figure 5. It can be seen that without GTAW arc, the continuous and smooth surface of deposited layer cannot be obtained due to the poor wettability between the liquid Al alloy and cool substrate.

As shown in figure 6, the GTAW arc has been found to have a profound influence on the solidified morphology of the deposited layers, the solidified morphology produced with GTAW arc is flat with good wetting and is ideal for fused-coating and overlays.

To check the capabilities of the numerical model, the computational results were compared with a representative set of experiments for fused-coating on AA2024 Al alloy. The corresponding process parameters such as substrate moving speed, arc welding current and voltage can be referred to the section 4, the substrate moving speed was 3.5 mm s⁻¹, the gap height between the substrate and fused-coating head was kept at 1.5 mm, and the volume flow rate of the fluid metal was 50 mm³ s⁻¹. The whole computational domain is defined by its length $L_p = 60$ mm, width $2 \times W_p = 18$ mm, and height $E_p = 10.8$ mm. A proper computational grid size (250 μm) and time step (10⁻⁶ s) for simulations are suggested. The calculations were carried out at Xi’an Jiaotong University’s High Performance Computing Center (HPCC), with AMD Opteron 6174 (2.2 GHz) CPU and 32 GB memory, and it took about 24 h to simulate 1 s of real-time fused-coating AM process.

Macrographs obtained at the cross-section to a single-track deposited layer are used as a basis of comparison. It is found from figure 6 that a relatively good agreement between the predicted and measured cross-sectional shape. The relative deviation never exceeded 11.5% in height and 5.7% in width of the single-track deposited layer. Based on this comparison, it turns out that the established model is able to reproduce the relevant quantities in fused-coating additive manufacturing.
6. Results and discussion

During the fused-coating deposition process, the zone where the heat source locates is characterized by the temperature local sharp increase and being heated up to the state of melting, as shown in figure 7. The solid fraction distribution and the complex evolution of liquid/gas and solid/liquid interfaces during a single-track deposition process can be obviously observed. The shape evolution of the single-track deposited layer, liquid metal flows, heat affected zone and final deposition height and width are revealed. The shape evolution of a single-track deposited layer can be generally divided into four typical stages: (i) stage of the molten pool formation and development, (ii) hot-melt extrusion process, (iii) evolution of complex free surface, and (iv) relatively steady stage. The successive stages will be illustrated in details.

During the first stage, the proper shallow molten pool on the moving substrate needs be obtained prior to beginning the extrusion process of liquid Al alloy. As the substrate moves along the horizontal direction, it is subjected to extremely high temperatures by the VP-GTAW arc until it starts to melt. It was assumed that the heat flux can be tilted towards the moving substrate, a periodic pressure and Lorentz force would be exerted on the molten pool by variable polarity plasma arc to produce molten pool oscillations. The thermal and flow fields in the liquid metal, and molten pool shape are presented in figure 8.

In the second stage, the extrusion process of liquid Al alloy begins when it will meet the melt in the shallow molten pool. Thus, there is always a time delay between the arc ignition and the extrusion process of liquid Al alloy. The high temperature generated by the VP-GTAW arc can substantially decrease the thermal contact resistance of the local deposition zone. Therefore, solid/liquid interactions become much stronger during the high-temperature spreading of liquid Al alloy on the moving substrate.

Figure 9 also shows the thermal and flow fields during the third stage of FCAM process.

In this stage, as the liquid Al alloy being extruded contacts and fuses together with the melt in the moving shallow molten pool, the shape of the melt’s free surface will experience strongly deformations in a very short period of time. Figure 10 shows the free surface shape of the liquid metal, here, molten pool depression and temperature distribution at the front part of arc-induced thermocapillary-driven flow can be observed clearly.

As shown in figure 10(a), the liquid metal between the arc center and fused-coating head exhibits characteristics of deposition at a higher temperature. The gouging region that is shaped like a teardrop is found at the front part of the thermocapillary-induced flow. The reason for these phenomena comes from the fact that the liquid metal loses heat by conduction to the substrate, meanwhile, the molten pool obtains partial heat from the being extruded liquid metal. The arc melted pool has an appreciable restriction effect on the thermocapillary-induced flow. In figure 10(b), it can be seen that there are the local fluctuations of the free surface and solidification front, which can be attributed to the spatial-temporal unstable momentum in the...
liquid metal in a pulsed-current mode. The absorbed arc energy is convected sideways so that a wider and shallower deposited shape induced by thermocapillary force is obtained.

With the passage of time, the thermocapillary-induced deposited shape tends to be stable because the various thermocapillary driven force including surface tension, arc pressure, Lorentz force, arc plasma drag force and the shear stress in the melt near the solidification front reaches a balanced state, as shown in figure 11. In the stage, the calculated transient temperature field and velocity magnitude in FCAM process can be illustrated as shown in figure 11(a). The characteristic dimension of the deposited layers can be demonstrated as $H$ and $W$. 

**Figure 8.** Side views of (a) temperature distributions, and (b) solid fraction distributions under pulsed current of $I_p/I_s = 220/183$ A.

