Comparative study of solidification behaviors of weld pool through modelling of heat transfer and fluid flow during single- and multiple-layer deposits of 2319-aluminum alloy based on variable polarity gas tungsten arc welding

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The resulting properties of parts fabricated by wire and arc additive manufacturing (WAAW) processes are determined by their microstructure, local composition, and porosity. The objective of this work is to compare the difference of the solidification behaviors by means of numerical simulation when it precisely deposits material upon the single- and multiple-layer. Here, a three-dimensional (3D) heat transfer and fluid flow model of arc-based additive manufacturing to calculate thermal-flow fields, deposit shape and size, cooling rates and solidification parameters was developed. The calculated fusion zone geometries for the single- and multiple-layer deposition processes considering convective flow of melts agreed well with the corresponding experimental data for AA2319 deposits. It was found that under the same process parameters, the cooling rate and the solidification rate of the molten pool for the single-layer deposition process are always greater than that for the multiple-layer deposition process. Specifically, the refined equiaxed grains are more easily obtained at a cooling rate greater than 50 K ps⁻¹ when the polarity is designated as direct current electrode positive (DCEP). Width of the deposited bead of multi-layer structures is significantly greater than that of single-layer structures due to the lack of material at the lateral sides and the ambient conditions for the heat loss.

Key Words: Wire and arc additive manufacturing, Thermal flow fields, Multiple-layer deposition, Deposited bead

1. Introduction

As a promising breakthrough for metal AM technology, arc-based additive manufacturing processes is gaining more favor because of its deposition rate, low maintenance cost, and the higher utilization of metal raw materials¹. Although there is a great deal of excitement about arc-based AM processes, it is also found that the processes are not as simple, or as repeatable as promised.

Obtaining a sound and defect-free deposited part needs appropriate selection of the process variables such as arc power, travel speed, wire feed rate and interpass temperature. However, up to now, the selection of these variables is mainly based on trial-and-error testing or empirical data, it is not only very expensive and time-consuming, but also cannot provide the fundamental understanding of how the transport phenomena affect the build quality.

A lot of 3D transient thermo-mechanical models of arc-based AM process have been presented, and these models bring a new perspective to the understanding complicated arc-based deposition processes. For example, a moving heat source is usually utilized considering material addition and temperature-dependent material properties, which can provide accurate predictions of temperature fields, distortions, and mechanical properties². The influence of wire-feed speed and deposition path orientation (unidirectional or continuous) on the thermal history for multi-layered walls of miscellaneous materials was also investigated³. The effect of molten pool size on the microstructure and tensile properties of GTAW-based AM-ed Ti-6Al-4V was systematically investigated⁴. The adoption of the interlayer idle times for arc-base AM process was obtained by a finite element analysis of the thermal behavior of the workpiece⁵. While most of the research mentioned above deal with analyzing the thermal fields in a single-bead deposition, the underlying formation mechanisms of surface morphology of deposited layers associated with thermal-flow fields and solidification behaviors in the multilayer deposition process are still poorly understood, especially in the variable polarity GTAW-based AM process, because the wire feed orientation in GTAW and PAW based AM is variable and affects the quality of deposits, which makes the process planning more complicated.

In this paper, a combined type of volumetric heat source model, i.e., double-ellipsoid, is employed to compute the heat and fluid flow in single- and multiple-layer deposits of 2319-aluminum alloy based on VP-GTAW. Comparative study of solidification behaviors of weld pool in these two cases is performed according to the thermal flow fields to describe the influence of deposited layers on the fluid flow and heat transfer inside the weld pool.

2. Experimental procedure

Aluminum alloy (2319) thin-walled structures were deposited using square wave AC/DC TIG inverter welder. The motion of the
turbulence was controlled by a numerical control program, the local deposition region is protected from atmosphere by pure argon (Ar) gas, and the flowing rate of the shielding gas was 15 - 18 L/min.

After deposition, the cross-sections of the deposited parts were obtained with metallographic analysis and microscopic inspection. The characteristic dimensions of deposited bead and molten pool were measured by metallographic test.

3. Development of the Numerical Model

In the present study, the liquid metal is assumed to be incompressible Newtonian fluid, and the flow should be laminar. The free surface tracking of the weld pool surface in VP-GTA welding is solved by volume of fluid (VOF) method.

