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Metal transfer in wire feeding-based electron beam 3D printing: Modes, dynamics, and transition criterion

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ABSTRACT

In electron beam three-dimensional (3D) printing, the metal-transfer behaviors play significant roles in determining the quality of the end product; however, these mechanisms have not yet been well understood. In the present study, we performed plenty of experiments and novel modeling of the wire feeding based electron beam 3D printing to reveal the metal-transfer mechanisms in depth. The coupling behaviors of the heat transfer and the fluid flow in the molten pool as a function of the process parameters in the electron beam 3D printing of the Ti–6Al–4 V alloys were simulated. The simulation results reasonably agree with the experimental data. Three types of metal-transfer modes (liquid bridge transition, droplet transition, and intermediate transition) are reproduced by simulations and confirmed by the experiments. The results show that as the heat input increases, the transfer mode changes from the droplet transfer mode to the liquid bridge mode. Therein, the liquid bridge transfer is the best for ensuring good print quality because of the stable metal-transfer behavior. More accurately, the liquid bridge is a dynamic equilibrium process. In the process, the metal transfer is mainly driven by the recoil pressure, while the surface tension always tends to break the bridge. The interaction between the two factors leads to the oscillation of the liquid bridge geometry morphology in the forming process, where the oscillation frequency is approximately 200 Hz. The droplet transition is observed when the dynamic equilibrium is broken. In this process, the Marangoni flow plays an important role in the droplet formation. Further, based on the transfer mode transformation mechanisms and a simple theory, a verified formula is proposed, according to which the energy required for maintaining the liquid bridge should be moderate. Therefore, the heat input conditions for maintaining the liquid bridge can be calculated quantitatively. This research is of considerable significance for understanding the physical processes in electron beam 3D printing and provides a promising avenue for process optimizations in industrial applications.

1. Introduction

Wire feeding-based electron beam three-dimensional (3D) printing is an efficient additive manufacturing technology, which was developed over the past decade to directly manufacture complex metal components [1–3]. In a vacuum environment, the metal wire is fed into the molten pool and deposited layer by layer to form a near net-shaped metal part [4–11], as shown in Fig. 1. In the process, the metal-transfer behaviors play significant roles in determining the quality of the end product such as the surface quality and dimensional accuracy [3,5–7]. However, the metal transfer mechanisms have not yet been well understood.

Over the past decade, efforts have been made to understand the metal transfer mechanisms in the electron beam 3D printing process [12–15]. Zhao et al. captured the metal-transfer process by using high-speed photography and found the existence of droplet transition and liquid bridge transition modes [12]. Zalameda et al. [13,15] used a near infrared (NIR) camera to measurement the temperature filed and image the melt pool and solidification areas. Although these experiments provided significant insights on the heat and mass transfer behaviors at the different metal transfer modes in electron beam 3D printing process, current experimental studies only provide a qualitative understanding of these behaviors.

Recently, some modeling studies of the metal transfer dynamics in 3D printing have been proposed [16–19]. Tang et al. [16] proposed a 3D mathematical model of electron beam 3D printing to simulate the heat and mass transfer behaviors in the droplet

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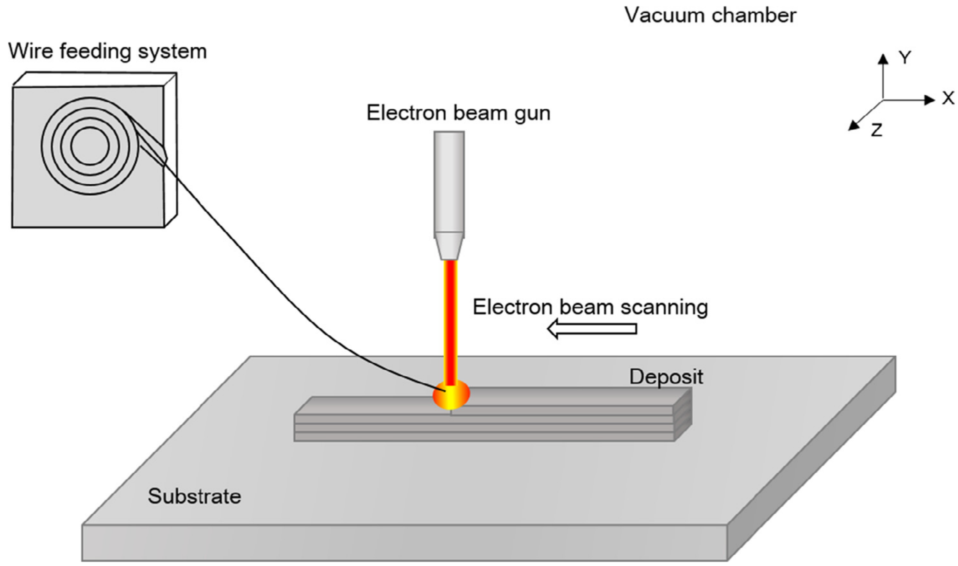

