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Closed-loop control of variable layer width for thin-walled parts in wire and arc additive manufacturing

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ABSTRACT

An intelligent single-neuron self-adjusting controller is proposed for variable layer width control in wire and arc additive manufacturing (WAAM). The travel speed is selected as the input control variable and the layer width is chosen as the output. The performance of the controller is validated by the disturbance of deposition current, inter-layer temperature, and given layer width. It is also evaluated through deposition of a 13-layered wall with variable layer width. The proposed controller is effective for increasing the process stability when the expected layer width ranges from 6 to 9 mm.

1. Introduction

With an increasing emphasis on sustainability, additive manufacturing for building metal parts offers a substantial merit in terms of decreased buy-to-fly ratios (Williams et al., 2015). In comparison to conventional subtractive manufacturing process, additive manufacturing is an additional technique for fabricating complex metal parts by adding of materials, in the form of powder or wire. A proposed approach in this field is wire and arc additive manufacturing (WAAM). Using welding arc as the heat source can offer a significant advantage of low cost for equipment. On the other hand, utilizing wire as the deposition material greatly improves material efficiencies, as all the wire is fed into the molten pool during the process.

In recent years, many researches have been focused on WAAM in terms of forming technology and metallurgical properties. For instance, Martina et al. (2012) investigated the forming geometry and microstructure of thin-walled Ti-6Al-4V parts deposited by plasma arc plus wire. In Baufeld et al. (2010), microstructure and mechanical properties of Ti-6Al-4V components fabricated by gas tungsten arc welding were investigated. Microstructure and residual stress of parts, built by metal inert gas welding, were improved by means of high-pressure rolling (Colegrove et al., 2013). As described in Martina et al. (2015), depositing Ti-6Al-4V parts with high-pressure interpass rolling can reduce the overall thickness of α phase lamellae and change the microstructure from strongly columnar to equiaxed. Effects of process variables on forming appearance were studied in WAAM through a passive vision sensor (Xiong et al., 2015), indicating that the deposition current was the major factor.

It is known that WAAM is a multi-variable and strongly coupled process, which is susceptible to small variations in process parameters, such as the arc current, arc voltage, and travel speed. As a consequence, changes in parts geometry and quality are inevitably produced in WAAM, even with identical process variables. Moreover, disturbances, including the inter-layer temperature, heat elimination condition, and previous forming geometry, have significant effects on the current layer geometry. Some control strategies, such as control of inter-layer temperature by natural cooling (Spencer et al., 1998), control of arc striking and extinguishing appearance through adjusting process parameters (Zhang et al., 2003), and combining additive manufacturing and milling process to improve the surface smoothness of components (Karunakaran et al., 2010), have been proposed to improve the forming quality. However, layer geometry variations, resulted from fluctuations in process parameters and work environment, cannot be eliminated by an open-loop control system. It is necessary to establish a closed-loop control system for WAAM.

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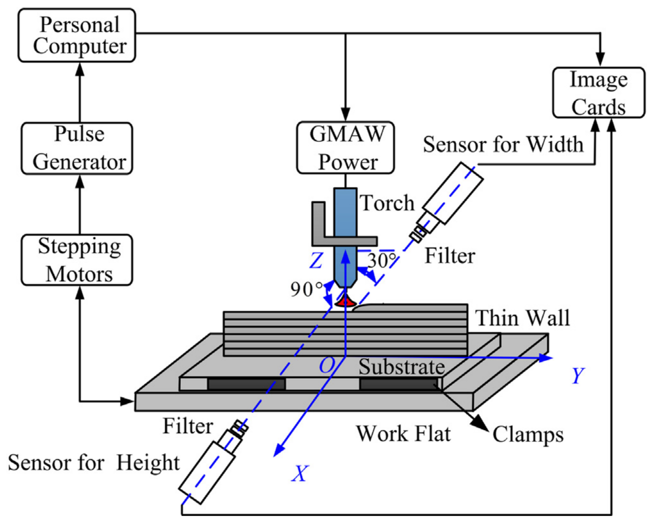

Fig. 1. The schematic diagram of WAAM system.

