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Deposition path planning strategy for geometries with varying cross-sections in wire arc additive manufacturing

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Abstract

Wire arc additive manufacturing (WAAM) method has emerged as a powerful platform for fabricating medium-to-large scale dense structural parts having low cost, higher deposition rate and material efficiencies compared to other additive manufacturing (AM) methods. This research work proposes a deposition tool path strategy for the parts with varying cross-sections in building directions. Different cross-section profiles in workpiece geometry complicate and increase the complexity of the tool path planning. Moreover, changing the cross-section profiles may cause to change in the heat dissipation and heat accumulation in various points of each layer. Thus, heat dissipation affects the dimensional tolerances of the workpiece during the process. In this study, firstly the deposition characteristics as Wire Feed Speed (WFS) and Torch Travel Speed (TTS) were determined based on the material, number of layers and thickness of the wall. Afterward, a specific tool path has been generated by considering the geometric attributes such as cross-section area, profile, type of border lines, curves, and their continuities. Finally, the workpiece was built up by using WAAM process with a robotic cold metal transfer (CMT) system using aluminum wire (AWS ER5356) material. The results have shown that the proposed deposition strategy results with steady transition from circular cross-section deposition to hexagonal cross-section with less distortion and waviness in the final geometry of the part.

Keywords: Wire arc additive manufacturing (WAAM), Aluminum alloy, CMT, Deposition parameters

1. Introduction

Wire Arc Additive Manufacturing (WAAM) is a welding based additive manufacturing (AM) method and it gives a promising potential for medium-to-large scale metal part manufacturing sector. WAAM technology uses welding arc as the heat source and wire as the feedstock material to deposit metal material layer upon layer which builds up the near-net shape part. WAAM commonly has three types of heat sources: Gas Tungsten Arc, Gas Metal Arc, and Plasma Arc. Compared to other AM techniques including powder feed and laser/electron beam heated processes, WAAM has few distinct advantages such as higher deposition rate with 100% material use, the possibility of manufacturing large scale dense parts, higher energy and material efficiency, possibility to rebuild damaged or worn parts, and lower equipment cost. Despite these advantages, WAAM suffers from a major drawback. For instance, higher surface roughness and high heat input of the welding arc causes a progressive increase in the internal energy of the workpiece that could lead to excessive melting of the lower layers, distortion and residual stresses [1].

One of the requirements for the WAAM process is to generate deposition tool paths and then to identify and optimize process parameters to achieve the desired deposition quality measured in terms of geometric, mechanical, and metallurgical properties. Tool path strategy that the torch follows, affects the deposited material quality and geometry. Therefore, the deposition tool path needs to be studied based on the manipulator capability and positioner that part is to be produced on. Some system uses robotic arm, and some uses Cartesian coordinate systems where the torch is attached on. Both need tool path planning for deposition. In tool path planning, sliced geometry is highly critical to create tool paths as lines or curves which are decided as the geometry of the part to be produced. The main objective should be to produce the part by depositing the material with minimum/no distortion, accurate and as fast as possible. Some of the literature works have focused on tool path planning and suggested some models to produce the part [2, 3]. However, tool path generation adapted to changing cross-section is highly critical and very limited or no dedicated work. The few studies in the area of toolpath generation for workpiece with varying cross-section which built up by steel wire have been investigated [4, 5]. However, in this work an aluminum wire has been used for building up a more complex-shaped workpiece.

The main input parameters stated in the literature are the Wire Feed Speed (WFS), torch travel speed (TTS), welding current and voltage [6, 7]. Welding current and voltage are connected to WFS and affect the heat input of the process [8]. The high heat input can lead to deteriorating layer forming quality [8, 9], which can cause collapsing layers due to insufficient solidification [8].

Presently, most WAAM processes are based on Gas Metal Arc Welding, in particular, the welding process Cold Metal Transfer (CMT) due to its high deposition rate, low heat input, and high bead quality production nearly without spatter [10]. Furthermore, CMT provides high arc stability and material transfer without spatters, leading to better quality parts. CMT process has been implemented by the researcher for the fabrication process for various engineering materials alloys such as steel base [6, 8, 11], aluminum base [10], titanium base [12, 13], and nickel base [7].

