Effect of Wire Arc Additive Manufacturing Process Parameters on Deposition Behavior of Steel

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Abstract. Additive manufacturing has gained a profound interest from the scientific community due to its economic benefits and the possibility to fabricate functional parts with complex geometrical structures using particularly any kind of material. Wire arc additive manufacturing is the cutting-edge additive manufacturing technology, which has a huge potential for industrial applications such as the production of real parts and their prototypes, maintenance, and repair operations. This article presents a study of the influence of process parameters on the deposition behavior of low-carbon low-alloy steel during the additive manufacturing process. The primary objective of the study is to identify the challenges and issues attributed to the utilization of this novel technology. During the experiments, the optimal process parameters were selected for the deposition of beads. The relationships between the process parameters and the bead geometry were determined. Adjustments of the parameters were made during the deposition of the walls consisting of a different number of layers. Once adjustments had been completed, more complex samples of square and cylinder geometric structures were deposited. After deposition, the common defects and their possible causes were identified, and recommendations for their elimination were given. At the end of the experiments, the quality of the samples obtained under these conditions and the available equipment was evaluated. Recommendations for improvement of the process are given and directions for future research are defined.

Keywords: Additive manufacturing · Wire arc additive manufacturing · Gas metal arc welding · Process parameters · Carbon steel · Deposition behavior

1 Introduction

The increased popularity of wire arc additive manufacturing (WAAM) in the industrial manufacturing sector over the past few decades caused by its capability to produce large metal components with high performance, relatively low-cost off-the-shelf welding equipment, and high material utilization [1]. Today, WAAM has become a promising fabrication process for various engineering materials such as titanium [2, 3], aluminum [4], nickel alloy [5, 6], steel [7, 8], and copper [9]. Compared to traditional subtractive

manufacturing, the WAAM system can reduce fabrication time by 40–60% and post-machining time by 15–20% depending on the component size [10].

WAAM is a pioneer additive technology that utilizes an electric arc as a heat source and metal wire, rather than powder, as a feedstock [11–14]. WAAM technology has many advantages such as the utilization of readily available welding equipment and the application of commercially available and relatively cheap welding wires instead of expensive powders and technically complex powder bed systems [15–18]. Along with the manufacturing of new components, WAAM can also be used for maintenance and repair operations [19].

Due to the highly complex nature of metallurgical and welding processes occurring during deposition, many different aspects of the process need to be studied, including process development, process parameters, material quality and performance, the influence of heat input on characteristics of a final part.

This paper reviews the study of the effect of various process parameters on the deposition behavior of low-carbon low-alloy steel after deposition by using WAAM technology. Finally, a discussion is given on improving the quality of WAAM parts fabricated through optimization of process parameters, deposition techniques, including proposals for future research.

2 Materials and Experimental Techniques

A commercially available Sv-08G2S wire (see Table 1) with a diameter of 0.8 mm was used in this study to investigate the effect of WAAM process parameters on the deposition behavior of steel components. A Fe37-3FN structural carbon steel plate of 16 mm thickness was used as the substrate on which the wire was deposited.

Table 1. The chemical composition of Sv-08G2S wire used in the study (wt%).

C	Si	Mn	Ni	S	P	Cr	N
0.06	0.8	1.9	0.2	0.02	0.02	0.1	0.01

An experimental robotic WAAM complex installed in the Irkutsk National Research Technical University was used to produce samples for this study and shown in Fig. 1. The deposition of the wire was performed by the gas metal arc welding (GMAW) method using a KUKA KR 210 R2700 prime (KUKA robotics, Germany) with a KEMPPI Kempomat 1701 in the flat position.

GMAW method, also referred to as metal inert gas (MIG) welding or metal active gas (MAG) welding, is a welding process in which an electric arc generates between a consumable wire electrode and the workpiece metal, which heats the workpiece metal, causing it to melt [20]. Along with the wire electrode, a shielding gas feeds through the welding gun protecting metal from the contaminants in the air. Welding grade carbon dioxide (CO_2) was used for shielding with a 10 L/min gas flow rate.
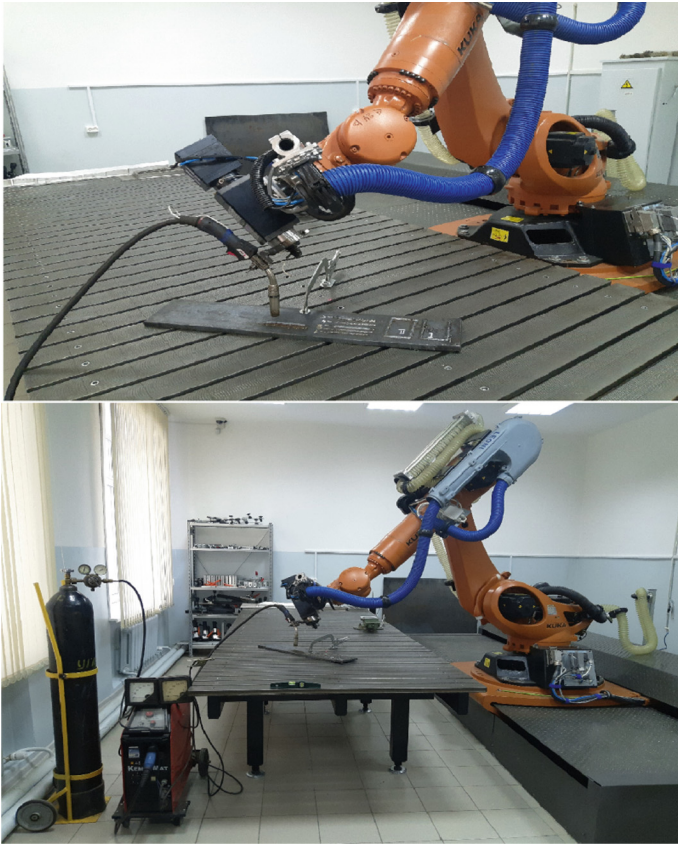
Fig. 1. An experimental robotic WAAM complex.

