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Effects of metal-vapor jet force on the physical behavior of melting wire transfer in electron beam additive manufacturing

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ABSTRACT

The effects of metal-vapor jet force on the physical behavior of melting wire transfer in electron beam additive manufacturing were analyzed by both means of theoretical and experimental studies. The maximum size of the droplet in metal transfer was calculated by the static force balance model theoretically. Meanwhile, the transfer behavior was observed by using a charge-coupled device visual system. The calculated maximum size of the droplet matched well with the experimental data, indicating that the model could effectively predict the critical size of the droplet. Our results revealed three transfer modes induced by different transition heights: metal transfer, big-droplet transfer and molten-metal-bridge transfer. There were two stages in metal transfer at the high transition height of 10 mm. In the first stage, the droplet with a radius of 1.5 mm flew horizontally and dripped outside the molten pool because of the horizontal component of the metal-vapor jet force. In contrast, in the second stage, the droplet with a radius of 3.93 mm flew vertically and dripped inside the molten pool with the reason of the vertical component of the metal-vapor jet force. When the transition height was reduced to 4 mm, the big-droplet transfer occurred, which was similar to metal transfer. As the transition height decreased further, the molten-metal-bridge transfer mode appeared. This was the most stable transfer mode. In addition, the mechanism of each transfer mode was also proposed. The metal-vapor jet force was proved to play an important role in droplet growth and stability. Finally, it is essential to decrease the transition height to avoid the metal-vapor jet force from influencing the stability of process.

1. Introduction

Electron beam additive manufacturing (EBAM) has been recognized as a revolutionary technique for producing many parts in near-net-shape from various metals and alloys recent years (Wanjara et al., 2007). It can be effectively used in manufacturing (Matz and Eagar, 2002). However, the weld appearance directly determines the quality of the near-net-shape parts. Moreover, in EBAM the behavior of melting wire transfer is important to determine the stability and weld appearance of the final parts. Therefore, to optimize part fabrications, the transfer behavior must be analyzed.

Recent research on the behavior of melting wire transfer has focused on gas metal arc welding (GMAW), laser beam welding and hybrid welding. One of the most useful methods for studying metal transfer is the static force balance model (SFBM) (Kim and Eagar, 1993). Other research has detailed how current affects droplet generation and droplet shape in GMAW, revealing that a higher current creates smaller droplets produced at a higher frequency (Hu and Tsai, 2006). To provide guidelines for producing good welds, a statistical model has been developed that estimates the number of droplets transferred during each pulse in GMAW (Praveen et al., 2008). Additionally, studies have assessed the relationship between welding velocity and the behavior of the globular metal transfer in GMAW. This work revealed that increasing the welding velocity also increased the flight velocity of the droplet and that good weld quality could be achieved by preventing the droplet from rebounding from the workpiece surface (Feng et al., 2012). Calculating the droplet size and frequency in GMAW by using modified force balance model (MFBM), researchers have controlled the droplet size by two proportional-integral controllers to achieve high weld quality (Mousavi Anzehaee and Haeri, 2011). SFBM was also adopted to analyze effects of the momentum flux on metal transfer in GMAW. The results indicated that the momentum flux could compensate the error in the high current range and the results showed a good agreement with the experimental data (Arif et al., 2008). In another

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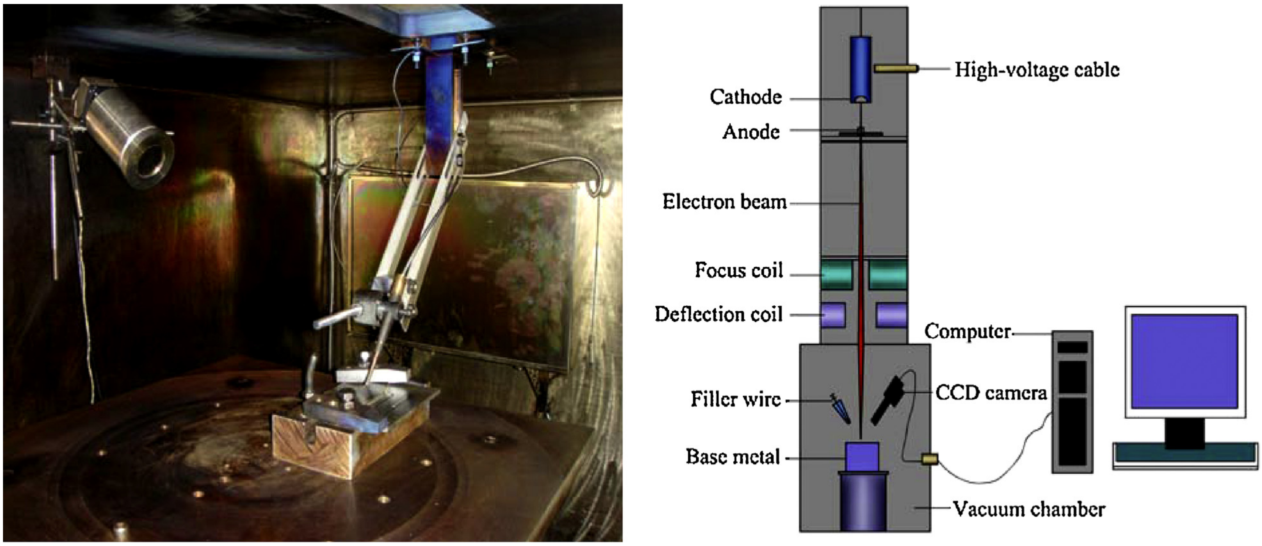