- VOF equation:

\[
\frac{\partial F}{\partial t} + \nabla \cdot (VF) = 0
\]

where \( F \) is the volume of fluid.

The body force mainly includes electromagnetic force (EMF), gravity, and buoyancy. The gravity acceleration is 9.81 m/s². The temperature-dependent properties were used for the density. The electromagnetic force, as an important body force, was considered by adopting the elliptically symmetric welding current density. The equations relating EMF are listed as below.

\[
F_x = -J_x B_0 \frac{\lambda}{r_c}
\]

\[
F_y = -J_y B_0 \frac{\lambda}{r_c}
\]

\[
J_x = \frac{I}{2 \pi r_c} \int_0^\infty \sinh(\lambda(c-z)) \sinh(\lambda(c-z)) d \lambda
\]

\[
J_y = \frac{I}{2 \pi r_c} \int \sinh(\lambda(c-z)) \sinh(\lambda(c-z)) d \lambda
\]

\[
\lambda = \frac{\sigma_0}{\sigma} (y-y_0) \frac{a}{c}
\]

where \( I \) is the arc current (DCEN phase: \( I = I_{a0}, \sigma_0 = \sigma_0 \); EN; DCEP phase: \( I = I_{a0}, \sigma_0 = \sigma_0, \) EP), \( F_x \) and \( F_y \) are the components of the EMF force in \( x \)-direction \((I = x, y, z)\), \( J_x \) and \( J_y \) are the axial and radial current density in the cylindrical coordinate system, \( B_0 \) is the angular component of magnetic field, \( J_0 \) and \( J_1 \) are the zero order and one order Bessel function respectively, \( z \) indicates the vertical depth from the top surface of workpiece, and \( c \) is the workpiece thickness.

The arc pressure distribution was assumed to follow the distribution of current density. It can be modeled by a Gaussian model with the same radius of arc drag force. The pressure boundary conditions on the weld pool surface can be described as Eq. (8).

\[
P = P_{arc} + \frac{\gamma}{R_e}
\]

where \( P_{arc} \) is the arc pressure, \( R_e \) is the curvature radius of the weld pool surface. The surface tension \( \gamma \) can be calculated as follows:

\[
\gamma = \gamma_0(T - T_s)
\]

The arc drag force on the weld pool is greatly dependent on the current, the composition of shielding gas, and the tip angle of electrode. Here, the effect of arc drag force is considered as a spatial boundary distribution, which can be represented as follows.

\[
P_{arc}(r) = P_{arc} \left( \frac{r}{r_{arc}} \right)^2
\]

where \( r_{arc} \) is the distribution parameter of arc drag force.

In this study, according to the actual processing conditions that the welding current in case of DCEP and DCEN \((I_{a0}/I_{p, p} = 160/80\) A) is high enough, arc stiffness and impact force exerted onto the weld pool surface is larger, and the arc column is perpendicular to the surface of the weldment. So, the Goldak’s double-ellipsoidal heat source model was adopted, which can provide relatively accurate results, especially for the low penetration surface melting process. In the moving volumetric heat source model, the power density distributions of the front and rear quadrants can be described by Eqs. (11) and (12), respectively.

\[
q_f = \frac{6 \sqrt{3} q_{arc}}{\pi a b c} \left( \frac{a^2 + b^2 + c^2}{c^2} \right)
\]

\[
q_r = \frac{6 \sqrt{3} q_{arc}}{\pi a b c} \left( \frac{a^2 + b^2 + c^2}{c^2} \right)
\]

| Properties | Value (unit) |
|------------|-------------|
| Density    | Temperature-dependent |
| Viscosity  | Temperature-dependent |
| Surface tension at liquidus temperature | Temperature-dependent |
| Thermal conductivity of metal | Temperature-dependent |
| Specific heat capacity | Temperature-dependent |
| Solidus temperature | 911.15 (K) |
| Liquidus temperature | 1131 (K) |
| Thermal expansion coefficient | 2.5e+10 (m³/kg) |
| Emissivity | \( \varepsilon = 0.4 \) |
| Magnetic permeability | \( \mu_0 = 1.26\times10^{-6} \) (H/m²) |
| Electrical conductivity | \( \sigma = 2.5\times10^{10} \) (Ω⁻¹ m⁻¹) |
| Ambient temperature | 298 (K) |
| Latent heat of melting | 8.37e+06 (J/kg) |
| Latent heat of evaporation | 1.08e+07 (J/kg) |
| Convective heat transfer coefficient | \( \xi = 100 \) (W m⁻² K⁻¹) |
| Vaporization temperature | 1163 (K) |
| Ambient temperature | 298 (K) |
| Moving speeds of the torch | \( u = 6 \) (mm/s) |
| Arc current | \( I_p = 160 \) (A) |
| Arc width | \( b = 80 \) (A) |
| Arc thermal efficiency | \( \eta_a = 0.8 \) |
| \( \eta_t = 0.5 \) |
4. Result and discussion