In order to determine the relationship between WAAM process parameters and behavior of metal during deposition, the following welding parameters have been specified for this study: welding current, welding voltage, wire feed rate, torch travel speed, stick out distance. Adjustment of optimal parameters was performed by deposition of five 100 mm long beads. Once adjustment and selection of optimal parameters have been completed, 100 mm long and 20 mm high thin-walled structures were deposited to investigate the behavior of metal during the deposition in a layer-by-layer fashion.

3   Results

The parameters that have a major effect on the formation of the layer are found to be the torch travel speed, wire feed rate, and welding current. The selection of welding current was based on a wire diameter which was 0.8 mm. The most suitable and optimal welding current for such diameter lies in the range of 100–120 A. Adjustment of these parameters allows achieving the desired quality of a deposited bead, its geometry, and the performance of the process. In particular, a linear relationship between the deposition

speed (torch travel speed) and the width of the deposited bead was determined during the experiment. Figure 2 shows five different beads produced at various deposition speeds.

Fig. 2. Deposited beads using different process parameters.

As can be seen from Table 3, the width of the bead varies depending on the torch travel speed. Bead №1 was deposited at a speed of 0.005 m/s, which resulted in a too narrow bead with uneven melting of the metal. If this speed is used for the deposition of a real part, the accuracy of the geometric dimensions will be low, and the process of layering as such will be unstable and difficult to control. Increasing the welding current while maintaining the same deposition speed did not give a positive result since it was necessary to increase the wire feed speed as well which led to the intensive scattering of the molten metal and the formation of an uneven geometry of the bead. When depositing bead №2, the deposition speed was reduced to 0.004 m/s at a welding current of 120 A. Reducing the speed of deposition contributed to the formation of a bead of high quality since the metal was melted evenly with small distortions along the central axis. However, applying such deposition parameters, the height of the bead along the central line is significantly bigger than the height of the bead on the sides. It will negatively affect the formation of the next layers since the metal will not be able to evenly overlap the uneven surface of the previous layer. As a result, the metal will flow along the sides of the layer, leaving the center line unfilled. In this case, it will be quite difficult to control the process and achieve the desired accuracy of the dimensions of real parts. Further reduction of the speed to 0.003 m/s during the deposition of the bead №3 showed the best results. The formation of the bead is more than satisfactory, the layer itself is straight having the least distortion. The height of the bead is optimal and will contribute to the qualitative deposition of subsequent layers. Utilizing these parameters, it will be possible to predict the behavior of the metal during the deposition process and achieve dimensional accuracy.

The subsequent reduction of the speed to 0.002 and 0.001 m/s during the deposition of samples №4 and №5 resulted in the production of the widest beads. Excessive heat input at these speeds leads to overheating of the metal and the formation of an inhomogeneous structure, which will inevitably contribute to the formation of defects. Additionally,

Table 3. Relationship between process parameters and the geometry of the deposited beads.

Weld bead, №	Width, mm	Height, mm	Welding current, A	Welding voltage, V	Wire feed rate, m/min	Torch travel speed, m/s	Stick out distance, mm
1	4	2	100	26	4	0.005	14
2	6	3	120	28	5	0.004	13
3	8	3	120	28	4.5	0.003	11
4	10	2	120	28	4.5	0.002	11
5	12	2	120	28	4.5	0.001	11

applying such parameters, it will be quite difficult to achieve the dimension accuracy and quality of the deposited surface.

Thus, the most optimal parameters for the deposition during this experiment are the following: welding current—100 A, welding voltage—26 V, wire feed rate—4,5 m/min, torch travel speed—0,003 m/s, stick out distance—11 mm). For the deposition of multilayer samples, a more precise parameter setting will be required during the layering process, depending on the geometry of the resulting part. Figure 3 shows multilayer walls deposited using the above-mentioned parameters. Table 4 shows the obtained geometry of the walls.

Fig. 3. Deposited walls.

As can be seen from Table 4, the average thickness of one layer was 2 mm. The deposition speed of 0.003 m/s is truly applicable for the deposition of even and fairly accurate layers, but the defects are still present. The most noticeable defects are the

Table 4. Characteristics of the deposited walls.

