INVESTIGATION AND CONTROL OF WELD BEAD AT BOTH ENDS IN WAAM

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Abstract

Control of bead geometry in wire and arc additive manufacturing is significant as it effect the whole manufacturing process. However, the weld beads at arc striking and arc extinguishing area are generally abnormal in which the dynamical process of the weld bead is unstable. In this paper, the abnormal areas in arc striking and arc extinguishing point were investigated. Different parameters were used to make the width and height closed to the middle area in the AS and AE point. A burning-back method was proposed to fill up the slant plane in AE point. Experiments were conducted to study and verify the abnormal areas of the weld bead. And the experimental result indicated that the methods at both ends were available and preferable in the optimization of weld beads.

Keywords: WAAM; additive manufacturing; arc striking; arc extinguishing; abnormal area; bead geometry;

1 Introduction

Metal additive manufacturing (MAM) [1] has gained great progress in recent decades. Most of the research is focused on the MAM technology using a laser [2] or electron beam [3] as a heat source on account of the advantage in forming precision. On the other hand, wire and arc additive manufacturing (WAAM) [4][5] which used welding arc as a heat source, shows a strong advantage in efficiency and cost. It has significant advantages in manufacturing large-size component. However, the low precision of WAAM is a limitation in geometry control, especially the arc striking (AS) and arc extinguishing (AE) point. The shape of the weld bead affects the whole deposition process as WAAM is a layer-to-layer process.

In the process of deposition, the geometry of the weld bead is unequal to the ideal shape, especially the (AS) and (AE) area. The geometry in the middle of the weld bead is usually stable in width and height, as the deposition process is stable. However, the AS and AE areas are unstable, resulting in an unnormal geometric dimension. The abnormal geometry will affect the adjacent bead both in the same layer or next layer. The negative impact will amass and bring vicious circles. In order to make the forming process stable and turn vicious circles into the cycle of conscience, the optimizing and control of weld bead is essential.

In order to figure out the process of arc striking and arc extinguishing point, Hu et al. [6]

established a three-dimensional transient fluid model. The heat input of welding arc and heat output of conduction and radiation were dynamically changed from the AS point to AE point. The state of the dynamic process has a great effect on the convection of the molten pool and the morphology features of the weld bead. The simulation revealed the formation of AS point and AE point, of which a hypertrophic shape and slant shape respectively.

In the aspect of bead control in AS and AE point, Xiong et al. [7] and Hu et al. [6] proposed path strategies to alleviate the height difference. For the closed-loop path, an overlap in AE point by repeating the path in AS point was conducted. For an open path, the direction of neighboring layers was inverse. The slanted shape of AE area was filled up by the hypertrophic shape of AS area. The proposed method could alleviate the height difference, but the processes at AS and AE point were unstable. Whether it is the closed-loop path or the open path, the deposition was in an inconsistent height. For the closed-loop path, the AE point needs to go through the AS area with a sudden addition of substrate height for overlap path, as shown in Figure 1. The sudden change of distance between arc torch and substrate has a negative effect on the forming quality and geometry, even cause defects. For open path, the AS point of next layer is just at the AE point, as shown in Figure 2. The big distance between arc torch and substrate has a negative effect on the stability of AS process. Thus, the control of path strategies is effective but not the best.

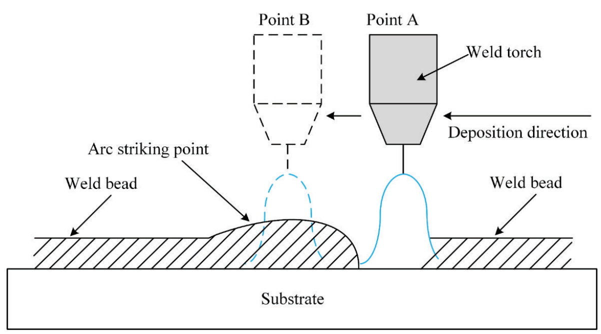

Figure 1 The schematic of deposition from flat plane to arc striking point.

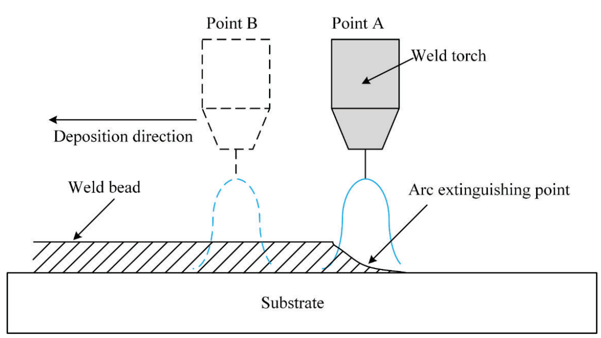

Figure 2 The schematic of arc striking at the arc extinguishing point.