Fig. 1. Wire feeding-based electron beam 3D printing process.

transition mode. Finite element simulations focused on the temperature evolutions and considered the deposit morphology evolutions very simplistically [16–19]. To our knowledge, no such phenomenological electron beam 3D printing model is used to simulate the wire feeding, heat transfer, and molten flow behaviors under variable metal transfer mode in the electron beam 3D printing process.

In the present paper, the metal transfer dynamics in wire feeding-based electron beam 3D printing process were investigated in depth by combining experiments and novel modeling of the heat transfer and molten flow behaviors. Different metal transfer modes were recognized according to the experimental and simulation results. The dynamics of the different metal transfer mode were revealed quantitatively. The relationship between the process parameters and the mode good for forming quality was established and criterion for maintaining that metal transfer mode is determined from a simple theory. This study can guide the selection of the process parameters, which is of considerable significance for controlling the shape of the deposits and improving the precision of the surface forming.

2. Materials and methods

2.1. Experiments

To understand the heat transfer and fluid flow behaviors of wire feeding-based electron beam 3D printing, single-path Ti–6Al–4V titanium alloy deposits were studied. The experiments were carried out with the electron beam additive manufacturing equipment (ZD60-60) at Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI), China. For studying the different metal-transfer modes, we adjusted the wire feeding speed, scanning speed, and beam power. Detailed process parameters are shown in Table 1. The materials used and other typical process parameters are as follows. Both the base metal and the wire were the Ti–6Al–4V alloy. The size of the base metal was 200 mm × 100 mm × 20 mm. The diameters of the wire were varied to be 1.2 mm and 1.6 mm to ensure the generality of the finding of metal transfer dynamics. The wire feeding angle was 45°. The initial beam-wire distance was set as about 0.4 mm to keep the electron beam acting on the wire tip and substrate at same time from experience. The focus radius of the electron beam was measured as about 0.6 mm through a lot of tests. The focus plane was on the substrate surface. The ambient temperature and the initial temperature of the wire and the substrate were about 300 K. The vacuum level was set as 0.01 Pa, typically. After depositions, the specimens were cut, grinded, polished, etched (Kroll reagent: 100 mL of H_2O + 2–6 mL of HNO_3 + 1–3 mL of HF, time: 6–10 s), and observed under an optical microscope.

2.2. Modeling

2.2.1. Mathematical model

To reproduce the transition behavior of metal directly, we proposed a 3D mathematical model considering wire feeding. In this model, we used the mixture theory and the Euler method to deal with the motion of the wire [20,21], and the volume of fluid (VOF) method to capture the interface of the wire and the molten pool [22,23]. Note that the substrate was stationary, and the wire was fed continuously and translations with the electron beam scanning in experiment. Thus in the modelling, the boundary conditions considering the continuous feeding wire inlet and electron beam scanning simultaneously are difficult to deal with. Technically, when the inlet of the feeding wire is continuously, the boundary condition is difficult to deal with. To solve this problem, here we referred to the transformation of the motion reference system. Under the principle of relative motion, we took the electron beam as the reference, namely the electron beam was supposed to be stationary. Then the inlet location for feeding wire was fixed while the substrate translated. Assuming that the molten metal was an incompressible fluid following previous studies [24–26], the mass, momentum, and energy conservation equations in the new reference system were derived as:

$$\nabla \cdot \vec{U} = 0, \tag{1}$$

$$\rho\left(\frac{\partial \vec{U}}{\partial t} + ((\vec{U} - \vec{U}_{move})\nabla)\vec{U}\right) = \nabla(\mu\nabla\vec{U}) - \nabla p - \frac{\mu}{K}(\vec{U} - \vec{U}_{move}) - \rho\vec{g}\beta(T - T_{ref}) + \rho\vec{g}, \tag{2}$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + ((\vec{U} - \vec{U}_{move})\cdot\nabla)T\right) = \nabla\cdot(\lambda\nabla T), \tag{3}$$