A considerable amount of literature has been published on the influence of WAAM process parameters and heat accumulation on metal deposition parts. The effect of process parameters, specifically wire feed speed (WFS), torch travel speed (TTS), and their ratio on bead geometry, microstructure, and mechanical properties, has been investigated by [6, 8]. Different deposition parameters of aluminum alloys have been studied in both experimental and modelling perspectives and provided guidelines for optimizing the process conditions. Mechanical properties such as total distortion and residual stress were the criteria for the manufacturability of the structure [14].

Varying cross-section affects the tool path planning strategy and deposition parameters in WAAM process. Furthermore, the heat accumulation and heat dissipation change in each layer due to the different cross-sections in each layer. This paper presents a research work that proposes a WAAM toolpath strategy for geometries with varying cross-sections and complex shapes.

2. Robotic WAAM system and experimental setup

A robotic welding system was used to deposit material on the substrate. The system consists of KUKA KR6 R 1820 HW industrial robot, a Fronius TPSi 500 welding power supply and a Fronius Robacta CMT torch which is fixed on the robot tool flange arm and hold vertical to the substrate during the deposition.

The process parameter such as voltage and current automatically were adjusted with the CMT power supply by choosing the wire feed speed. The Torch Travel Speed and weld path were controlled by the robot arm. The aluminum welding wire with 1.2 mm diameter has been used for the experiment. The substrate is Al 6061, and the standard of the wire is AWS ER 5356 with a chemical composition given in Table 1. The shielding gas was 100% Argon at a gas flow of 18 L/min. The employed robotic system was shown in Fig 1.

Table 1. The chemical composition of standard AWS ER5356 welding wire

Materials	Si	Fe	Mg	Mn	Cr	Al
AWS ER5356	0.15	<0.4	4.5-5.5	< 0.20	< 0.15	Rest

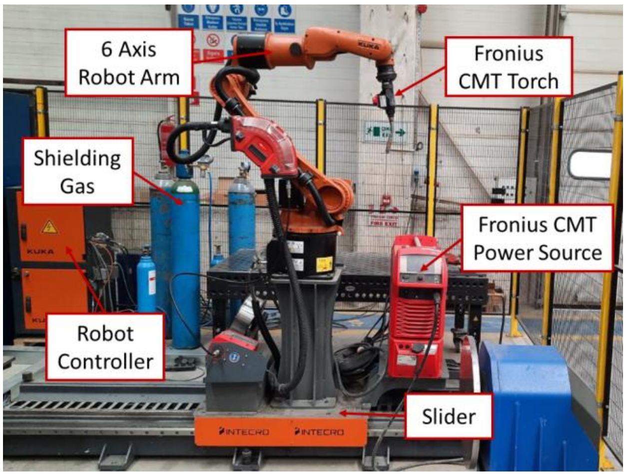

Fig 1. Robotic welding system and experimental set-up.

3. Deposition tool path planning and manufacturing

The most important factors in the WAAM process are CAD modeling, slicing technique, tool path planning, deposition parameters (e.g. wire-feed speed, torch travel speed, interpass temperature), coding and post-processing. In this section deposition parameters and path planning of the WAAM process with CMT technology have been studied. First, by using an offline program, the CAD model has been sliced and the tool path strategy has been planned. Then, to determine the deposition parameters, four walls were deposited with different WFS and TTS in 100 mm length with 20 layers. After each layer, the deposition process paused until the temperature of the layer decrease to 40-50 °C. The walls were shown in Fig 2 and their deposition parameters were given in Table 2. The deposition parameters of Wall 3 has been selected for building up the workpiece. These parameters have been selected due to the height and width of the walls in each layer. The flowchart of the WAAM process was shown in Fig 3.

Fig 2. Four Walls produced by WAAM with different deposition parameters.

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Table 2. WAAM Deposition parameters.