Solving the topography problem of a single pass is the key to the quality of the subsequent forming process. Zhang et al. [8] proposed a speed control strategy at the AS and AE point.

High speed was used in AS point to decrease the height of bead and low speed was used in AE point to increase the height of bead. The geometry of the head bead at AS point was improved but the slant plane at the AE point still existed. The width of the weld bead was also not well controlled. Ma et al. [9] established a weaving bead method to achieve consistent size for large size parts. The method can improve the geometry of abnormal area in the way of path control strategy but cannot eliminate, and the negative impact also existed. Akula et al. [10] and Tang et al. [11] developed a hybrid AM process to remove the salient point by milling. The method of milling could be time-consuming and waste the materials.

Yang et al. [12] developed a double-electrode system to temper the welding arc. A control electrode was added into the main arc to improve AS and AE point. But the control of the double-electrode system was difficult and the manufacturing process was complex. The width of the weld bead was also uncontrolled. Bai et al. [13] used a magnetic field to control the arc shape in the forming process. The weld bead of AS area was tiled and the geometry of weld bead was improved. Zhang et al. [14][15][16] established a hybrid AM system using micro-roller to improve the accuracy of weld bead and parts called hot-rolling. The AS area became flat except the slant plane of AE area. This method of rolling was also studied by S. Williams et al. [17]. The difference was that the rolling process was after the deposition process called cold-rolling. The above-mentioned methods using the aided process to improve the shape of weld bead only considered the height of weld bead and ignored the width of the weld bead, which had a significant deficiency to the multiple-pass overlap deposition.

The control of weld bead should consider not only the height of bead, but also the width of bead, not only the middle of bead, but also the abnormal area of bead. The height of bead affects the next layer, while the width of bead affects the adjacent bead in the same layer. Thus, the height and width of the weld bead must be controlled conjunctively and synchronously.

In this paper, the arc striking (AS) and arc extinguishing point (AE) were studied meticulously. The method and strategy were proposed to control the geometry of weld bead in both height and width. In the AS and AE point, different parameters were used to make the width and height closed to the middle area. A burning-back method was proposed to fill up the slant plane in AE point.

2 The experimental design

Figure 3 shows the equipment used in the experiment. A Lorch welder was used as weld source, and low-carbon steel was used as deposition material. An expert welding program was set in the welder and a control order system was established to change the welding parameters online. A CNC machine was used as a moving platform.

Figure 3 The experimental platform

3 Study of arc striking and arc extinguishing area

The deposition of WAAM is a dynamic process with multi-parameters. With the input of arc heat source, a weld molten pool is generated, as shown in Figure 4. The molten pool is effected by a series of physical quantities, such as droplet transfer, gravity, arc force, heat radiation, and heat conduction. The liquid metal inside the weld molten pool is flowing dynamically. Due to different forming conditions, the flowing direction of the molten pool is different at the arc striking, middle point and arc extinguishing area, result in a different weld geometry.

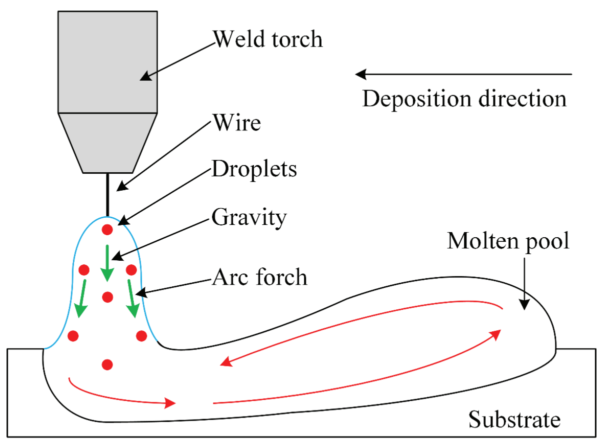

Figure 4 The schematic of weld molten pool in WAAM

The regions of weld bead were divided into three parts, as shown in Figure 5. At the arc striking area, the breaking out of heat input brings about a weld trench. With the moving forward of weld touch, the liquid metal inside the molten pool flowed to the tail of the molten pool with the pressure of arc force. The tail area of the molten pool cooled down quickly as the heat radiation and heat conduction was more than heat input. The rapid cooling effect resulted in a hypertrophic shape of weld bead.