From the available literatures, effective detection and control methods for layer geometry in WAAM have not been developed in depth. Doumanidis and Kwak (2002) established a multi-variable adaptive control system in WAAM through an active vision sensor that can produce a large detection lad. As described in Heralic et al. (2012), height control in laser metal-wire deposition was realized based on iterative learning control. By contrast, several publications have been reported in powder-based deposition process, e.g. height control through a feedforward proportional-integral-derivative (PID) controller (Fathi et al., 2007), layer-to-layer height control for laser metal deposition process using iterative learning control (Tang and Landers, 2011).

In our previous study, a passive vision system for layer width and height detection has been designed (Xiong and Zhang, 2013). This paper aims at realizing an interesting variable width control for various layers in WAAM through a closed-loop control system. The thin-walled structure is chosen to evaluate the effectiveness of the proposed controller.

2. Experimental details

WAAM system is mainly composed of a gas metal arc welding power supply, a moveable workflat, a visual-sensing system, and a personal computer for control, as presented in Fig. 1. The power supply was Panasonic YD-500FR. The deposition torch was fixed on a slide rail. Gas metal arc, struck between the wire electrode and the top surface of the thin wall, was used as the heat source. The shielding gas was 95% Ar and 5% CO_2 with a flow rate of 18 L/min, with a view to protecting the molten pool. The wire electrode with the diameter of 1.2 mm was H08Mn2Si, which is a trademark of wire made in China. The geometry of the mild steel substrate was 260 mm × 80 mm × 9.5 mm. Table 1 presents the composition of the electrode wire and substrate. It should be noted that if no special instructions, the deposition current was set at 150 A, and the arc voltage was 22 V.

The work flat, driven by two stepping motors, can move in the Y-axis and lift in the Z-axis, respectively. During the process, the torch was kept fixed, and thin-walled parts were built by the movement of the workflat along the Y-axis. As one layer was performed, the arc was extinguished and the work flat was made a descent by a given layer height along the Z-axis. Then, another layer was begun to be deposited.

The personal computer with a data acquisition and an image grabbing card was the center of the control system. It was responsible for arc on/off, adjusting wire feed rate as well as travel speed, and displaying sensing images.

As seen in Fig. 1, a passive vision sensor, consisting of a neural filter, a narrow-band filter with center wavelength of 650 nm, and a CCD camera, was used for layer width detection. The vision sensor for width detection was mounted on the rear of the torch. Due to multi-layer depositions, the distance between the nozzle and the top surface of the thin wall is variable. Consequently, the calibration of the sensor system is difficult. In this circumstance, another vision sensor system with the same optical components was applied to monitor the nozzle to the top surface distance. The detailed image processing algorithms and calibration procedures can refer to Xiong and Zhang (2013). The flow chart of image processing is presented in Fig. 2.

Table 2
Time constant, time-delay, and gain coefficient of layer width with travel speed step.

Positive step	K	−0.689
	T_s	0.5933
	T_d	1.0
Negative step	K	−1.1035
	T_s	1.783
	T_d	1.4

3. System identification

Generally, a control system is composed of dynamic characteristics of the controlled object and the controller design. The principle of the controller design is to devise reasonable control algorithms for acquiring the excellent performance index of the controller, through establishing a dynamic model of the process. As a consequence, it is essential to develop the dynamic model relating the controlling and controlled variables. In this research, the travel speed is selected as the control input, and the output is the layer width.

At first, step response experiments were conducted to study the dynamic characteristics of WAAM process. It was achieved by performing a step change in the travel speed. After depositing three layers on the substrate, the step response experiment was conducted on the fourth layer. As seen in Fig. 3, the positive step of the travel speed increases from 5 to 7 mm/s, and the negative step decreases from 7 to 5 mm/s. It is demonstrated that the travel speed has a negative effect on the layer width. The response of layer width under the step change has no overshoot. Therefore, WAAM can be assumed as a first-order process, the transfer function of which can be formulated as:

$$G(s) = \frac{K}{1 + T_s} e^{-\tau s} \qquad (1)$$

where K is the static gain, τ is the time-delay constant, and T_s is the time constant.

The coefficients of the transfer function models are displayed in Table 2. The deposition process for layer width has a certain time-

Table 1
Composition of experiment materials (wt.%)

Materials	C	Mn	Si	Cr	Ni	S	P	Fe
Wire	0.06–0.15	1.8–2.1	0.65–0.95	≤0.2	≤0.3	≤0.025	≤0.025	Reminder
Substrate	0.12–0.2	0.3–0.7	≤0.3	≤0.3	≤0.3	≤0.045	≤0.045	Reminder