A thin-wall component was deposited on the substrate fixed on an immobile platform, as shown in Fig. 1. Each layer was 50 mm in length with consistent travel direction. Two of the most influential and easily controllable variables, the arc power and travel speed, were investigated. The roles of these variables on the morphology of deposits are examined both experimentally and theoretically in Figs. 1.

Fig. 1 shows the effects of varying travel speed. The cross-sectional area of the deposited layer decreases in size with increasing travel speed in both the theoretical calculations and the experimentally observed results. This is because of the lower heat input per unit length at faster deposition speed.

Figure 2 shows the temperature variation with time monitored at the specific point of the substrate while fabricating a single track 2319 deposit.

It can be seen from Fig. 2 that when the multiple-layer deposits were carried out, there was a more obvious time delay in the maximum fluid temperature because it took time to deliver heat via Marangoni convection in the larger weld pool. The peak temperature at point A is observed at around 260 s. However, the peak temperature at point B is observed at about 300 s, because the arc source takes a longer time to reach the monitoring location. Heating takes place rapidly as the electric arc approaches the monitoring location.

Using a 80/160 A pulsed current, with three different frequencies of 2, 10 and 50 Hz, the effect of the current frequency on the shapes of deposits was analyzed.
As seen in Fig. 3 the shapes of deposits evolve at the same frequency as the corresponding arc current. During the peak duration, the weld pool width increases while the depth decreases and during the background duration the width decreases while the penetration depth increases, this situation is always valid for all cases.

5. Conclusions

A 3D 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 VP-GTAW based WAAM process. The model was validated by comparing measured and predicted shape of the deposited layer and thermal cycles. Two process parameters, travel speed and pulse frequency, 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) The cross-section of the deposited layer decreases in size with increasing travel speed.

3) It was found that the weld pool width increases while the depth decreases and during the background duration the width decreases while the penetration depth increases.

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Reference

1) D. Ding, Z. Pan, D. Cuiuri and H. Li: Wire-feed additive manufacturing of metal components: technologies, developments and future interests, Int. J. Adv. Manuf. Technol., 81 (2015) 465-481.
2) M. Mughal, R. Mufti and H. Fawad: the Mechanical Effects of Deposition Patterns in Welding-Based Layered Manufacturing, P. I. Mech. Eng. B-J Eng., 221 (2007) 1499-1509.
3) A. U. Ulgö, O. Almusawi and A. R. J. Almusawi: Development and control of shaped metal deposition process using tungsten inert gas arc heat source in additive layered manufacturing, P. I. Mech. Eng. B-J Eng., 232 (2016) 1628-1641.
4) M. Graf, A. Hälsig, K. Höfer, B. Awiszus and P. Mayr: Thermo-Mechanical Modelling of Wire-Arc Additive Manufacturing (WAAM) of Semi-Finished Products, Metals, 8 (2018) 1-10.
5) A. B. Murphy, A. J. D. Farmer and J. Haidar: Laser-scattering measurement of temperature profiles of a free-burning arc, Appl. Phys. Lett., 60-11 (1992), 1304-1306.
6) J. Du, G. X. Zhao and Z. Y. Wei: Effects of Welding Speed and Pulse Frequency on Surface Depression in Variable Polarity Gas Tungsten Arc Welding of Aluminum Alloy Metals, 9 (2019) 114.
7) A. Kumar and T. Debruy: Calculation of three-dimensional electromagnetic force field during arc welding, J. Appl. Phys., 94 (2003) 1267-1277.
8) J. Goldak, A. Chakravarti and M. Bibby: A new finite element model for welding heat sources, Metall. Trans. B, 15 (1984) 299-305.