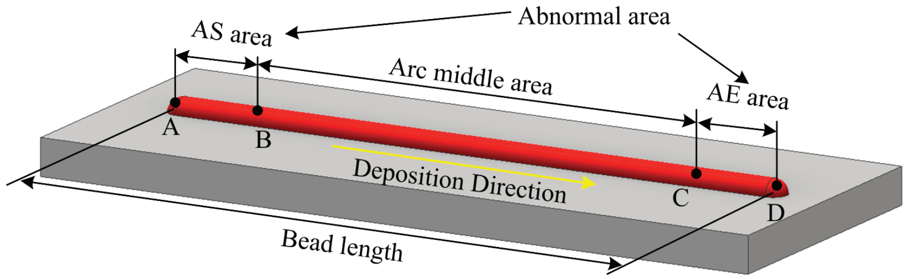

Figure 5 The different areas of weld bead

After the arc striking area, the welding process moved into a stable state. The heat input entered into dynamic balance with the heat radiation and heat conduction. The liquid metal was flowing in a cycle as the liquid flowed to the tail and flowed back inside the molten pool. The state of dynamic balance makes the shape of weld bead into a steady profile.

At the arc extinguishing area, the sudden stop of the welding arc resulted in the disappearance of heat input. The liquid metal that flowed to the tail of the molten pool solidified quickly because of the heat dissipation caused by heat radiation and heat conduction. Then the shape of the arc extinguishing area became slant.

Figure 6 shows the dynamic process of the molten pool in AS area. The temperature was monitored by an IR sensor. The molten pool starts from a round dot to banded shape over time. After a while, the state enters into dynamic equilibrium in middle area.

