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Numerical and experimental investigation of deposition accuracy in GTAW-based additive manufacturing

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Abstract

In gas tungsten arc welding (GTAW)-based additive manufacturing (AM), directional dependence of the deposition process may lead to a shift in the deposition position, and non-uniform bead shapes. In this study, the deposition accuracy in GTAW-based AM was investigated by simulation using a particle method and experiment. In the particle method simulation, heat input due to the arc, phase change, heat conduction, and surface tension were considered. As the simulation result, in the side-feed condition, the deposition position shifted compared with other feed conditions. In addition, under the back-feed condition, when the wire was fed to a position slightly off the torch center, the molten pool that interfered with the wire flowed in a direction that avoided the wire, resulting in a bead position deviation. These tendencies were also observed in the experiments, and the results suggest that particle method simulation is useful for predicting deposition accuracy and examining appropriate deposition conditions.

Keywords: Gas tungsten arc welding (GTAW), Additive manufacturing (AM), Particle method, Moving particle simulation (MPS) method

1. Introduction

Wire and arc additive manufacturing (WAAM), in which welding wires are melted and stacked by arc discharge, has attracted widespread attention because of the advantages of relatively high deposition efficiency and low equipment and material costs. Especially in WAAM using gas tungsten arc welding (GTAW), an arc discharge is generated between a tungsten electrode and an object, and a wire supplied from the side is melted and deposited for three-dimensional fabrication. Therefore, the heat input and material input can be controlled independently, allowing high flexibility in deposition conditions. However, because the wire is fed from a fixed lateral direction relative to the central arc heat source, the wire feed conditions will change, such as front-feed, back-feed, and side-feed, relative to the torch travel direction. Although accurate fabrication of 3D shapes is required in AM, this directional dependence of the deposition process may lead to a shift in the deposition position, and non-uniform bead shapes.

Previous studies showed experimentally that GTAW causes a deviation of bead position depending on the wire feed direction [1]. Wang et al. [2] proposed a simplified model to simulate the wire melting position and showed that the deposition conditions could be optimized based on it. In contrast, to simulate the welding process more accurately, numerical methods are needed, such as calculating the molten pool flow. However, few studies have examined in detail the issues and mechanisms of deposition accuracy in GTAW using numerical simulation. Therefore, in this study, the deposition accuracy in GTAW-based AM was investigated by numerical simulation using a particle method and experiment.

2. Numerical and experimental method

In this study, a moving particle simulation (MPS) method [3] was used and heat input and pressure due to the arc, phase change, heat conduction, and surface tension were considered to simulate the deposition process. The fluid flow is calculated according to the following Navier-Stokes equations (1).

$$\frac{d\boldsymbol{u}}{dt} = -\frac{1}{\rho}\nabla P + \mu\nabla^2\boldsymbol{u} + g + \frac{1}{\rho}F_s \tag{1}$$

where $\boldsymbol{u}$ is the velocity, ρ is the density, P is the pressure, g is the gravity acceleration, μ is the dynamic viscosity, and F_s is the surface tension. The gradient and Laplacian operators are discretized by the general particle interaction model of the MPS method, and the particle motion is computed. In addition, the surface tension was calculated by the following equation (2).

$$F_s = -\sigma\kappa\delta\boldsymbol{n} + \frac{d\sigma}{dT}\delta(\nabla T - (\nabla T\cdot\boldsymbol{n})\boldsymbol{n}) \tag{2}$$

where σ is the surface tension coefficient, κ is the curvature, $\boldsymbol{n}$ is the normal vector of the interface, T is the temperature, and δ is a delta function considering that the surface tension was only applied to the interface particles.

As the deposition process to be investigated, three different wire feed conditions: front-feed, back-feed, and side-feed were set up. In addition, the back-feed condition is considered to decrease deposition accuracy due to interference between the wire and the molten pool. To confirm this wire interference effect, a condition in which the wire feed position was shifted in the back feed was also investigated.

In the experiments and simulations, SUS304 was used as the base plate and wire material. Table 1 shows the physical properties of SUS304 used in the simulation. Figure 1 shows a simulated deposition process under the front wire feed condition as an example. The size of the base plate was 40 × 15

Table 1 Physical properties of SUS304

Density	kg/m^3	7930
Kinematic viscosity	m^2/s	5.04×10^{-7}
Specific heat	J/(kg·K)	590
Thermal conductivity	w/(m·K)	$0.0148T+10.271$
Latent heat	J/kg	2.67×10^{5}
Melting point T_m	K	1727
Surface tension at T_m	N/m	1.872
Surface tension gradient	N/(m·K)	-4.3×10^{-4}

× 5 mm, and 30 mm bead-on-plate deposition was performed. The particle size was set to 0.3 mm basically, and only the particle size at the bottom of the base plate was set to 0.5 mm to reduce calculation time. The time step of the simulation was set to 0.1 ms. As deposition conditions, the wire diameter was 1.2 mm, the wire feed speed was 2.5 m/min, and the torch travel speed was 200 mm/min. In the experiment, the current value was set to 150 A. In the simulation, the arc heat input was assumed to follow a Gaussian distribution, with a total heat input of 1400 W and a heat input radius of 3 mm.