**Figure 9.** Side views of (a) temperature distributions, and (b) solid fraction distributions in the second stage.
The simulated results show that the convection of heat transfer is taken place during the FCAM process where there are differences in temperature, meanwhile the temperature at locations which already undergo the merging process are slightly reduced. A maximum liquid metal speed as high as 0.6 m s\(^{-1}\) is achieved near the center of molten pool.

6.1. Effect of melt flow rate

The effect of melt flow rate on the surface morphology and dimensions of single-track deposits is shown in figure 12. Here, the gap between fused-coating head and substrate \(h\) is 1.8 mm, the moving speed of substrate is 6 m ms\(^{-1}\).

It can be seen that an approximate linear increase in the heights of deposited single tracks was observed when the melt flow rate increase from 20 to 120 ml min\(^{-1}\). But in the widths of deposited single tracks there are many highly nonlinear relationships, and we need to recognize what is the mechanism of the thermal flow dynamics.

\[\text{Figure 10. Free surface shape at the front part of thermo-capillary flow and temperature distribution: (a) 3D views, (b) side views.}\]
The question can be answered by the principle of minimum enthalpy for the liquid metal in fused-coating AM. The principle is as follows: the thermocapillary-induced flow is of characteristic keeping the minimum enthalpy value by means of automatically changing its size and adjusting its enthalpy in the given heat input and boundary condition, namely the thermocapillary-induced flow is of the minimum enthalpy value. In FCAM process, the area of the absorbed arc energy is thermalized and stays in the material as residual heat. This residual heat is accumulating from pulse to pulse, continuously increasing the local temperature, the heat accumulation as a function of the processing parameters is proportional to the duration of the arc heat input.

When the arc heat input and substrate moving speed keep invariant, the range of local high-temperature regions and the weld pool size will remain unchanged. However, the status of wettability and melting/solidification behaviors will be partially changed with liquid metallic coatings in contact with weld pool. With increasing melt flow rate, heat sink effect on the penetration depth as observed in deposited single tracks becomes more markedly because the additional heat energy from being coated melt is partially transferred to weld pool and the remaining thermal energy would increase solidification time.

6.2. Effect of the gap height

In another study, the effect of the gap height between the substrate and fused-coating head on the shape of single-track deposits is also discussed under the conditions of different melt volume flow rate, the results are shown in figure 13. Here, the melt volume flow rate changes from 30 to 70 mm³ s⁻¹. The substrate keeps moving at a constant speed of 5 mm/s.

As displayed in figure 13, it was proved that with an increase in the gap height, there are approximate changing trends in the height of the deposits, but the deposition width shows the opposite trend.
By analyzing the deviation of the local free surface contour from the corresponding equilibrium shapes and the characteristics of the flow and thermal fields of liquid metal around the fused-coating head, two main causes for this phenomenon are pointed out: (i) liquid metal being squeezed, (ii) the adhesion properties at the interfaces of liquid metal and fused coating head.

Squeeze flow of the liquid metal within a narrow gap plays a dominant role in the fused-coating AM process, the penetration depth must be deeper than in a pure thermocapillary shear flow, due to the presence of the pressure gradient. In this situation, the flow increases from the centerline towards the outside; this phenomenon indicates that the deposition widths actually increase.

It is also found that when the volume flow rate of melt is fixed, a larger gap leads to a narrower and higher deposition layer. This can be attributed to the fact that when the gap between substrate and fused-coating head $h$ is sufficiently large, the generated liquid metal flow tends to relax the non-uniformity, resulting that the thermocapillary force at the interfaces of liquid metal and substrate becomes weak accordingly. Under these conditions, the adhesion between the liquid metal and fused-coating head will become stronger. When the gap height exceeds a certain value, a tenacious bond will not generally be obtained between the coating melt-substrate.

7. Conclusions

A multiphysics numerical model devoted to calculate relevant deposition characteristics (shape of deposited layers, thermal and flow fields in the liquid metal, etc) has been developed for fused-coating additive manufacturing. It is focused on the thermocapillary-driven spreading of liquid metal on a moving arc-heated substrate. The model was validated by comparing measured and predicted shape of the deposited layer and thermal cycles. Two process parameters, substrate moving speed and the gap height were considered to account for an individual’s deposition characteristics. The major findings of the current work are summarized briefly as follows:

(1) The prediction capability of the proposed model was evaluated by comparing measured and predicted shape of the deposited layer and thermal cycles.

(2) It is found that the shape evolution of deposited layer during FCAM can be approximately divided into four stages. In relatively stable stage, there are the local fluctuations of the liquid/gas and solidification interfaces at the front part of thermocapillary-induced flow, which can be attributed to the spatial-temporal fluctuations of momentum in the fluid metal by pulsed current mode.

(3) It is clear that the moving speed of the substrate can dramatically affect the shape of single-track deposited layers, and rational control of the substrate moving speed is crucial. Width and height of deposited layers are found to decrease with increasing the moving speed of the substrate. However, deposition width is more sensitive to the substrate moving speed than deposition height.

(4) It was proved that with an increase in the gap height, there are approximate changing trends in deposited layer height and width.
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