Wall, №	Number of layers	Height, mm	Length, mm	Wall thickness, mm	Welding current, A	Welding voltage, V	Wire feed rate, m/min	Torch travel speed, m/s	Stick out distance, mm
1	13	27	100	8	100	26	4.5	0.003	11
2	10	20	100	9	100	26	4.5	0.003	11
3	10	20	100	9	100	26	4.5	0.003	11

spreading of the metal and the slope of the wall at the end of the layer, which was the result of constant and severe heat input during the deposition process (see Fig. 4).

Fig. 4. Slope at the end of the wall.

Furthermore, there are elements of non-molten wire and splashes of metal. Some layers are deposited with a slight offset relative to the central axis of the wall, which leads to uneven overall wall thickness. To obtain a more accurate geometry and reduce defects, it is necessary to control the heat input and constantly adjust the parameters during the deposition process.

During the course of the further experiment, a box with dimensions of 60×60 mm was deposited, the number of layers is 15, and the total height is 30 mm (see Fig. 5). The average value of the layer thickness of 2 mm, determined in previous experiments, is also preserved during the deposition of a sample with a more complex geometric shape.

Layers' deposition in a square-shaped sample differs from that in the wall due to the presence of angles and the constant change of the movement trajectory of the welding torch. Since the torch was moving along a trajectory consisting of 4 linear movements, there were minor stoppages of the torch in the corners of the square. This has led to a slight widening of the beads at the corners, but this is not an issue since post-process machining will help to correct the situation. Essentially, the formation of a square-shaped part is quite successful, the deviation from the specified dimensions are within the allowance for machining, which indicates the potential of WAAM technology for production parts of the complex angular shape.

Then, the cylindrical samples were deposited (see Fig. 6). Cylinder №1 has a diameter of 80 mm and consists of 11 layers with an overall height of 22 mm. Cylinder №2 has a diameter of 50 mm and consists of 24 layers with an overall height of 48 mm.

The previously defined layer height of 2 mm remains unchanged during the deposition of cylindrical shaped samples. A cylinder with a larger diameter has a more even bead shape and has less distortion over the entire length of the layer in comparison with a

Fig. 5. Deposited box.

cylinder with a smaller diameter. A special effect on the process of forming the cylinder has the choice of the point, where the deposition of the next layer should starts. Since the deposition of each subsequent layer began at one point, a small roll was formed at this very place, which led to an uneven height of the cylinder and a broadening of the wall at this point. In order to eliminate this defect, it is necessary to change the start point of the deposition of each subsequent layer or to reduce the dwell time of the welding torch right before the deposition of the next layer.

4   Discussion

In order to improve the stability of the process, eliminate or reduce the number of defects in the deposition process, as well as to achieve the accuracy of the deposited parts, it is necessary to choose the optimal process parameters. Since a one-time parameter setting is inadequate for obtaining a high-quality part, monitoring and controlling of all parameters is required during the actual deposition process. To do this, appropriate sensors and a video camera with special light filters are needed to be integrated into the existing WAAM system for remote monitoring and controlling of the process. Moreover, to improve the quality of deposited beads, it is imperative to utilize shielding gases of higher quality. Carbon dioxide alone is not able to provide the necessary quality, so it is preferable to use a mixture of argon and carbon dioxide. To increase the metal deposit factor and hence the WAAM process performance, the wire diameter should be

Fig. 6. Deposited cylinders.

increased from 0.8 to 1–1.2 mm. For the production of real functional parts, it is vital to implement modern closed-loop welding machines that allow adjusting the process parameters directly from the robot control interface.

5   Conclusions

This article presents the results of the study of the influence of process parameters on the formation of steel parts. During the course of the experiment, the relationship between the deposition speed and the geometry of the resulting bead was obtained. The most optimal torch travel speed for the deposition of steel parts using a 0.8 mm wire is 0.003 m/s at a welding current of 100A. This speed allows achieving the best bead formation with the least distortion. The deposition process itself is quite stable and allows produce beads with approximately the same geometry. At this speed, all layers of the walls, box, and cylinders have a thickness of 2 mm. The most common defects were detected during the deposition of walls, square and cylindrical samples. Due to the constant and repeated heat input, the geometry of the bead at the beginning and end of the layer is different, which leads to the formation of a slope at the end of the wall. Additionally, there are elements of non-molten wire and splashes of metal. During the deposition of square and cylindrical samples, noticeable defects are unevenness and widening at the transition points of the layers, which is caused by the peculiarity of the torch movement. In order to eliminate these defects, it is necessary to develop a path-planning program for more effective planning of the torch movement trajectory. In

general, the parameters determined during the experiments can be used for the deposition of real parts prototypes. Further adjustment of the parameters will be required during the actual deposition process to achieve better results. The directions of future research are to study the parameters of forming real parts made from steel, titanium, and nickel, as well as to investigate the influence of process parameters on the microstructure and mechanical properties of the final parts.

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