Chapter 5
Influence of Various Tool Path Patterns on Hardness Used in Weld Deposition-Based Additive Manufacturing

Panchagnula Kishore Kumar and Panchagnula Jayaprakash Sharma

Abstract Identification of optimal tool path is critical for successful fabrication of bulk metallic parts using weld deposition-based additive manufacturing (AM). The various features of tool path, i.e., the number of starts and stops, convolutions, and continuity, have a significant effect on the geometric as well as physical properties of manufactured parts. Ideally, an optimised tool path is a continuous path with no self-intersecting pattern, with a minimum of starts and stops and minimum convoluted patterns. The tool paths available in the literature are unable to achieve all the listed requirements. Further, there are no one-to-one comparisons of these tool paths in detail in the literature. The present work aims in comparing various tool path techniques based on flatness achievable by minimum material skinned out during face milling (thickness of the deposited layer) and the hardness achieved. Experiments are performed using the in-house developed weld-based metallic AM workstation (weld deposition torch is retrofitted with a CNC).

Keywords Weld deposition · Metallic additive manufacturing · Tool path generation · Hybrid layer manufacturing · Hardness

5.1 Introduction

To constantly concur with the rapid developments in the fields of aerospace, automobile and biomedical, there is a momentous need for manufacturing complex lightweight functional parts within a very short time span. These parts must also have minimum sub-parts for assembly and must incur minimum production costs. Currently, traditional manufacturing processes such as casting, forming (forging, extrusion) and material removal processes (turning, milling) and joining process (welding

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or soldering) play a pivotal role in achieving this task. However, due to the inherent machine and process related limitations, traditional manufacturing processes are unable to achieve this task within the speculated time and with all design details faithfully reproduced. On the other hand, additive manufacturing (AM) commonly referred as 3D printing is the prospective technique that can achieve this task successfully. This technique is a layer-by-layer manufacturing approach which is only dependent on design and is not influenced by the machine limitations such as accessibility [1–4].

In AM, three-dimensional (3D) computer-aided design (CAD) model is used to build a component in layer-by-layer manner using a specific material. The stereolithography file (.stl) is the de facto file used to convey geometric data from the CAD file to AM machine. In this way, AM provides a high degree of design freedom.

Components made of several classes of materials such as plastic, metal, glass, ceramics and artificial biocompatible materials can be easily manufactured using AM. This technique in its infant stage was termed as rapid prototyping and was mainly used for developing prototypes for illustrative purposes. With dedicated research and development of customised machines, AM is now widely used to fabricate end-use products [1]. For both polymers and metals, the cost of commercially available rapid prototyping machines is relatively high. Since most of the functional parts are metallic, there is a need for developing economically viable machines for depositing complex metallic objects.

For fabrication of metallic components, AM using welding processes such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) is gaining popularity due to its high deposition rates, high material and power efficiency, lower investment costs, simpler setup and work environment requirements [2]. However, the surface finish of the final product fabricated by weld deposition-based AM is of inferior quality when compared to traditional machining. A process termed hybrid layered manufacturing (HLM) has been found to be suitable for producing complex metallic components [5]. This process is a combination of the traditional subtractive manufacturing process using CNC and the weld deposition-based AM, and both the processes are performed in a synchronous manner.

In HLM process, initially, the near net shape of the product is deposited using weld deposition (additive), and then, the final shape of the product is achieved by using finish machining operation [5]. In this study, the same has been used for weld-based AM or in other words an in-house weld-based metallic additive manufacturing machine is developed for depositing complex metallic objects.

Manufacture of thin-walled structures using arc-based deposition has been studied in detail by researchers [3]. These structures have also been presented to the aerospace industry for commercial application [6, 7]. However, for dense components manufactured using metallic AM, in spite of intense research done, there is a lacuna when it comes to identifying an optimised area filling technique. The most crucial task in weld-based AM for dense components is generation of optimised tool path which guides the welding torch to fill the sliced 2D layer that represents the cross section of a 3D model. These tool paths are generated by offsetting a defined pattern in a sequential manner, and the offset distance is termed as road width or step-over value.