Deposition parameters	Wall 1	Wall 2	Wall 3	Wall 4
WFS (m/min)	6	6	7	7
TTS (m/min)	0.4	0.5	0.5	0.4
Layer height (mm)	2.22	2.04	2.55	2.75
Width (mm)	7.11	6.65	7.38	7.75
Interpass temperature (°C)	40-50	40-50	40-50	40-50

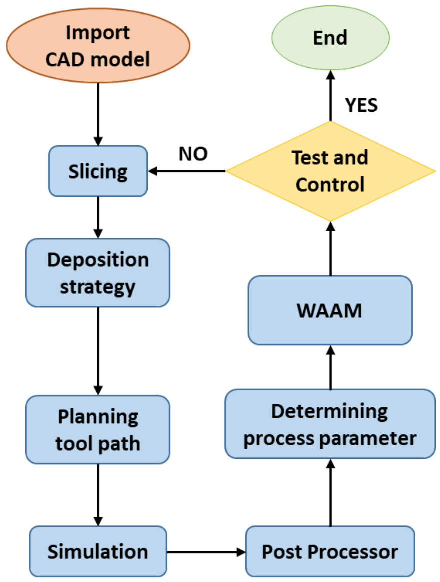

Fig 3. Flowchart of WAAM process.

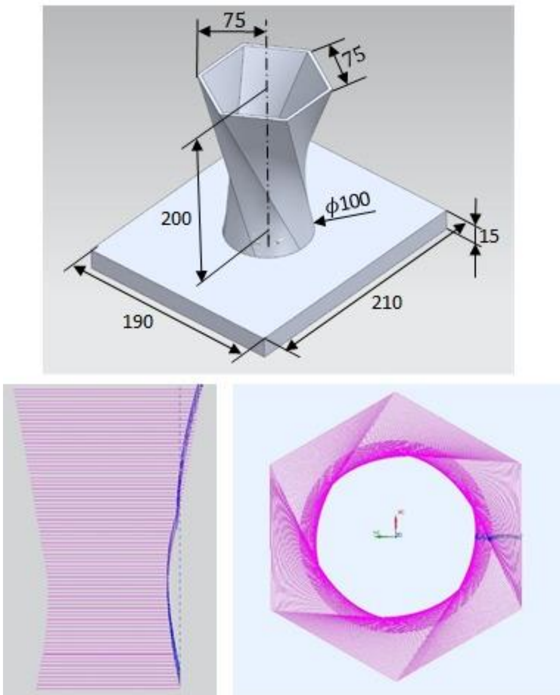

Fig 4. Isometric view of the CAD model and robotic tool path of the workpiece from front and top view (in mm).

The workpiece that has been shown in Fig 4 has circle geometry in the bottom and gradually changes to hexagon in the last layer with 30° twist. The cross-section of the sliced workpiece which is change in different layer was shown in Fig 5. In the WAAM process varying cross-section make the process more complicated which may cause uneven heat dissipation during WAAM process.

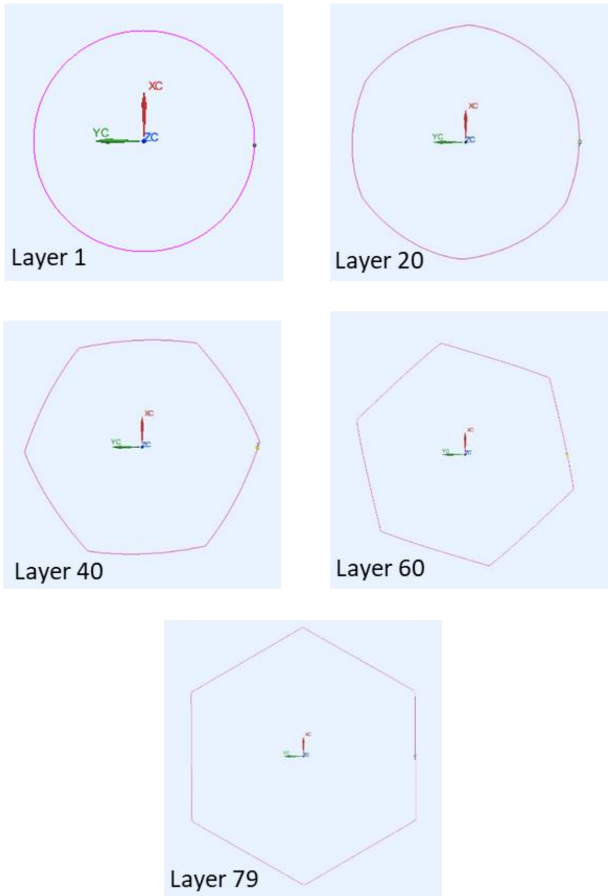

Fig 5. Cross-sections of tool path in different layer of workpiece. First layer is fully circular and last layer (79) is fully hexagonal.