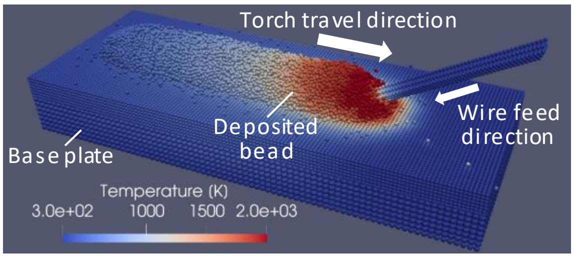

Figure 1. Bead deposition in particle method simulation

3. Results and discussion

3.1. Wire feed conditions and deposition accuracy

Figure 2 shows the deposition state and bead cross-section under each wire feed condition. The red line in the figure shows the center position of the torch (arc heat source). In front-feed and back-feed conditions, the wire was fed to the torch center, and the beads were deposited without deviating from the torch center. In contrast, under the side-feed condition, the position at which the wire was completely melted shifted from the torch center in the wire-feeding direction, and as a result, the bead position also deviated in the same direction. Figure 3 shows the deposition state and the bead cross-section under the side-feed condition in the experiment. The torch center position in the bead cross-section was calculated based on a reference bead previously welded by scanning only the arc without wire material. Figure 3(a) shows that the wire melt position was shifted from the torch center in the experiment as well. In addition, Fig. 3(b) shows that the bead position deviated about 0.3 mm in the wire feeding direction. Therefore, the numerical model using the particle method was able to simulate the same tendency and the same degree of bead position deviation as in the experiment.

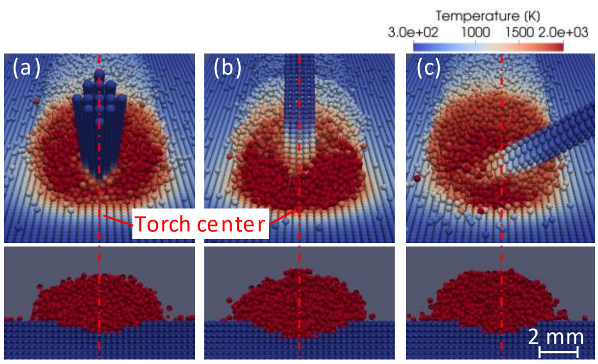

Figure 2. Deposition state and bead cross-section under each wire feed condition: (a) front-feed, (b) back-feed, and (c) side-feed

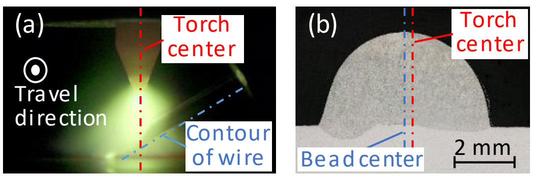

Figure 3. Experimental results under the wire side-feed condition: (a) deposition state and (b) bead cross-section

3.2. Effect of interference between wire and molten pool

Figure 4(a) shows the simulation results when the wire feed position was offset from the torch center by 0.6 mm under the back-feed condition. The offset of the wire feed position caused the molten pool to flow in a direction that avoided the wire, and as a result, the bead position was deviated. Figures 4(b) and (c) show experimental results with offset and correct wire feed positions. When the wire feed position was offset, the bead was deposited in a displaced position in the direction to avoid the wire, similar to the simulation results. In this study, the wire feed position was intentionally offset, but in WAAM, the wire aiming position sometimes shifts due to the curvature of the wire. From these results, it can be assumed that the accuracy of GTAW-based AM could be decreased due to such wire curvature, especially under the back-feed condition. Moreover, AM needs to be able to accurately fabricate not only straight paths but also curved paths such as circular arcs. In the case of such a curved path, even if the wire feed position is not misaligned, interference between the molten pool and the wire could cause the bead deviation from the desired position. In contrast, the problem of deposition accuracy due to wire interference seems to be suppressed by changing the wire feed angle and the heat input. In the future, it is necessary to consider deposition accuracy in curved paths and appropriate deposition conditions.

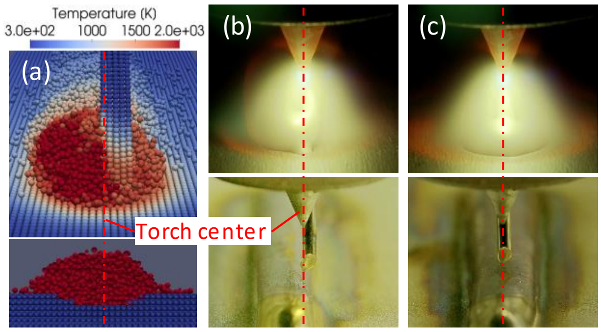

Figure 4. Relationship between wire feed and bead position under the back-feed condition: (a) simulation result with offset wire feed position and experimental result with (b) offset wire feed position and (c) correct wire feed position

4. Conclusion

In this study, the deposition accuracy in GTAW-based AM was investigated by particle method simulation and experiment. As a result, experiments and simulations showed that the bead position deviated under the side wire feed condition and the back-feed condition with offset wire feed position. The numerical model could simulate the experimental results well, which suggests that particle method simulation is useful for predicting deposition accuracy and examining appropriate deposition conditions.

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