The step-over value is the distance between two consecutive weld beads. Approximating the weld bead geometry as a parabola, for smooth overlapping of weld beads, Suryakumar et al., had arrived at the optimal step over value to be two-thirds of the single bead width [8]. Based on Suryakumar et al.'s findings, throughout this work, the optimal step-over value is considered as two-thirds of the single bead width.

5.2 Tool Paths Used in Weld-Based AM Available in the Literature

The various tool paths available in the literature are tabulated in Table 5.1. Table 5.2 lists the merits and limitations of these commonly used tool paths. For uniform defect-free material deposition in weld-based AM, a continuous and self-intersection avoiding tool path with a minimum number of starts and stops is preferred [9].

There have been several attempts to arrive at a continuous tool path which is non-convoluted, non-self-intersecting, with a minimum number of starts and stops and easy to implement for complex geometries. Medial axis transformation along with other skeletonisation approaches has also been studied in detail to achieve an optimised area filling algorithm [10]. Conversely, none of the existing path planning algorithms has been able to achieve all the listed requirements at the same time. Further, details on one-to-one comparison of the techniques are not completely available in the literature. Information on how these tool paths affect the final properties of the part is also not available in the literature. Hence, a comparison on various tool path techniques based on flatness achievable, minimum material skinned out during face milling (thickness of the deposited layer), time taken to complete the deposition, and the final hardness achieved are done as a part of this preliminary study. Based on the observations, identification of an optimised generic area filling tool path algorithm is attempted.

5.3 Experimental Setup

The experimental setup for weld deposition-based AM is depicted in Fig. 5.1. This system is consisting of two major units,

1. GMAW weld deposition unit (additive) and
2. CNC milling system (subtractive).

A GMA welding unit is used for the weld deposition process in which a consumable electrode is surrounded by a gas mixture (82% argon + 18% CO_2). This gas mixture encapsulates the entire weld pool to avoid the oxidation during the deposition. In the present study, ER70S-6 is used as a filler wire, in other words, electrode.

Table 5.1 Commonly used tool paths for weld-based AM

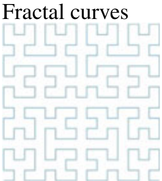
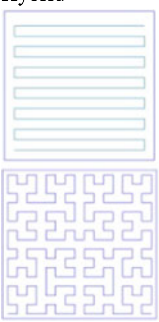
S. No.	Type of tool path	Description
1	Raster/line 	The path described is a line
2	Zigzag 	The path fills the area in a zigzag fashion
3	Contour 	Path is generated by offsetting the outline of the part towards its interior, or from inside out with suitable step-over value
4	Spiral	The path is generated by connecting the offsetted contours (either in to out or out to in)
5	Fractal curves 	Fractal curves such as Hilbert curve is used to cover an entire region
6	Hybrid 	The path is generated by combining more than one existing patterns to achieve a continuous and void free tool path