According to the sliced model, the tool path in each layer has been generated in the form of the model geometry. As can be seen from Fig 5, the change of the cross-section in each layer is based on the CAD model. The start and stop of the tool path are the same. The transition between layers has been selected as raster type. The deposition in each layer starts when the temperature decreases to 40-50 °C.

4. Results and discussion

The complex toolpath planning approach is one of the critical steps in WAAM. Mathematical uncertainty influences toolpath planning for AM steps that have roughly estimated deposits. In the toolpath planning of this work, twist around Z-direction and the varying cross-section which gradually change from circle to hexagon have been considered. The single-directional slicing (SDS) technique has been used with raster transition and the distance between each layer is 2.55

mm. Fig 5 shows the edges and twists of these transitions in the toolpath. As can be seen from the figure, the edge of the hexagon gradually appears in toolpath by a twist as it rises in the Z-direction. The disadvantage of this toolpath is that the start and end points are the same where the deposition is different at these points.

In the offline programming of the tool path for varying cross-section, the outside border line type is critical for the torch to be programmed to follow the border and deposit the material. Although a general tool path programming may generate the necessary tool path for the given border line, the most influential factor is to control the process parameter which causes the heat accumulation during the deposition. In this work, the temperature of each layer was controlled via temperature measurement and a heuristic interlayer delay time was determined to prevent distortion and dimensional disorder as much as possible. The determined delay time may affect the deposited material to cool down and solidify and reacts as a solid basement for further layers. Improper interlayer delay time may cause heat up on each layer and uncontrolled melting and solidification time during deposition. This results with uneven layer thickness, very rough wave surface texture and material pour out form the layer.

Fig 6 shows the deposited part with varying cross-section starting with fully circle in the basement and hexagonal shape in the top layer. It is very clear to see the transition of the cross-section from the shape and layer thicknesses were controlled not having too much deviate between each other. Besides, material pour out cannot be seen in the whole part surface.

The nominal height of the CAD model to be produced is 200 mm. However, the height of the deposited workpiece was measured at different locations, and they have been measured between 185.48 to 193.36 mm. The deviations between the CAD model and the deposited part dimensions could be because of the heat dissipation that is not equal in the whole process and quick melting and solidification. Furthermore, this unequal heat dissipation affected the width of the workpiece which is changed between 7.13-7.44 mm. The heat of the layers has been measured by a pyrometer before deposition. According to the cross-section in each layer, the heat in various points varied between 41-52°C. This heat dissipation affected the geometry of the workpiece, especially its height shrinkage.

The effect of heat input and heat dissipation in WAAM process have been extensively studied in literature and proposed solutions for this problem [15, 16]. One of solution is to utilize a cooling system for controlling heat input and heat dissipation [17, 18]. The cooling system will be investigated in future study to decrease the height differences in the workpiece.

Fig 6. Deposited workpiece with changing cross-section from circle to hexagon.

5. Conclusions

This work is based on the generation of tool paths for building up the varying cross-section workpiece by using WAAM technologies. The tool path strategy for building up the workpiece has been generated by an offline program. This study has examined the impact of the toolpath and deposition parameters on workpiece geometry. By building up the walls with different WFS, TTS, the deposition parameters have been determined. The results of this investigation have shown that the heat input and heat dissipation have a huge influence on the build-up of the workpieces by WAAM technology. The measured value of the heat by pyrometer indicated that the heat accumulation and heat dissipation were different in various points of layers. These differences caused deformation and deterioration in the workpiece. Therefore, the heat input and heat dissipation are the key factors that should be controlled during the fabrication of workpieces by WAAM technology.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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