(a) Photo of EBAM system

(b) Schematic diagram of EBAM system

Fig. 1. Experimental EBAM system. (a) Photo of EBAM system and (b) schematic diagram of EBAM system.

study, researchers used the spring-mass-damper model (SMDM) to analyze the oscillation and detachment of droplets in GMAW, finding that the ejection level and its acting moment strongly affected the detachment of droplets (Wu et al., 2004). Researchers found that increasing the distance between laser and arc which strongly affected the arc characteristic, droplet mode and weld bead geometry could change the transfer mode from globular transfer to the best transfer projected transfer in CO_2 laser-MAG hybrid welding process (Liu et al., 2012). Additionally, plasma-gas metal arc hybrid welding exhibited no in-flight explosion during droplet transfer which was common in conventional GMAW. The weld appearance was also optimized (Kim et al., 2012). The velocity and temperature distributions, the rate of mixing and solidification caused by filler droplets in laser-MIG hybrid welding were calculated by mathematical model (Zhou and Tsai, 2008). In CO_2 laser-metal arc gas hybrid welding, the arc energy determined the mode of droplet transfer. The droplet velocity decreased with the increasing of laser power because of the attraction force of laser plasma to arc, as well as the metal-vapor jet force (Liu et al., 2013).

Many of these reports have focused on theoretical calculation and experimental studies of melting wire transfer to reveal the transfer behavior and to optimize the weld appearance. However, little attention has been paid on how the metal-vapor jet force affects the physical transfer behavior during EBAM. This is an oversight because the transfer process directly influences the weld appearance, which itself affects the quality of the near-net-shape in EBAM. In the present paper, the influences of the metal-vapor jet force on the physical transfer behavior were investigated. Here SFBM method was used to calculate the critical maximum droplet size in metal transfer. Meanwhile, the physical transfer behavior was collected by a charge-coupled device (CCD) visual system. Subsequently, the calculated results were verified by experimental results. The mechanism of each transfer process was found. Finally, the processing parameters for producing good weld appearance in EBAM were given out.

2. Experimental

These experiments were performed with electron beam welding equipment at a maximum power of 15 kW and spot diameter of 0.4 mm. The transfer processes were monitored by a CCD visual system. The camera had a micro-distance lens with a focal length of 90 mm, as well as a narrow-band filter with a center wavelength of 632 nm and a half-band width of 10 nm. Fig. 1 shows the experimental system.

Table 1
Chemical compositions of materials used (wt.%).

	C	Si	Mn	P	Cr	Ni	S	Cu	Fe
304 stainless steel	0.04	0.60	1.09	0.04	18.3	8.01	–	0.18	Balance
Filler wire	0.08	0.85	1.48	0.01	0.01	0.01	0.01	0.13	Balance

Bead-on-plate welding was adopted in all experiments. The plate was 304 stainless steel with the dimensions of 150 mm × 100 mm × 6 mm, and the filler material was ER50-6 low carbon steel wire of 1.2 mm in diameter. The chemical compositions of materials are listed in Table 1. The processing parameters are provided in Table 2. Before welding, the oxide layer was removed by grinding, cleaning and drying.

Because the adjacent-axis sensing method was used here, the image it collects may have distorted length and width. Thus, the camera should be calibrated to obtain the accurate results. In our study, the distance from the lens to the workpiece was 400 mm. When the beam current was set to be 20 mA, the size of molten pool was about 6 mm × 6 mm. The surface geometry can be considered to be planar due to its low proportion of the whole visual field. Therefore, pinhole camera model is an effective way to calibrate our visual system here. Fig. 2 shows the concentric circles used during camera calibration. The four intersections of the center line and circle with a radius of 5.5 mm are denoted as A_i ($i = 1, 2, 3, 4$) with coordinates of (X_i, Y_i), respectively. The correction factors for

Table 2
Processing parameters.

Processing parameters	Details
Accelerate voltage	60 kV
Beam current	25 mA
Welding speed	300 mm/min
Wire feed rate	0.9 m/min
Wire feeding angle	60°
Vacuum degree	2.5×10^{-2} Pa