Table 5.2 Merits and limitations of commonly used tool paths for weld-based AM

S. No.	Type of tool path	Merits	Limitations
1	Raster/line	(1) Very simple to implement (2) Suitable for any arbitrary geometry with multiple pockets and islands	(1) Too many weld starts and stops leading to weld defects such as hump and crater at the start and end of the weld-bead respectively. (2) Maintenance of uniform weld bead height and layer thickness is difficult (3) Since it is unidirectional deposition, the part tends to have anisotropy in its material and physical properties (4) Does not capture the contour boundary accurately due to the discretisation errors at curvatures or edges that are neither parallel nor perpendicular to the deposition direction
2	Zigzag	(1) Simple to implement (2) Suitable for complex geometry with internal pockets and islands (3) Since the deposition happens alternately in two directions, the material and physical anisotropy of the part can be reduced (4) The path is continuous; hence, there is a significant reduction in the number of starts and stops (by dividing the complex entire region into sub-regions)	(1) Similar to line pattern, it does not capture the contour boundary accurately due to the discretisation errors at curvatures or edges that are neither parallel nor perpendicular to the deposition direction
3	Contour	(1) Suitable for complex geometry with internal pockets and islands (2) Since the deposition is made in several directions, there is minimum material and physical anisotropy in the part (3) Captures outline profile of the slice accurately	(1) The path has too many discontinuities (at the beginning and end of the contour), in turn too many starts and stop (2) Maintenance of uniform layer thickness is difficult

(continued)

Table 5.2 (continued)

S. No.	Type of tool path	Merits	Limitations
4	Spiral	(1) The path is continuous, which led to a minimum number of starts and stops (2) Similar to contour path, material and physical anisotropy of the part is minimum (3) Captures outline profile of the slice accurately	(1) Tool path generation for arbitrary shapes and geometries with islands or pockets is difficult
5	Fractal curves	(1) The path is continuous with a minimum number of starts and stops (2) The material and physical properties of the parts tends to be almost isotropic	(1) The path is highly convoluted (2) Arriving at an optimised order of curve and generation of tool path for complex geometries is laborious
6	Hybrid	(1) The path captures all the geometric details accurately (2) Suitable for complex geometries with multiple pockets and islands (3) Material and physical properties of the part tends to be almost isotropic	(1) Arriving at an optimised path is difficult

ER70S-6 is a copper-coated mild steel (MS) wire. The general composition (percentage, %) of ER70S-6 is as follows: carbon 0.075, manganese 1.22, sulphur 0.014, silicon 0.67, phosphorus 0.01, and remaining is iron. Earlier studies on ER70S-6 reveals that it is suitable for fabricating fully dense components through weld deposition-based AM process [11]. For positioning the weld torch at a specified location with the required feed, the weld torch is retrofitted with the commercially available CNC milling centre. These two units are working on a single station in a synchronous manner without disturbing the actual purpose of the machine. The optimal process parameters to achieve continuous and uniform welds in weld deposition-based AM are voltage (V), current (I), touch speed (T_S), wire feed (W_F), and contact tip to work piece distance (CTWD).

5.4 Results and Conclusions

The optimal process parameters for weld deposition-based AM (continuous welds) were found to be 19 V, 135 A, 0.36 m/min as T_S, 4.5 m/min as W_F, and 10 mm as CTWD. The bead width and height obtained using the above-mentioned optimal