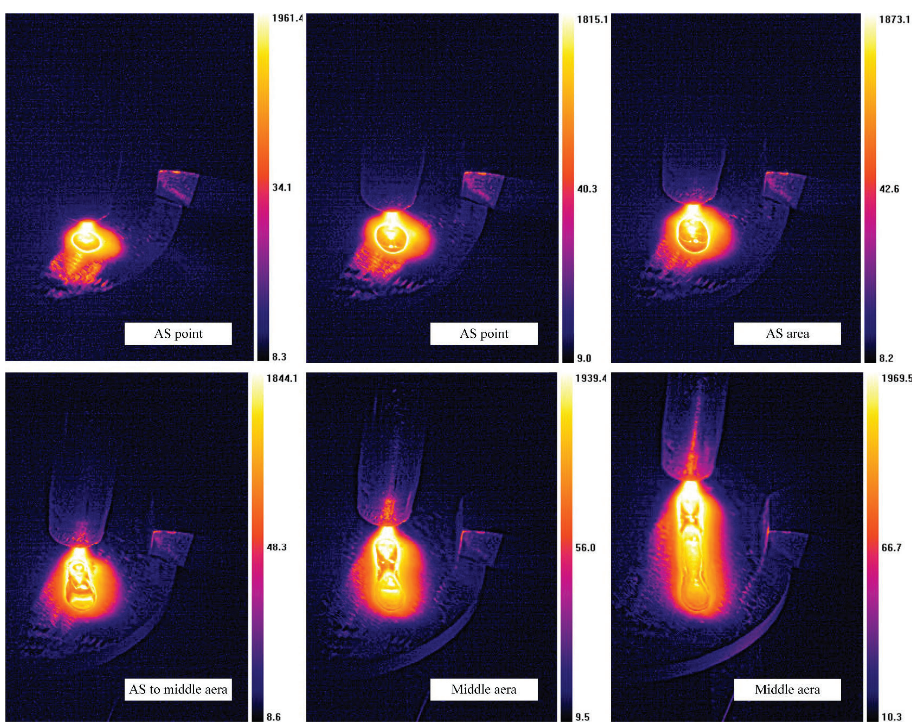

Figure 6 The dynamic process of molten pool

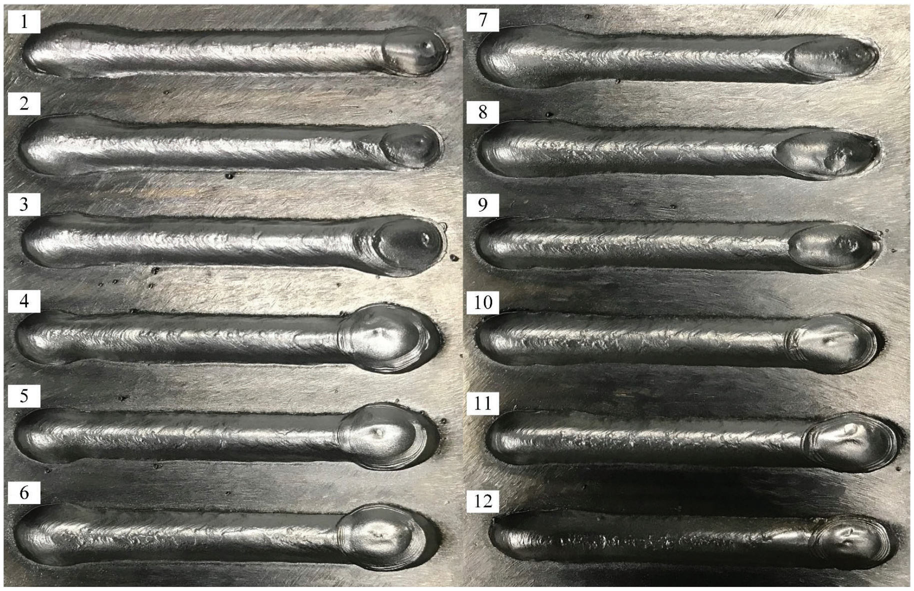

Figure 7 Twelve beads (80 mm) with different parameters.

In order to understand the factors that affect the appearance of the weld bead, especially in the AS and AE area, a series of experiments were conducted with different parameters, as shown in Figure 7. The welding parameters were set into three parts in which the parameters in AS, middle, and AE area were different. The range of parameters is shown in Table 1. The parameters of traveling speed (V), welding current (I), and length of dynamic parameter (*L*) were changed and adjusted to investigate the effect of parameters and improve the geometry of weld bead. In the middle of the weld bead, the parameters were kept the same. In bead 1, the parameters were conventional and constant from AS point to AE point. The head of weld bead was hypertrophic in height and width, and the tail of the weld bead was slant. In bead 12, the parameters were optimized at the AS and AE point with the burning-back process. The height and width of the weld beads in the experiments were shown in Figure 8 and Figure 9. It can be seen that the width and height in the middle area were stable but abnormal in AS and AE point. The height of middle area was lower than the AS area and higher than the AE area. The widths in the abnormal area were various due to the change of parameters. The height and width were difficult to be applicable and equal to the middle area at both ends.

The burning-back method works as follows (A, B, C, and D were in Figure 5):

(1) Select the suitable parameters in the AS, middle, and AE of the bead, including the length of AE area;

(2) Arc on at the AS point (point A);

(3) Deposition along the path (line A-D) from AS point (point A) to AE point (point D) using selected parameters;

(4) Turn back from the AE point (point D) to point C in the inverse direction of the path;

(5) Arc off at point C.

It can be seen from the geometry of twelve beads with different parameters in the experiment, the burning-back method can alleviate even eliminate the slant characteristic of AE area. The different parameters used in AS and AE area were available to improve the morphological characteristics of weld bead.