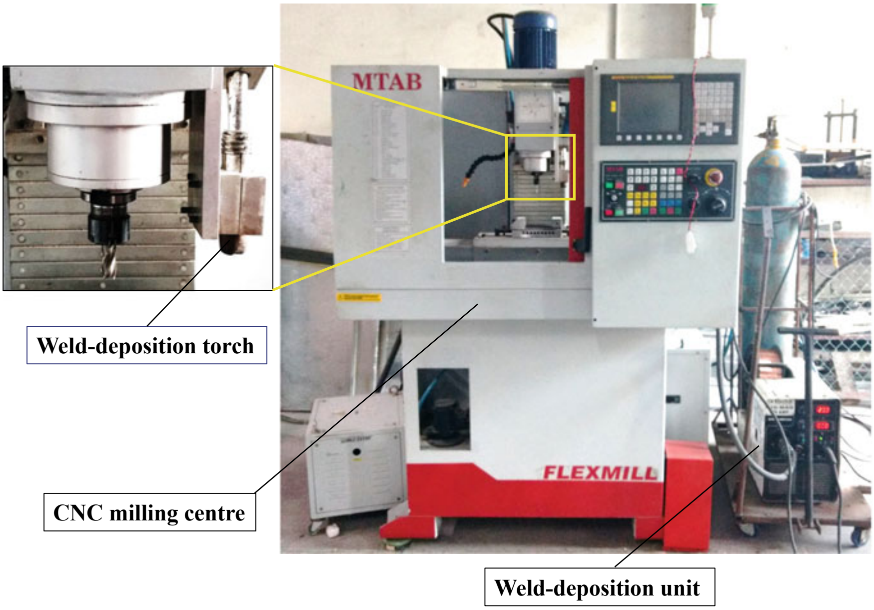


Fig. 5.1 Experimental setup

process parameters are 5.01 and 3.80 mm, respectively. The step-over value is taken as 3.30 mm (2/3rd of the bead width). For comparison of various tool paths planning listed in Table 5.1, a square geometry of 45 mm is considered for weld deposition. Figure 5.2 shows the various area filling paths considered for deposition and the final deposited layer.

After the layer deposition, face milling operation is performed to achieve the flat surface which is suitable for next deposition (Fig. 5.3). This face milling operation not only help in arriving at *Z* accuracy but also helps in removal of scales and oxides which are present on the top surface. Table 5.3 presents the comparison of various tool paths based on the weight of the deposited layer, the weight of the material skinned, the final layer thickness, and the hardness of layer deposited measured using Rockwell test (HRB, 100 kg load).

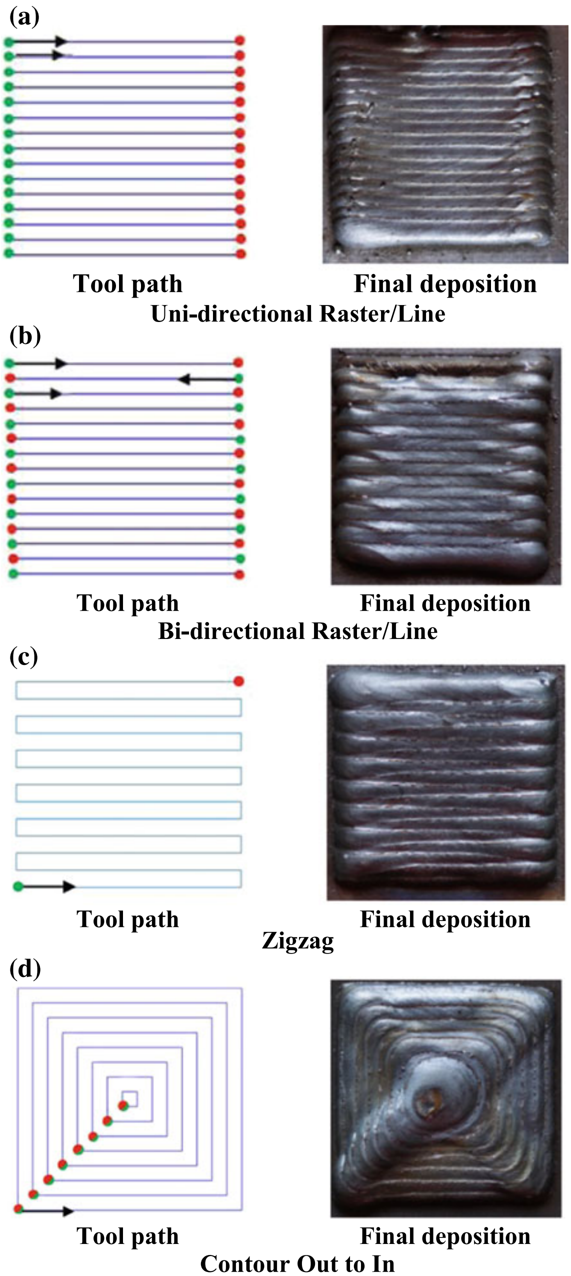


Fig. 5.2 Comparison of various tool paths used in weld-based AM

Fig. 5.2 (continued)

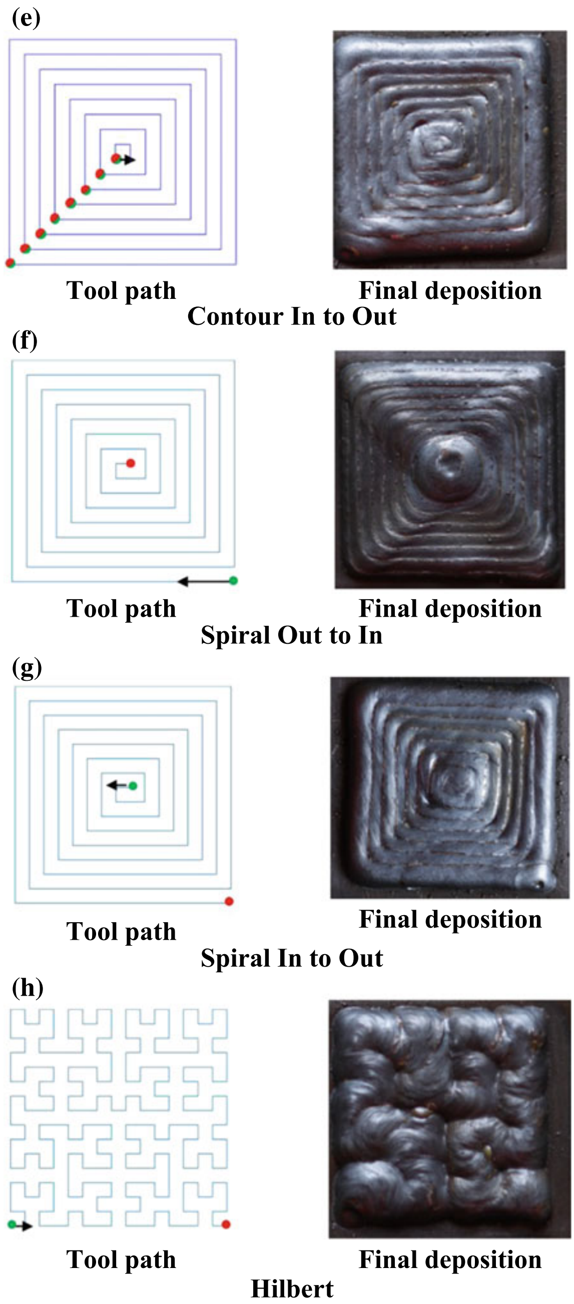
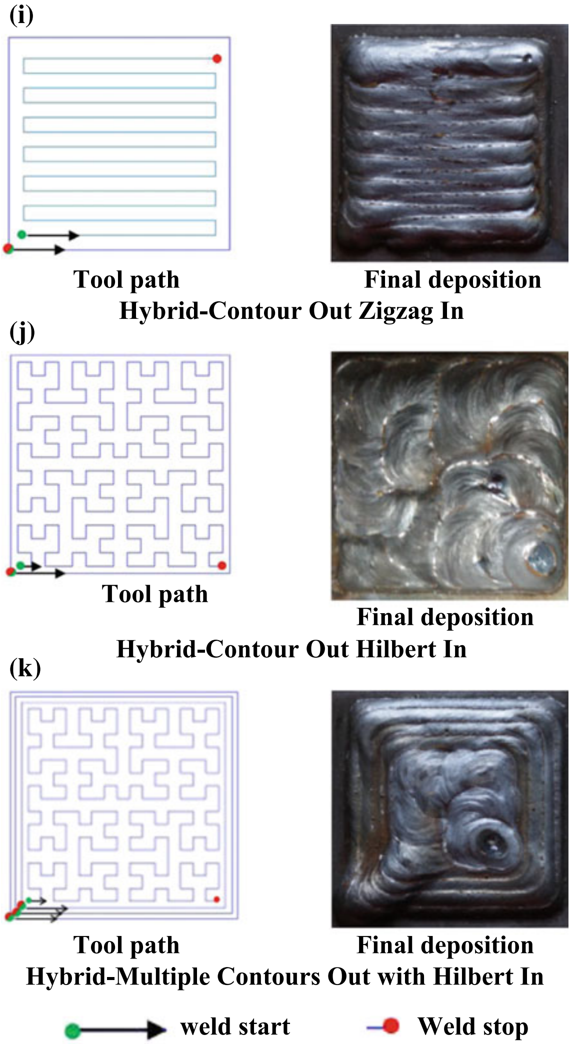