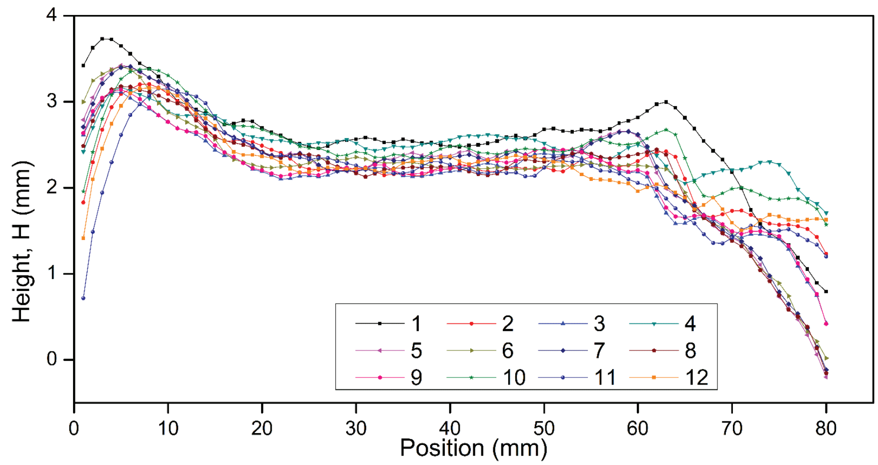

Figure 8 The height of weld bead in the experiment

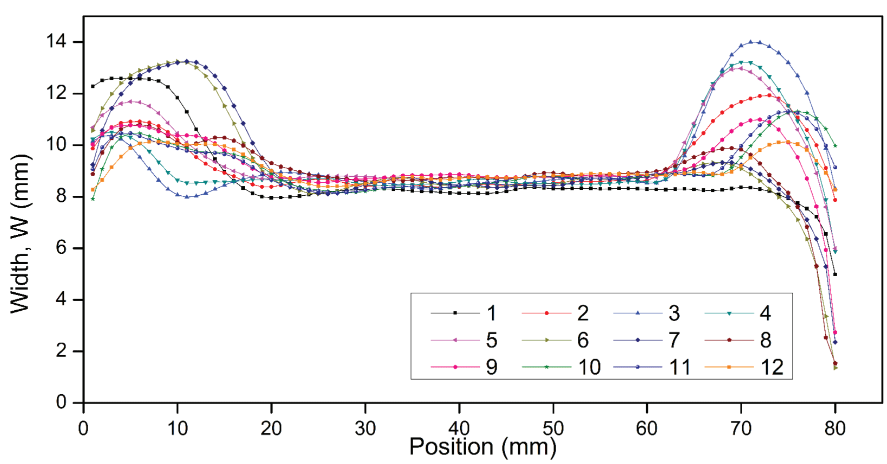

Figure 9 The width of weld bead in the experiment

Table 1 The range of parameters in the experiment

Bead area	Travel speed, V (mm/min)		Current, I (A)		Length of dynamic parameter, L (mm)	
	Min	Max	Min	Max	Min	Max
AS	500	900	200	240	10	20
Middle	500		224		-	
AE	300	700	180	240	10	20

4 Result and discussion

Optimized parameters were obtained by experimental test in AS and AE area. The experiment result was shown in Figure 10. In AS area, the optimized parameters were 700 in traveling speed (*V*), 208 in current (*I*), and 15 in length (*L*). In AE area, the optimized parameters were 650 in traveling speed (*V*), 180 in current (*I*), and 10 in length (*L*), with burning-back process. The bead width and bead height of the optimized bead were shown in Figure 11 and Figure 12. The width and height in AS area were smooth and appropriate, which indicated that the hypertrophic shape in AS area had been solved. The bead height of AE area was bulging and the bead width was adaptive, which indicated that the slant plane in AE area had been settled.

Figure 10 The deposition result of optimized parameters

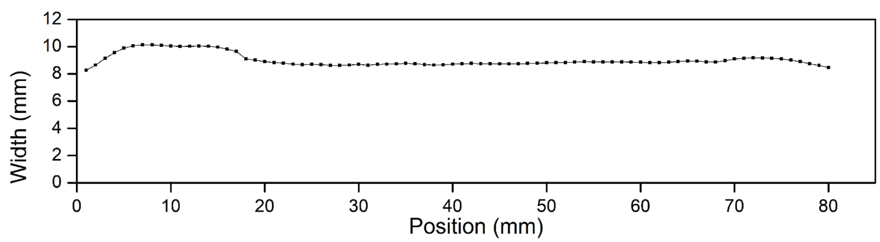

Figure 11 The bead width of optimized parameters

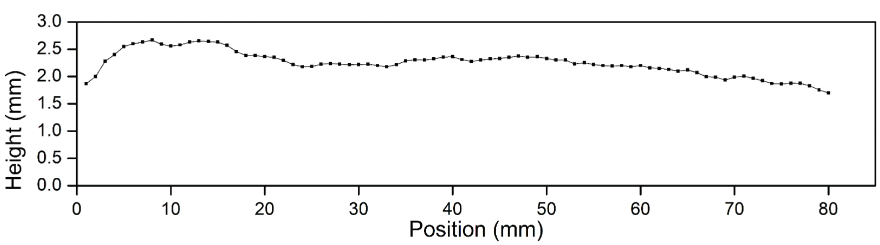

Figure 12 The bead height of optimized parameters

5 Conclusion

This paper highlights the investigation of the abnormal area in arc striking and arc extinguishing area. The input parameters that have a significant effect on the geometry of weld bead were studied and chosen, that is traveling speed (V), welding current (I), and length of dynamic parameter (*L*). To fill up the slant plane area in AE area, a burning-back method is proposed and investigated. The research results verified the effectiveness of this method. Experiments were carried out and the results showed that the methods at both ends were available and preferable in the optimization of weld beads.

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