Fig. 5.2 (continued)



Based on the observations, following conclusions are drawn:

- The hybrid tool paths (layer height 3.00 mm for contour out and zigzag in, 3.04 mm and 3.02 for contour out and Hilbert in) provide maximum layer thickness and also capture the outer boundary accurately. Further, contours with Hilbert curves are densely packed and record the highest hardness values (HRB 87.00 only Hilbert, 88.00 one contour out and Hilbert in, and 88.60 three contours out and Hilbert in).
- Raster unidirectional and bidirectional (3.02 and 2.81 mm) also provides maximum layer thickness. However, the outer boundary is not completely captured. The hardness values are raster and zigzag are almost same.

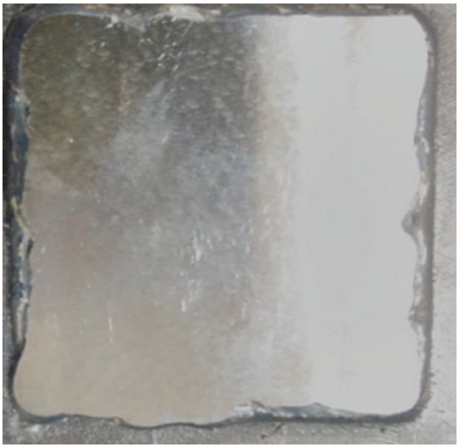


Fig. 5.3 Final layer achieved after face milling operation

- Zigzag requires less material to be skinned (10 g), and the layer thickness is also comparable with hybrid tool path.
- In case of contour tool paths and spiral paths, the layer heights after face milling operation are varying only by 0.03 mm and the hardness is slightly less than zigzag and raster.
- Spiral in to out provides higher layer thickness than spiral out to in. However, the hardness values are lower.
- In case of Hilbert, as the path is fully convoluted, voids were present in the deposited layer; hence, more material had to be skinned. To avoid this, one has to either increase the order of Hilbert curve or decrease the step-over value suitably.

Based on the above observations, it can be concluded that, for bulk material deposition, even though the material skinned is high, the hybrid tool path is suitable as the layer thickness is high; the boundary is captured well, and the hardness values are higher.

Table 5.3 Summary of results obtained from analysing various tool paths used in weld-based AM

S. No.	Type of tool path	Substrate weight (g)	Substrate plus weld deposition weight (g)	Weight of the plate after face milling (g)	Weight of the material skinned (g)	Layer height (mm)	Hardness (HRB)
1.a	Raster—unidirectional	668	734	724	10	3.02	85.66
1.b	Raster—bidirectional	662	730	716	14	2.81	85.00
2	Zigzag	652	718	708	10	2.92	85.66
3	Contour out to in	660	726	716	10	2.71	86.00
4	Contour in to out	664	734	722	12	2.68	84.30
5	Spiral out to in	664	730	714	16	2.64	81.33
6	Spiral in to out	666	732	720	12	2.83	83.33
7	Hilbert	664	730	716	14	2.84	87.00
Hybrid							
8	Contour out + zigzag in	670	736	722	14	3.00	85.00
9	Contour out + Hilbert in	666	740	722	18	3.04	88.00
10	Three contours out to in + Hilbert in	660	740	720	20	3.02	88.60

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